FRAMEWORK FOR ASSESSMENT OF ECONOMIC FEASIBILITY OF VOLTAGE SAG MITIGATION SOLUTIONS

A thesis submitted to The University of Manchester for the degree of
PhD
in the Faculty of Engineering and Physical Sciences

2010

JHAN YHEE CHAN

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

TABLE OF CONTENTS

Final Word Count: 70,853

ABSTRACT

Title: Framework for Assessment of Economic Feasibility of Voltage Mitigation Solutions

Candidate:	Jhan Yhee Chan	The University of Manchester
Degree:	Doctor of Philosophy (PhD)	30 Sep. 2010

Current practices of power quality mitigation in the industry are characterized by sub-optimal investment decisions where over compensation is often the norm such causing huge wastage in financial resources. Providing power quality management services to industrial customers in the form of power quality contracts could yield substantial return for the network operator. With better understanding of network parameters, and the option of installing network level mitigation devices, network operators could employ wider range of cost effective mitigation solutions. Tapping into the market however, entails bearing the risks for the customers which network operators are not always willing or encouraged to do. With potentially millions at stake, extensive risk assessments are crucial for any proposed power quality management scheme. This thesis investigates the voltage sag aspect of the problem as part of a larger power quality management scheme. The aim is to develop general framework for technical and financial assessments of voltage sags prior to the introduction of power quality management service. The thesis focuses on five major aspects of voltage sag assessment: identification of customer requirement, financial loss assessment, network sag performance estimation, sag mitigation, and financial appraisal of mitigating solutions. The first part of the thesis gives a comprehensive overview of current power quality problems faced by industrial customers and provides ranges of typical financial losses incurred by different types of industries around the world. It then proposes robust methodology for assessment of typical financial loss, i.e., customized customer damage function (CCDF), for a given industry based on available survey data and taking into account characteristics of the assessed customer plant. For failure and financial risk assessments, the thesis introduces new customer models employing probabilistic methods to quantify risks induced by voltage sags and proposes generic models that incorporate full flexibility in failure risk assessment, taking into account the effect of unbalanced sags on equipment behavior. It further quantifies the error introduced by sag performance estimation using limited monitoring data with a case study on actual sag profile. It demonstrates how different estimation methods and different durations of monitoring period affect accuracy of estimation of voltage sag profile and associated risk of industrial process failure. Following this, the thesis presents new models for plant and network level sag mitigation devices. They include power injecting mitigation devices, devices that reduce number of faults in the network and devices that reduce the severity of faults. Developed models are then used to investigate the cost-effectiveness of sag mitigation at different levels. Finally, the thesis presents Genetic Algorithm based methodology for deciding on optimal investment scheme in voltage sag mitigation in the network. The sensitivity of the solution to various influential parameters, including plant type and size, sensitive equipment type, process characteristics, financial loss resulting from process interruption, cost and effectiveness of mitigating solution and network fault rates is also established.

DECLARATION

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

COPYRIGHT STATEMENT

ACKNOWLEDGEMENT

I would like to express my gratitude to my supervisor Prof. Jovica Milanovic for his help, guidance and support throughout the period of this research. His ideas were truly inspirational, and the exceptional effort he spent on reviewing this thesis has led to the successful completion of this thesis.

Special acknowledgement to E.On UK for sponsoring the project, and the project members from E.On whose input and feedback ensured that the research is practically sound and inline with future needs of the industry. The E.On team includes Miss Alice Delahunty, Mr Bob Ferris, Dr. Chris Horne and Miss Kate Grant.

My appreciation to Dr. Yan Zhang, Dr. Soon Kiat Yee, Mr. Manuel Avendano-Mora and Mr. Nick Woolley for their help and advice on the issues faced in the research. Special thanks to Mr. Muhammad Ali for his help during the writing-up period of this thesis.

Last but not least, I would like to extend my gratitude to Dr. Sarat Chandra Vegunta, Dr. Mustafa Kayikci, Mr Abdulaziz Almutairi, Miss Samila Mat Zali and all other members of the Power Quality and Power System Dynamics Group in Ferranti whose friendship provided crucial mental support throughout the period of this research.

To my dearest Chui Fen

Chapter 1 Introduction

1.1 Background

Contemporary electricity customers exposed to power quality disturbances could suffer from significant financial losses as their business activities may get affected. Large penetration of sensitive devices in industrial and commercial facilities has substantially increased their susceptibility to power quality disturbance. Process disruptions as a result of equipment-electricity supply quality incompatibility translate to huge financial losses, which heavily impact the operation and in some extreme cases survival of these businesses. A recent survey estimates the annual power quality related losses at 150 billion for the European Union. [1]

From an electrical distribution company's point of view, investing in power quality mitigation could potentially bring huge return even if only a fraction of the losses (86 billion Euro) [1] is recovered. In fact, market for power quality management services have been steadily picking up, with distribution companies around the world offering enhanced quality of supply to customer in the form of power quality contracts.

By guaranteeing and providing the high level of power quality supplied to customers, a premium price of electricity is charged in return. The income from higher tariff are invested into power quality improvement schemes, with the hope that savings induced by better power quality would outweigh investment and generate a profit, and that the improved quality of supply would translate into customer satisfaction and brand loyalty.

However, like with all investments, the profitability of the investment in power quality cannot be assured without thorough knowledge of the cost and value of the service. Therefore, before venturing into potentially costly projects, it is essential to quantify the potential value of power quality in the network. In other words, customer and overall network financial losses due to power quality related disturbances.

Quantifying the financial losses caused by power quality disturbances is a complex task. Customer financial losses depend on many variables, from equipment response, process sensitivity, to the severity of the disturbances. With high levels of uncertainty in all of these variables, new techniques and methods have to be established to ensure consistency of the assessment and practicality of the approach.

On the power quality mitigation side, decisions have to be made in determining the type of mitigation, and the optimal level of mitigation. Hence, all potential mitigation schemes have to be investigated in terms of their costs and effectiveness. This involves complex modeling, simulation and optimization of the schemes using representative customer facility models, and wider network model if the solution is to be area wide.

In the United Kingdom and many other countries around the world, power quality contracts are almost non-existent at the moment. However, power quality monitoring as one of the major pre-requisites is set to be on irreversible trend, and its scale is covering entire networks. For the first time distribution network operators (DNO) will be in position to have a true image of network wide quality levels. Network level power quality management could becomes a feasible option. It is crucial for DNOs therefore to start developing models and technique for network level power quality assessment as foundation for future power quality management schemes.

1.2 Voltage Sag and Short Interruption

Amongst the array of power quality disturbances known to incur financial losses in businesses, voltage sags and short interruptions have been singled out as the most damaging of all, contributing an annual loss of 86 billion Euros in the EU [1].

Voltage sag is a decrease to between 0.1 and 0.9 p.u. in rms voltage at the power frequency for durations from 0.5 cycles to 1 minute [2]. The simplest representation of a sag is described by two sag characteristics; sag magnitude and sag duration, as shown in Figure 1-1. The lowest retained rms voltage out of the three phase voltages during the sag is defined as sag magnitude, while sag duration is defined as the time that the voltage is lower than the 0.9 p.u. threshold in all three phases. For sags recorded by monitors, sag magnitude is calculated from a one cycle instantaneous voltage updated every half cycle [3].

Besides sag magnitude and sag duration as the two most widely and frequently used sag characteristics, the other two characteristics also relevant to this research study are:

- Phase-angle shift: The difference in voltage phase angle between the pre-sag voltage and the voltage during the sag.
- Point-on-wave of sag initiation: The phase angle of the instantaneous voltage at the moment the voltage magnitude shows a significant drop.

Detailed description of the above two characteristics can be found in [4, 5].

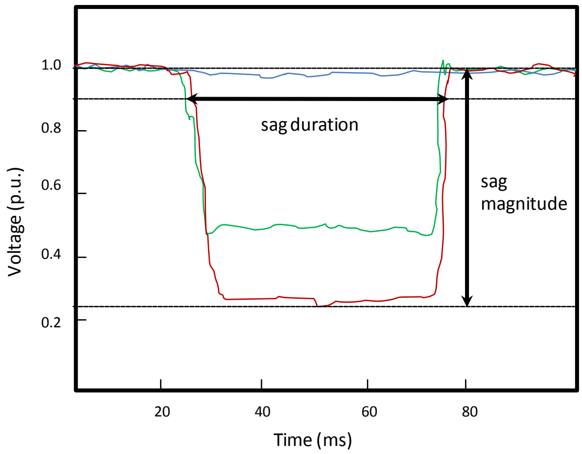


Figure 1-1 Voltage sag

Voltage sags and short interruptions are usually caused by power system faults. Figure 1-2 illustrates the principles behind fault caused sags and interruptions. From the moment the fault occurs until recloser 1 operates, Customer A will experience an interruption while all other customers will face a voltage sag. When Recloser 1 opens, the voltage sags end but the interruption remains for Customer A. A reclosing action reconnects the circuit after a set time. If the fault is permanent, the network reconnects to the fault and once again introduces a sag to Customers B to D. This process will repeat itself until Recloser 1 trips completely. As a result, Customer A encounters a sustained interruption whilst all other customers experience multiple voltage sags in quick succession. However, if the fault is temporary, and the short circuit is gone after the first recloser operation, Customer A will experience a short interruption the duration of the reclosing time setting of Recloser 1. All other customers will encounter a single voltage sag.

Different types of faults cause different types of sags. In total, there are seven general types of sags according to [6]. The most common types of voltage sags are summarized in Figure 1-3 below [6]. Type A sag is a three phase sag caused by symmetrical 3-phase faults. Type B, C and D are asymmetrical sags caused by single phase (line to ground), phase to phase (line to line), while type E, F and G sags are caused by two phase to ground (line to line to ground) faults. Voltage sags can also be caused by energizing of heavy loads and transformers, and starting of large motors.

Customers close to a low impedance fault may experience a sag so severe that it would be classified as a short interruption. Short interruptions occur when the supply voltage or load current decreases to less than 0.1 p.u for a duration not exceeding 1 minute [2]. Interruptions are solely measured by their duration since their magnitude is always less than 0.1 p.u [7]. Short interruptions may also be caused by fuse-saving arrangements in the network [6].

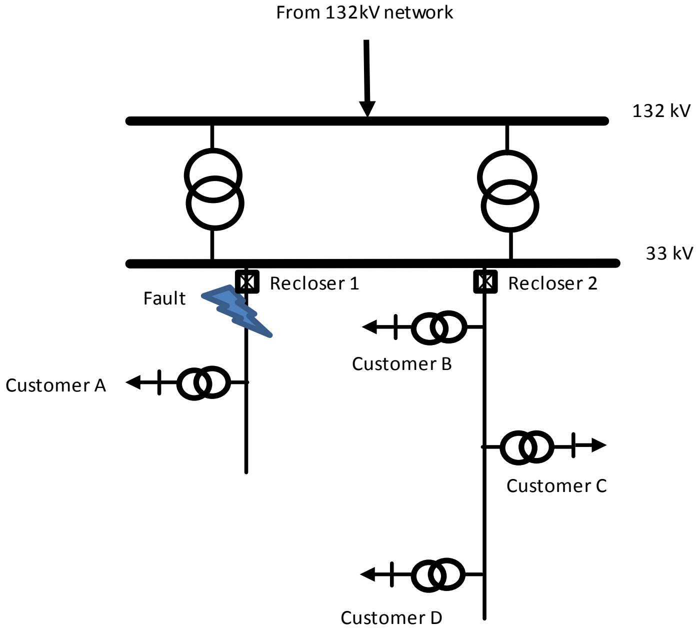


Figure 1-2 Fault caused sags and interruptions

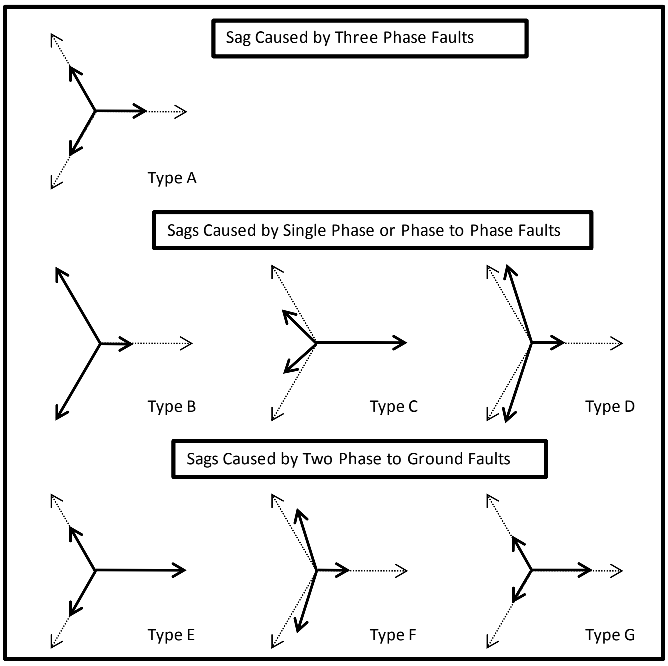


Figure 1-3 Types of voltage sags [6]

1.2.1 Voltage Sag Management Arrangements

European standard EN 50160:2007 [8] specifies that the number of voltage sags (sag magnitude <82%) in low and medium voltage networks (<35kV) shall be from a few tens to up to a thousand per year. Given that a single voltage sag could incur millions of pounds losses to a single plant, many customers with sensitive processes have found that the indicative limit is inadequate to ensure proper business operation.

Alternative arrangement for tighter voltage sag performance is set in some countries. In Norway, a limit of 24 sags per 24 hours for ≤35kV and below networks, and 12 sags per 24 hours for higher voltage networks is set by the regulator [9]. Network operators must ensure that this limit is satisfied. It is also possible to offer voltage sag management as part of a wider power quality enhancement scheme. In France, customers are able to get into customized contracts where the number of sags is limited by contractual obligations. A penalty is payable if the limit is exceeded.

Further trends in South Africa and the United States indicate that customers would consider paying higher tariffs for enhanced power quality management. A summary of power quality management schemes around the world is shown in Table 1-1. It can be seen that voltage sags are always included in the schemes and the maximum number of sags are also limited to the guaranteed level.

The role of distribution network operator in voltage sag management typically involves identifying voltage sag performance at customer busbar, installing and operating mitigation schemes and performance monitoring. Before any contract can be offered, thorough understanding of the economics of voltage sag management is crucial.

1.3 Economics of Voltage Sag

Voltage sag incurred losses and/or malfunction are compatibility issues between customer process immunity and network performance. When customer requirement is higher than network performance, some form of mitigation is needed to reduce or eliminate any sag caused losses. On the other hand, the amount to be invested in mitigation depends on the severity of the problem, and the value placed on power quality. Therefore, the economics of voltage sag is an optimization problem with the aim of minimizing the financial loss caused by sags with minimum investment.

$$Optimum\ Case = min(Sag\ Caused\ Financial\ Loss + Cost\ of\ Mitigation) \quad (1\text{-}1)$$

Table 1-1 Power Quality Management Schemes Across the World, adopted From [10]

Quality Assurance of Electricity Delivery	**EDF (France)**	**Eskom (South Africa)**	**Detroit Edison (Michigan)**	**San Diego Gas & Electric (California)**	**Duke Energy (N.Carolina)**
Benchmarking					
Against own network	Yes	Yes	Yes	Yes	Yes
Against regional network	Yes	Yes	Yes	Yes	Yes
Against national level	Yes	Yes	Yes	Yes	Yes
Methodology	Own	EPRI RBM	EPRI RBM	EPRI RBM	EPRI RBM
Index	Interruption Sag	Interruption Sag	Interruption Sag	Interruption Sag	Interruption Sag
Measurement					
Systematic	Yes	Yes	When necessary	When necessary	When necessary
Ad hoc	No	No	No	No	No
Interruptions, at PCC	Yes	Yes	Yes	Yes	Yes
Interruptions, at customer	Emeraude	On request	Acc. to agreement	Acc. to agreement	Acc. to agreement
Voltage sags	Emeraude	NRS 048	Acc. to agreement	Yes	Yes
Harmonics	EN/IEC	Yes	IEEE	IEEE	IEEE
Flicker	IEC	IEC	IEEE	IEEE	IEEE
Guarantees					
Restore time	Yes	Yes	Yes	Yes	Yes
Number of interruptions	Yes	Yes	Yes	Yes	Yes
Number of voltage sags	Yes	Yes	Yes	Yes	Yes

From the business point of view, the most important parameter in voltage sag management is the value of the service provided, given by (1-2). A positive value indicates a gain in return of investment and potential profit for both the customer (savings) and service provider. Maximizing the "value of service" brings maximum profit.

$$Value\ of\ Service = Initial\ Financial\ Losses - (Cost\ of\ Mitigation + Residual\ Losses) \quad (1\text{-}2)$$

It is clear from (1-2) that the value of service is the difference between pre and post mitigation financial cash flow. To obtain the necessary financial figures for (1-2), the interaction between network performance, customer requirement, and mitigation schemes need to be thoroughly considered, as illustrated in Figure 1-4.

Guidelines to assess financial losses at customer facilities due to voltage sags are stated in IEEE Standard 1346-1998 [2]. The aspects considered are voltage sag performance at utility and industrial plant levels, equipment compatibility to voltage sags, and financial evaluation of the losses incurred by process disruptive sags.

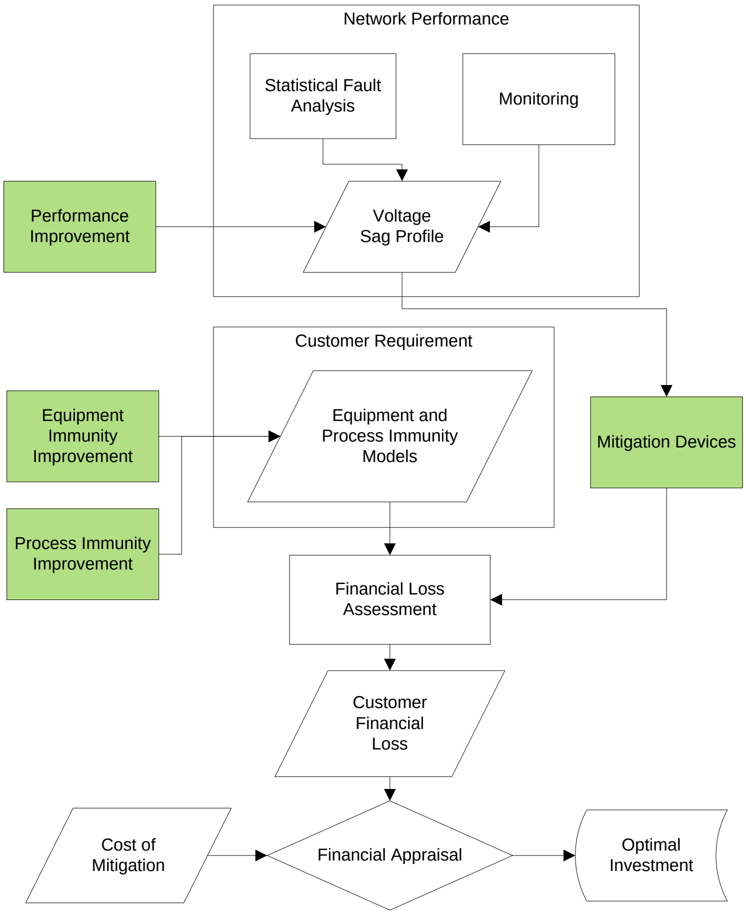


Figure 1-4 Economic considerations in voltage sag management

1.3.1 Network Performance

The performance of the network is the most important factor in voltage sag management. It represents the severity of the problem for the customer, and is the benchmark for power quality contractual terms. In financial appraisal of mitigation investments, the voltage sag profile at customer busbar is the most important input representing the magnitude of the problem faced, which directly affects the "profitability" of an investment.

A voltage sag profile is an estimation of the number of voltage sag for different sag magnitudes and durations at the point of common coupling (PCC) between network and customer plant. Voltage sag profile is usually acquired from either statistical prediction using measurement records from power quality monitors, or network simulation with historical fault profile.

Network sag performance can be represented, for this purpose in particular, using sag performance contours. Figure 1-5 shows an example of such representation. The set of contour lines shown are similar to elevation contour lines on a topographic map. Each contour curve in the figure, has a label that represents the number of voltage sags per year more severe than the corresponding voltage-duration characteristics [3]. For example, the site represented by the sag performance contours in Figure 1-5 has the 5-event contour line intersecting the 480ms duration axis at the 60% magnitude axis. This means 5 sags will have a 480ms or longer duration and have a 60% or lower magnitude. The 5-event contour line also intersects the 320ms duration axis at the 40% magnitude axis, this also means that the site has 5 sags of 320ms or longer duration and 40% or lower magnitude. More detailed explanation of the sag performance contours can be found in [3] and [11].

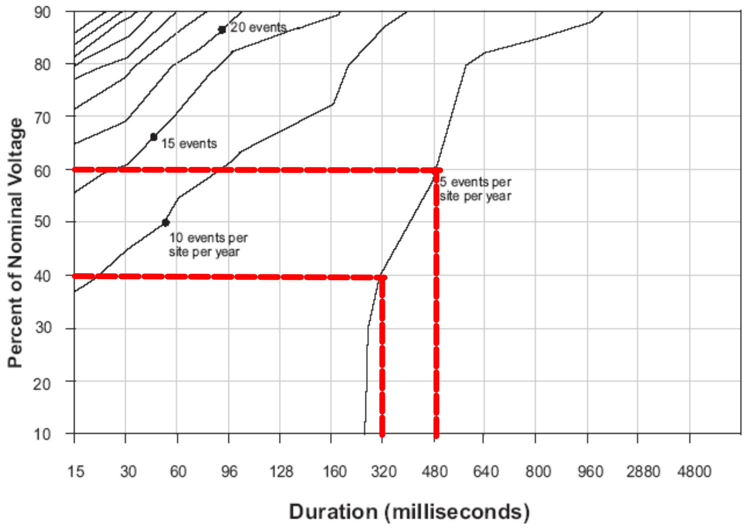


Figure 1-5 Example of supply sag performance contours. Adopted from [2]

1.3.2 Equipment and Process immunity

Equipment and process immunities to voltage sag are very comprehensively discussed in [3]. Equipment behavior when subjected to sags is usually represented with a voltage tolerance curve. In Figure 1-6, the vertical and horizontal axis represents the magnitude and duration of a voltage sag. A sag could fall on one of the three areas on the curve, causing different response from the equipment. The main focus of equipment immunity assessment is on the area of "uncertain behavior" of the voltage tolerance curve.

Equipment immunity represented by sag magnitude and duration alone is sometimes insufficient as other sag characteristics do influence equipment immunity. Table 1-2 shows the influence of different sag characteristics on different equipment.

Tripping an important equipment could lead to process disruptions. The main parameter to consider in such cases is the Process Immunity Time (PIT) [3]. PIT is the maximum time a process could continue operating after its equipment has tripped due to a sag. PIT is determined by the allowable change in process parameters following an equipment trip, and may vary from less than a second to several hours.

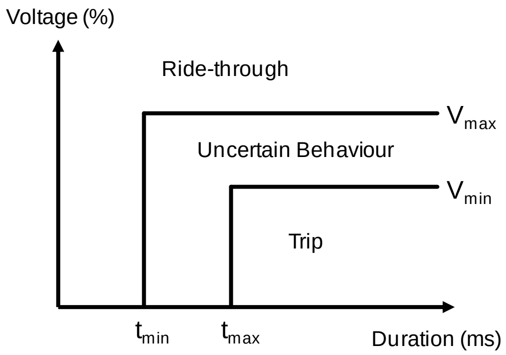


Figure 1-6 General voltage tolerance curve

Table 1-2 Impact of sag characteristics on equipment immunity. Adopted from [12]

Sag Characteristics	Sag Magnitude	Sag Duration	Point on Wave	Phase Angle Jump	Unbalance
AC Contactors	Yes	Yes	Yes		
DC Contactors	Yes	Yes			
Induction Motor	Yes	Yes		Yes	Yes
AC Adjustable Speed Drives	Yes	Yes			Yes
DC Adjustable Speed Drives	Yes	Yes		Yes	Yes
Personal Computers	Yes	Yes			
Programmable Logic Controller	Yes	Yes			

1.3.3 Process Disruptions and Financial Loss

An efficient method of representing voltage sag profile at customer facility using contour lines and comparing it with equipment voltage tolerance curve to obtain the number of disruptive sags was given in IEEE Standard 1346 [2].

Basically, equipment sensitivities (voltage tolerance curves) are overlaid on the supply sag performance contours to form sag coordination chart as shown in Figure 1-7. The sensitivity of process is defined by the most sensitive component, with knee point located at the upper most left hand portion of the chart. In the case of Figure 1-7, the most sensitive component is the double-pole-double-throw (DPDT) relay and its knee point is in the 20 to 25 sags per year band. The maximum number of voltage sags leading to process interruption therefore can be estimated (through interpolation) to be 23 per year.

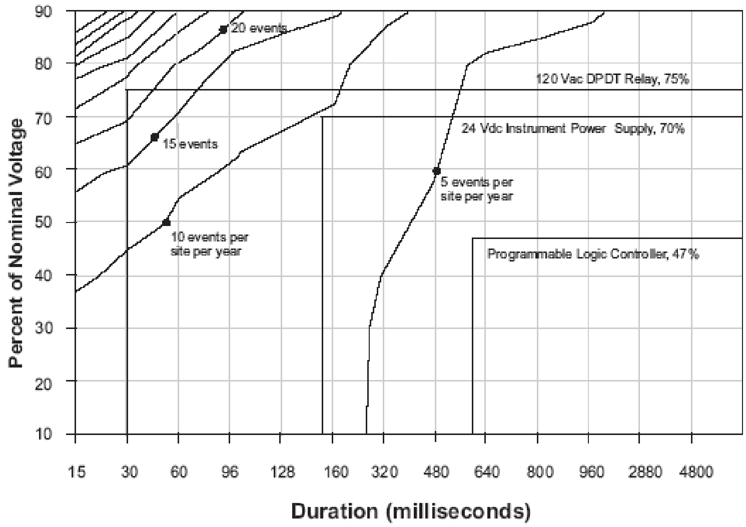


Figure 1-7 Example of voltage sag coordination chart. Adopted from [2]

The next step involves cost estimation of process disruption. All the losses involved are listed in a cost of disruption evaluation form which should be completed by those who are familiar with the operational impact of process stoppage (frontline workers, supervisors), finance, accounting, sales and marketing personnel to ensure all aspects of financial losses are considered. Briefly, the costs of disruption in industrial processes are made up of downtime related costs (lost production, idled labour, equipment damage, recovery cost), product quality related costs (scrap and rework costs) and other indirect costs (customer dissatisfaction, employee and customer safety, fines and penalties).

The total financial losses of the facility are obtained by multiplying the cost of process disruption and the number of disruptive sags per year.

The method proposed by this standard is useful for estimation of financial losses due to voltage sags. However, there are a few important issues yet to be addressed. These issues include:

- The sensitivity of the entire industrial process is determined by the most sensitive equipment in the process. This assumption may not be appropriate because the process sensitivity also depends on the function and significance of the equipment involved. Tripping of the most sensitive equipment does not necessarily disrupt the entire process.

- The interconnections between equipment and sub-processes have significant impact on process operation but are not considered in this standard.
- It is shown that all equipment types have a range of voltage tolerance. This range is not considered in the method when evaluating the number of disruptive sags.
- The cost values used for financial assessment are based of historical data or experience; this may not be useful for evaluation of new industries at the planning stage.
- Cost related data require insight knowledge of sensitive financial information which is not readily available for the network operator.

1.3.4 Mitigation

Voltage sag mitigation can be approached from different levels by different stakeholders. For example, equipment manufacturers can improve voltage sag ride-through by increasing equipment immunity in the design phase. Plant engineers can take extra considerations in getting the right control settings for equipment level ride-through improvement. Plant owners can install sag protection devices for a group of processes or the entire plant, while network operator can improve network performance by reducing faults, or reducing fault clearing times. It is generally agreed that the mitigation cost increases when sag mitigation is performed at a higher level, as shown in Figure 1-8.

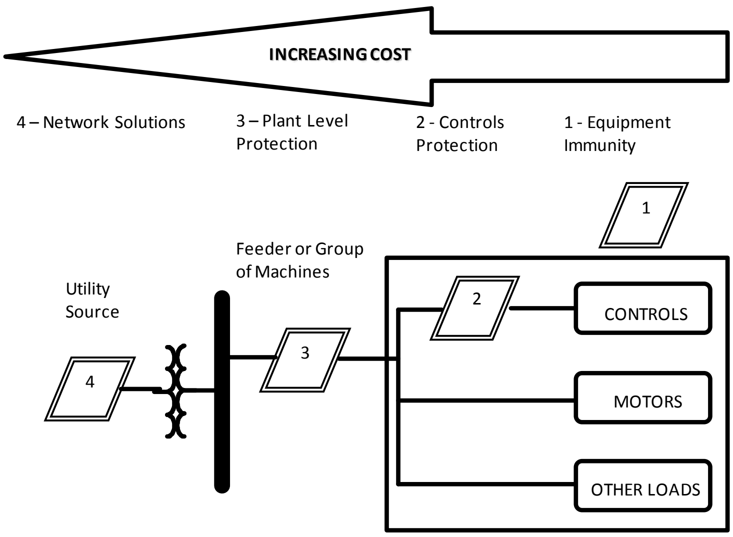


Figure 1-8 Levels of voltage sag mitigation. Adopted from [13]

On the other hand, the effectiveness of mitigation varies on a case by case basis and cannot be determined without further investigation into customer equipment and process immunity to incoming voltage sags.

1.3.5 Financial Appraisal

Assessment of voltage sag mitigation would often produce several technically feasible solutions. These solution options would have different costs and effectiveness, hence requiring proper financial appraisal tools to ensure that the most suitable option is selected. Based on [14], financial appraisal tools are divided into two categories; those that take into account the time value of money, and those that do not.

It is generally agreed that money received today can be invested to earn interests that it becomes more valuable than the same amount of money received in the future. If this early preference of money needs to be taken into account, discounted cash flow tools are used. The most common of all is the Net Present Value (NPV) method. NPV converts all spending from the future into the present equivalent, assuming a discount rate that represents the effect of interest.

$$NPV = I + \frac{CF_1}{(1+n)^1} + \frac{CF_2}{(1+n)^2} + \cdots + \frac{CF_t}{(1+n)^t} \tag{1-3}$$

Where:

NPV	=	net present worth in monetary terms
I	=	initial investment
CF	=	net cash flow at the end of year
n	=	discount rate
t	=	project lifetime

When a quick assessment is needed, rough estimates of project viability could be determined using non-discounted cash flow tools such as Payback Time and Break Even Analysis [14].

1.4 Literature Review

1.4.1 Estimating Sag Performance in the Network

For sag investment analysis that extends to tens of years, proper estimation of the sag performance at customer busbar for the entire period of analysis is crucial. Voltage sag profile at customer busbar provides information regarding the density of voltage sag and short interruption events of various severity levels. Normally, this information is obtained from historical data or from site monitoring. However, when there are no records available, voltage sag profile has to be estimated.

Fault positioning method is the most common method used to determine sag magnitudes and durations of voltage sags occurring in the network. This method calculates sag magnitude and duration by simulating faults at different parts of a modelled network. The use of this method is demonstrated in [15-18]. By combining fault positioning method with historical network information, and through stochastic treatment, researchers [19-21] were able to estimate the network performance easily.

Though these estimations are theoretically sound, they are only as accurate as the information used in network modeling. Network parameters crucial for fault positioning analysis such as historical fault rates of feeders and transformers are in most circumstances inaccurate. Without precise information, any assumptions made would undoubtedly and seriously compromise accuracy, as proven by the 42% error obtained in [21].

Recent trend to install power quality monitors across networks poses a new potential for better sag performance estimation. With sufficient monitoring period, long term sag performance at customer busbar could be predicted. However, one common concern for such an approach is the required period of monitoring to ensure accurate representation of customer profile. In other words, how long should one monitor to yield acceptable accuracy in estimation? According to [22], the answer to this question depends on the occurrence frequency of events (e.g. trips), where a shorter monitoring period is needed for frequent events, and much longer monitoring period is required for rare events. Table 1-3 (adopted from [22]) shows the monitoring period required to achieve a certain level of accuracy.

Table 1-3 Monitoring period and accuracy in estimation. Adopted from [22]

Event Frequency	Required Accuracy		
	50%	10%	2%
1 per day	2 weeks	1 year	25 years
1 per week	4 months	7 years	200 years
1 per month	1 year	30 years	800 years
1 per year	16 years	400 years	10000 years

***Problem Statement 1:** Though [22] established the general figures in Table 1-3**,** the accuracy of estimation is not calculated with financial loss in mind. With more and more monitoring devices being deployed in networks around the world, it is crucial that the accuracy of sag performance estimation is clearly quantified in financial terms.*

1.4.2 Financial Loss Assessment of Voltage Sags and Short Interruptions

Over these years, various methods have been proposed to overcome the shortfall of current standards, and place a value on voltage sag and short interruption caused events. There are two main approaches to the assessment: analytical analysis and indirect analysis.

1.4.2.1 Analytical Economic Analysis

In analytical analysis, financial losses due to power quality disturbances are often calculated or estimated through detailed assessment processes. These assessments generally involve modeling of customer equipment and process immunities, calculation of number of process disruptions, and calculation of the costs of process disruptions.

In the past, some researches focused on network wide [15, 16] losses, while others concentrated on loss assessment for specific customers [23-27], with the later involving customer process modeling to a greater detail.

The immunity of equipment used in industrial processes directly influences the response of the processes towards incoming voltage sags and interruptions, and therefore has direct impact on the financial losses consequent to these events. Voltage tolerance curves can be obtained from either the equipment manufacturer or standards available. The commonly used standards for characterizing equipment sensitivity are the Computer Business Equipment Manufacturers Association (CBEMA) curve, Information Technology Industry Council (ITIC) curve [28] and the "semiconductor processing" (SEMIF47) curve [29].

Due to the reason that different types of equipment exhibit different sensitivities to voltage sag events, equipment specific voltage tolerance curves developed from laboratory tests are developed in [30-32].

According to IEEE Standard 1346-1998 [2], there is a range of voltage tolerance where equipment behavior in this range is uncertain. To account for this uncertainty, fuzzy logic [33] and probabilistic methods [17, 18, 34-36] are being developed and used in assessment of equipment sensitivity to voltage sags.

In probabilistic assessments [17, 35, 36], the area of uncertainty in equipment behavior is represented by a distribution function. Instead of a definite response, voltage sags that fall in the area would be assessed and given a probabilistic risk of equipment failure.

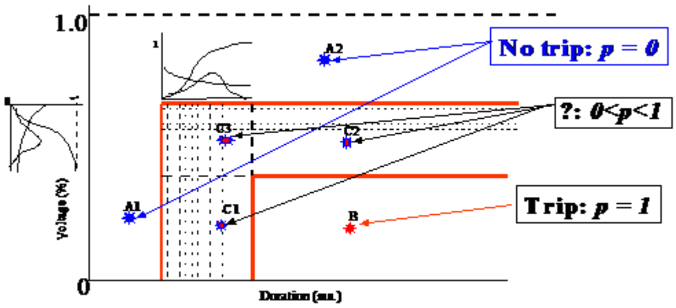


Figure 1-9 Expected behaviour of sensitive equipment against voltage sags of different characteristics. Adopted from [17]

A major advantage of probabilistic method is that the uncertainties regarding equipment sensitivity are represented using probability density functions. Probabilistic representation is more realistic and efficient as compared to deterministic approach, especially when large number of equipment is to be evaluated. Furthermore, there is flexibility for different equipment sensitivity level to be represented using different probability density functions. However, the probability distribution functions chosen for equipment sensitivity evaluation are based on hypothetical decisions. The actual probabilistic distributions were not modelled.

To date, the most flexible method developed for equipment level assessment is probably the fuzzy logic model [33]. With this method, the area of uncertainty in equipment immunity is modelled using an artificial curve fitted to resemble the probability density function of actual equipment test results. The model is also flexible enough to consider different levels of equipment sensitivities, as shown in Figure 1-10.

Problem Statement 2: *Even the state of the art models for assessment of equipment sensitivity only use the most severely affected phase, and still do not account adequately for three-phase unbalanced sags. Given that equipment immunity is such an important factor that determines customer financial loss, better models are inevitably needed to ensure viable assessments.*

On a higher level, process sensitivity depends on many factors, including equipment interconnections, composition ratio of equipment, function and significance of each equipment type, and the relationship between equipment failure modes and process operation. To address these factors, various different approaches are being developed by researchers around the world. The approaches include probabilistic method [17, 18, 34], fault tree analysis [37, 38], fuzzy logic [38], loss of voltage during sag [39], loss of energy during sag [39] and one-parameter characterization method [39].

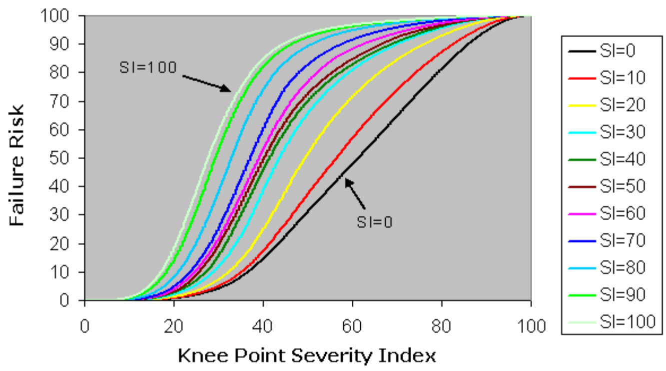


Figure 1-10 Output of fuzzy model with various levels of equipment sensitivity. Adopted from [33]

One particularly interesting method is presented in a report by STRI AB, Sweden [40], where a structural way to investigate voltage sag immunity of industrial processes, and their related costs is proposed. The idea of cost index and fault index is proposed to represent process contribution to the overall cost due to voltage sags, and the fault frequency of the process. This method can be effectively used to determine the financial losses of processes due to voltage sags and is also capable of including the interconnections of sub-processes into calculations.

Problem Statement 3: *Despite the number of studies involved in process level assessments, there are two important components that are still missing. The influence of Process Immunity Time on process disruptions and assessment of financial loss due to process disruptions at different stages of the process.*

With information of voltage sag profile and customer load sensitivity in hand, the number of process disruptive sags can be determined. The subsequent step involves estimation of the financial losses due to process disruption.

There are several studies [26, 41-44] that proposed detailed procedures to calculate the costs associated with voltage sags. Cost calculation involves careful investigation of all direct and indirect costs caused by voltage sags. Theoretical and mathematical formulas are derived to represent various causes of losses. The cost function of equipment, sub-processes and processes are then incorporated into the technical states of the processes to determine the financial costs of each process and the plant.

Determining the cost of voltage sag and interruption from calculations will generate very accurate cost estimation for every sag events. However, one may need huge amount of information regarding all direct and indirect costs regarding every sub-process and process of a plant. Some costs are difficult to obtain without time consuming and detailed investigation, which is sometimes prevented by business confidentiality.

Over the years, numerous surveys have been done around the world to gather information regarding financial losses of various industrial, agricultural, commercial and even residential customers. By reviewing the studies till date, the financial loss information can be gathered and aggregated to represent different customer types and sizes. This information can be conveniently used to estimate power quality related costs of a particular customer.

To obtain realistic cost estimation from historical events, one would have to use historical values from the customer type that best resembles the customer of concern. Ideally, the historical values used should be obtained from customers of similar nature and size, and within the same geographical region as the customer of concern. Unfortunately, information gathered from historical events till date is still insufficient to meet the abovementioned requirements. Most studies produced cost values for total power interruption (CIC), not considering the impact of other power quality disturbances. Some managed to produce cost values of voltage sags but have yet to obtain cost values for different severity levels of voltage sags.

In most cases, the losses incurred by voltage sags had to be adopted from customer interruption cost (CIC). CIC is the financial damage on customers incurred by power interruption (outages) of a specified duration [45]. Customer damage functions due to power interruption are well studied and documented, thus provide a convenient reference for voltage sag related cost analysis. CIC is used in [17, 36, 46, 47] for voltage sag studies.

Basically, CIC can be obtained from survey results. Information is obtained from large number of customers of various industrial sectors. This information is then analyzed, aggregated, and averaged to give a general cost per voltage sag or cost per kW of power per voltage sag (normalized cost) [23] for various industrial sector. Studies that use cost per event for voltage sag financial analysis include [15-18]， while [23, 48] uses cost per kW power per voltage sag event for evaluation. Specifically, [49] proposed a power quality index that uses CIC/kWh for financial loss assessment.

Some studies realize that the cost may vary for different process disruption events depending on the severity of events. Therefore, weighted cost per sag method is used in [34, 37, 50-53] where different weighting factors are assigned to different magnitudes of voltage sags. In this way, cost of severe sags are equal to cost of interruption, while less severe sags incur a fraction of the cost of interruption.

Problem Statement 4: *Using CIC from surveys is indeed convenient, but with so many different surveys conducted by different researchers around the world, questions arise as to which survey result to use and how to condition raw results before they can be used in further studies.*

In addition to the above, there are also ways to estimate the economic impact of voltage sags and short interruptions indirectly. In [27] the power consumption of customer plant is used as basis for cost evaluation. The losses incurred by voltage sags and short interruptions are estimated as a percentage of the annual cost of power consumption.

1.4.2.2 Indirect Economic Analysis

When the information required for analytical economic analysis is not available, indirect economic analysis is the only option to estimate the financial losses due to power quality disturbances. Common ways of analysis include the customer willingness to pay method [54], customer willingness to accept method [54], and cost estimation from the size and value of mitigation solutions.

The customer's willingness to pay (WTP) method has been used in several studies [54-56] to obtain the costs of power supply interruptions. Usually, customers are given several hypothetical outage scenarios and asked to express the amount of money that there are willing to pay in order to avoid each outage scenarios. In terms of power quality, customers are asked to express their willingness to pay for different levels of power quality improvements. Though the WTP method may not be as technical as the analytical approaches, it reflects the value customers place on electricity supply and power quality.

However, one should anticipate the amount a customer is willing to pay to be lower than the actual financial damage caused by power quality disturbance [54]. This is because economic benefit could only be achieved if the financial damage due to power interruption is greater than the amount paid to avoid the damage. Therefore, from the customers' point of view, the WTP amount will always be less than the actual damage due to power quality disturbances.

Besides, the WTP method only makes sense when customers understand the damaging effects that power supply interruption has on their processes. Usually, the effects of total power interruption are more apparent and well-known. However, the effects of other power quality disturbances such as voltage sags that cause partial disruption of processes are not straightforward. In most cases, customers do not know the financial damages due to power quality disturbances, and therefore cannot place an accurate WTP value on them.

In the customer's willingness to accept (WTA) method, electricity users are given various imaginary outage scenarios and asked to estimate the amount of compensation that they are willing to accept for each outage scenario. The WTA are similar to the WTP method as they both require customers to place a monetary value on hypothetical outage scenarios. However, in most cases, the WTA method gives substantially larger values compared to the WTP method. According to [54], the reason behind this is that customers consider electricity supply as a social right rather than a market commodity. It is also recommended by [54] that the two methods can be used together to produce upper and lower limits for power interruption costs.

Both WTP and WTA methods are heavily dependent upon customer's subjectivity in placing a value on power quality costs, and may be influenced by other considerations, such as customer's perception on electricity supply, their knowledge on power quality disturbances, and their ability to pay.

Overall, cost estimations without considering customer's equipment and process sensitivities will not produce financial loss values as accurate as analytical approaches.

1.4.3 Sag Mitigation

Studies on sag mitigation have provided insight into the types of mitigation options available. In general, all sag mitigations employ one of the following principles [57]:

- Improvement of equipment immunity.
- Injection of power to compensate lost voltage.
- Provide redundancy in supply.
- Preventing sags from propagating to sensitive loads.
- Reducing the number and duration of faults.

Equipment immunity can be improved at equipment design phase (e.g. increasing capacitor size), the controls settings (e.g. tuning the protection settings), and installing mitigation devices (e.g. coil holding devices for contactors) [57].

Improving equipment tolerance can be very cost effective in the long run given similar nature of most solutions. With new proposed equipment immunity standards [3] on the way, plant owners will have much more flexibility in choosing the right level of equipment immunity for their plant. However, even the highest equipment tolerance class (Class A [3]) would not survive deep sags (<40%) with long durations (>200ms). Hence, improving equipment immunity alone would not solve all disruptions. Moreover, immunity of existing equipment would not be covered by any new standards, and would have to be improved through conventional methods. Also, not all equipment employed in industrial and commercial processes need the same level of immunity. If blanket improvement across the range is done some of the equipment might end up being "over immune" and many of the users would end up paying for the level of immunity that they do not need.

Ways to improve equipment immunity is a very specified subject as different equipment requires different approach. Hence this thesis will not consider the technical side of improving equipment immunity, but focusing on the economic return for improved immunity.

On the other hand, new technologies of devices that inject power to compensate lost voltage have been continuously proposed and experimented within actual facilities. The most common devices used are dynamic voltage restorers (DVR) [46, 58, 59], static VAR compensator (SVC) [46, 58], distribution static compensator (DSTATCOM) [46, 58, 60], and uninterruptible power supplies (UPS) [61]. These devices inject power from either stored energy or from less affected lines on the network. Studies [62, 63] provide an overview of existing storage technologies. Stored energy can be in the form of capacitors (reactive power) [63], chemical batteries [63], superconducting magnetic energy storage [64], or rotating mass (flywheels) [62].

In terms of economic evaluation, comprehensive studies [47, 65-69] have developed general technique in choosing the optimal device for network wide assessment and specific customer plants. This area of research is considered saturated. However, almost all past studies were done based on simple customer plant models. Repeating the studies with more realistic customer models would provide useful improvements in the field by proposing practical solutions for classes of customers.

To increase redundancy in supply, customer plants can be supplied from two independent sources, with one main supply and a standby supply. The standby supply can be from an alternate power line or energy storage [70]. A fast switch is required to switch supply during a sag or interruption. Practical use transfer switch is demonstrated in [71]. Due to the expensive nature of supplying standby feeders and static switches, thorough economic analysis is still needed in this area.

To prevent voltage sag from propagating to customer site, the system has to be designed such that minimum number of sags reaches customer load. An effective way is to isolate customer site from other users through dedicated feeders [72]. This ensures that no sags originate downstream of the busbar connecting the customer feeder. If this is not possible, reducing the number of feeders originating from the same bus would limit the number of faults leading to a voltage sag for equipment fed from that bus [57]. Connecting the customer to higher voltage level improves the fault level ratio between customer and network, and prevents sags from lower voltage levels from affecting customer busbar [72]. These methods to reduce sag propagation can also be achieved through network reconfiguration [72-74]. The use of fault current limiters [75-77] to alter system impedances during fault has also been proven successful in reducing sag propagation. Placement of fault current limiters at strategic locations around the network can reduce the severity of sags at selected busbars. However, the effectiveness of fault current limiters needs to be quantified economically.

The final approach for sag mitigation is fault reduction. To achieve this, the causes of faults have to be identified and mitigated. In the past, numerous studies have investigated technical options to reduce faults caused by animals [78-80] , weather [81-84] and trees [85, 86]. The most common options for protection from animals are animal guards, electric fences and acoustic devices [78]. Lowering ground resistance of tower [57], shield wires [81], surge arresters [84] and underground cables [57]would reduce lightning caused faults. The use of covered overhead wire [87] would reduce tree and other contact induced short circuit faults such as those by wind and animals. Other approaches include increasing tree trimming schedule [85, 86] and improved hardware replacement strategy [86].

Problem Statement 5: *Most of the technical approaches discussed in the past were not designed for economic quantification. Therefore, the true cost effectiveness of these approaches are not well known.*

Problem Statement 6: *Investigations into optimal voltage sag mitigation combining different mitigation approaches and taking into account the economic benefits of those would be of great value as they would lead to practical and feasible solutions.*

1.4.4 Summary

Review of past research in the field identified several areas that need to be addressed. These areas are summarized as follow:

Problem Statement 1: *Though [22] established the general figures in Table 1-3***,** *the accuracy of estimation is not calculated with financial loss in mind. With more and more monitoring devices being deployed in networks around the world, it is crucial that the accuracy of sag performance estimation is clearly quantified in financial terms.*

Problem Statement 2: *Even the state of the art models for assessment of equipment sensitivity only use the most severely affected phase, and still do not account adequately for three-phase unbalanced sags. Given that equipment immunity is such an important factor that determines customer financial loss, better models are inevitably needed to ensure viable assessments.*

Problem Statement 3: *Despite the number of studies involved in process level assessments, there are two important components that are still missing. The influence of Process Immunity Time on process disruptions and assessment of financial loss due to process disruptions at different stages of the process varies.*

Problem Statement 4: *Using CIC from surveys is indeed convenient, but with so many different surveys conducted by different researchers around the world, questions arise as to which survey result to use and how to condition raw results before they can be used in further studies.*

Problem Statement 5: *Most of the technical approaches discussed in the past were not designed for economic quantification. Therefore, the true cost effectiveness of these approaches are not well known.*

Problem Statement 6: *Investigations into optimal voltage sag mitigation combining different mitigation approaches and taking into account the economic benefits of those would be of great value as they would lead to practical and feasible solutions.*

1.5 Aims of Research

This research aims to address the issues that have not been satisfactorily resolved in the past and to provide answer to the problems identified. The main objective is to establish comprehensive understanding of all relevant aspects involved in voltage sag economic assessment. The main aims of the research are:

1. To summarize power quality disturbances experienced by customers, and types of sensitive equipment whose trip or mal-operation causes process disruptions.
2. To provide critical overview and summary of past studies conducted to quantify the cost of voltage sags and interruptions, and establish typical financial loss value from these studies.
3. To develop methodology to calculate customized customer damage function for different classes of customers based on past studies.
4. To investigate methods for sag performance estimation taking into account uncertainty caused by different periods of monitoring.
5. To develop equipment models for sag studies that take into account phase unbalance in voltage sags, i.e., asymmetrical voltage sags.
6. To develop industrial/commercial process models that include PIT and process cycle into financial loss assessment.
7. To develop methodology for economic assessment of solutions that allows for decoupling of the technical and financial aspects of the assessments.

8. To investigate available techno-economic options for improvement of sag performance in the network.
9. To establish potential value for the distribution company in reducing voltage sags and short interruptions
10. To optimize sag mitigation combining common mitigation approaches in an actual UK distribution network.
11. To develop technical software for assessment of customer financial losses due to voltage sags and short interruptions, and for calculation of customized customer damage functions based on the methodologies developed.

1.6 Major Contributions of the Research

The research has contributed to several areas in the field of voltage sag economic assessment. These contributions are summarized in the following sub-sections.

(Note: Paper numbers given in the parentheses indicate that the related results are published in international journals, in proceedings of international conferences or in technical reports. A full list of thesis-based publications is given in Appendix E.).

1.6.1 Calculation of Nominal Financial Loss

Presented in Chapter 3, the research provided comprehensive summary of past studies conducted to quantify the nominal financial loss due to voltage sags and interruptions. Typical financial loss values for various classes of industrial and commercial customers is established. (E8)

Using the typical losses obtained from various studies as input, a methodology for calculation of customized customer damage function for different classes of customers is developed. This methodology is presented in Chapter 4. (E6)

1.6.2 Equipment Sensitivity to Voltage Sag

The research developed comprehensive models for assessment of equipment sensitivity to voltage sags. The concept of severity indices is extended to assess equipment response to asymmetrical sags. Equipment models for the most common sensitive devices, namely programmable logic controllers, personal computers, AC contactors and adjustable speed drives are developed, using probabilistic and fuzzy logic methods. These model converts physical voltage sags experienced by the equipment into equipment failure risks. These models are presented in Chapter 5. (E1) (E3) (E4)

1.6.3 Industrial Grade Assessment Software

A software tool is developed for practical implementation of the developed methodology for calculation of customized customer damage functions, and implementation of equipment and failure risk models for financial impact assessment due to voltage sags and interruptions.. The software is developed for a UK distribution network operator to assist in strategic planning of network investments in reliability improvement and voltage sag mitigation. (E9)

1.6.4 Network Sag Profile Estimation

The research explored the uncertainties posed by sag performance estimation from voltage sag monitoring. It demonstrates how different methods and different durations of monitoring period affect accuracy of sag profile modelling. Results are presented in Chapter 5. (E5)

1.6.5 Financial Loss Assessment of Voltage Sag

The research investigated the factors that influence the outcome of financial loss analysis in voltage sag studies. Parameters of the financial loss assessment, namely, process operation cycle and process load profile, that typically were not considered in the past in this type of studies, were taken into account. The effects of the individual factors are analysed through Monte Carlo simulation. The research is discussed in Chapter 5. (E2)

1.6.6 Framework for Financial Appraisal of Mitigation Solutions

A framework for general financial appraisal analysis is proposed to demonstrate the use of proper appraisal tools to obtain the best mitigation option, taking into account the uncertainties of various assessment parameters. This framework is presented in Chapter 6. (E7)

1.6.7 Optimal Sag Mitigation

The research obtained the typical value of optimal deployment of mitigating solutions in reducing financial loss of industrial customers caused by voltage sags. Various power injecting devices, redundant supply and network level fault reduction solutions are modelled and optimally deployed in an actual UK distribution network. The value of each mitigating solution for a range of industrial/commercial plants is obtained for the first time. The sensitivity of the assessment to different input parameters, such as the type and size of customer plant, sensitive equipment type, customer process characteristics, financial loss resulting from process interruption, cost and effectiveness of mitigating solution and network fault rates are also found. The models developed and the assessments are presented in Chapter 6 and Chapter 7 respectively.

1.6.8 High Quality Power Zones

The financial benefit of grouping customer plants into a single location with high quality of electricity supply is explored. The research obtained potential savings in mitigation costs achieved through cost sharing amongst plants within the zone, and the potential savings achieved through demand side management. The results are presented in Chapter 8.

1.7 Overview of the Thesis

This dissertation consists of nine chapters. The outline of the dissertation is detailed below:

Chapter 1: Introduction

This chapter provides background knowledge in voltage sag and short interruption phenomenon, a summary of voltage sag management arrangements around the world, and an overview of economic considerations in voltage sag management. This is followed by an in depth literature review of past studies and the state of the art technique in sag performance estimation, voltage sag financial assessment and mitigation. Problems identified in the review is then summarized to formulate a set of aims for the research, which is presented at the final section of the chapter.

Chapter 2: Power Quality In End User Facility

This chapter summarizes power quality disturbances experienced by industrial, commercial and residential customers, and identifies sensitive equipment that are known to trip causing process disruptions.

Chapter 3: The Cost of Voltage Sags and Interruptions

This chapter provides a comprehensive summary of past studies conducted to quantify the nominal financial loss due to voltage sags and interruptions. Typical financial loss values for various classes of industrial and commercial customers is established.

Chapter 4: Customized Customer Damage Functions

A new method capable of combining loss values from different studies is proposed. This method is demonstrated to obtain customized damage functions for a selected customer plant.

Chapter 5: Voltage Sag Risk Assessment

This chapter proposes new equipment and process models for failure risk assessments. These models solve the shortfalls identified in current models, and provide more realistic results in sag assessment. The chapter also investigates factors that influence financial risk in sag assessments, including the uncertainties in sag performance estimation, customer load and process cycle. In addition, software tool is developed for practical implementation of the developed methodologies and models. The software will be used by a UK distribution network operator to assist in strategic planning of network investments in reliability improvement and voltage sag mitigation.

Chapter 6: Modeling of Mitigation Devices and Solutions

This chapter presents models of mitigation devices, and provides a demonstration on financial appraisal of mitigation devices. A technique is proposed to isolate the technical and financial aspects of appraisal to account for potential confidentiality in financial values.

Chapter 7: The Value of Voltage Sag Mitigation

A series of simulations of mitigation devices is performed on an actual UK distribution network model. Mitigation devices are deployed in different locations in the network, with their effectiveness assessed using models developed in previous chapters. The results obtained are analyzed and compared with all other mitigation options. The best mitigation scheme is obtained using Genetic Algorithm Search.

Chapter 8: High Quality Power Zone

A series of simulations of mitigation devices is performed on an actual UK distribution network model, with a group of customer plants placed in a High Quality Power Zone. The potential savings in financial loss as a result of customer segregation are investigated, and discussed in this chapter.

.

Chapter 9: Conclusions and Future Work

The main conclusions of the research are discussed and suggestions are given for future works and potential improvements on the models and methodologies developed.

Chapter 2 Power Quality at End User Facility

2.1 Introduction

Investment in power quality mitigation is aimed at and ultimately paid for by the end user. From the service provider's point of view, a firm knowledge of customer requirement for power quality is the first step of the equation. Understanding the type of disturbance that customers are susceptible to would form the basis of mitigation strategy. On the other hand, it is equally important to recognize the type of sensitive equipment used by specific industrial customers, so that similar equipment can be tested for sag immunity and suitable equipment models can be developed.

This chapter provides a summary on typical customer requirements for power quality of various industrial, commercial and residential customers. The main focus is on end user immunity to voltage sag. A summary of typical sensitive devices and power quality disturbance known to have caused process disruption to customer facility is also presented.

2.2 Continuous Processes

2.2.1 Paper Industry

High quality power supply is essential in the main production line of the paper industry to enable synchronized and precise operation of coupled motors [88]. Voltage sags and momentary interruptions being the main power quality problems in the industry, often cause process interruption by tripping the paper machine. In a case at the South African Pulp and Paper Company plant, voltage sags of less that 80% retained magnitude and longer than 40ms sag duration cause paper breaks and long downtime [88]. In the case of the Caledonian paper mill, voltage sag of less than 90% retained magnitude trips the protection of DC drives, which halts the paper machine [88]. As paper manufacturing is a continuous process, tripping of the paper machine causes other areas to stop production.

In terms of equipment sensitivity, typically, the most sensitive equipment are the high horsepower paper machine DC drives and large variable speed AC drives that supply the stock to the paper machines. Smaller DC drives are also very sensitive to voltage sags [89].

Besides, motor loads with electromechanical controls may be easily tripped by voltage sags. The sensitivity of these loads is often determined by the ride-through capability of magnetic contactors.

Other sensitive equipments include distributed control systems (DCSs), programmable logic controllers (PLCs) and industrial computers [90].

Typical power quality disturbances known to cause disruption of production process in these types of industry include [89, 90]:

- Voltage sags
- Momentary interruptions
- Harmonics

2.2.2 Steel Manufacturing

A typical characteristic of steel manufacturing facility is use of arc furnaces for melting and refining process. Arc furnaces and rolling mill loads operate at low power factors which incur penalty charges and causes voltage drop that lowers the voltage at the plant bus. The plant operating cost per ton of production would be increased due to increased melt time as a result of low system voltage [91]. Also, frequent switching of furnace transformers may result in overvoltage transients that burdens insulation systems.

In addition, arc furnaces and rolling mill drives are non-linear loads that generate significant harmonic currents. Harmonic currents increases power loss in the system, and can interact with power factor correction capacitors, leading to equipment failures [91].

Sensitive equipments in steel manufacturing include [91]:

- Electronic control circuits
- Timers

Problems with power quality include [91]:

- Voltage and current harmonics
- Low power factor
- Overvoltage transients

2.2.3 Cement Plant

Cement manufacturing is a combination of continuous and batch processes [92]. Continuous processes like cement kiln can be easily affected by short interruption of power, while longer interruptions can cause thermal cycling problems with the refractory brick inside the kiln [92]. On the other hand, processes like crushing, raw and finish grinding and packing are batch processes which will also be affected by power interruptions [92].

Power quality disturbances can cause the following problems to cement plants [92, 93]:

- Control error – power interruption to control circuitry results in inability to control processes.
- Contactor dropout – voltage sag causes dropout of contactors which halts motors.
- Lighting – voltage sag extinguishes plant lighting.
- Annoying flicker – flicker causes human irritation.
- Motor operation – voltage sags cause motors to stall and re-accelerate, resulting in more voltage sags, with typically extended duration.
- Protective devices – voltage sag causes nuisance tripping of protective devices.
- Harmonics – harmonics cause increased losses in transformers, motors and generators, mechanical vibrations, tripping difficulties, dielectric breakdown, and malfunction of electronic equipment, telecommunication problems or metering errors. Harmonics also result in over-heating of equipment, tripping of breakers, faulty drive operation, blown fuses and capacitor failures [92].

Sensitive equipment include:

- Adjustable speed drives (ASD)
- Contactors
- Lighting

Typical power quality disturbances for cement plants include [92-94]:

- Voltage sags
- Interruptions
- Harmonics

- Low Power Factor
- Voltage flicker

2.2.4 Food Processing Plant

Modern food processing plants are highly automated and therefore are very susceptible to power quality disturbances. Most food processes are continuous, and a disruption in a single process may potentially halt the entire plant. Typically, a long downtime is incurred due to the requirement to scrap product and cleanout of process lines and pumps to maintain a sterile processing environment [95]. For instance, in fruit processing operations, power quality event can lead to one to two hours of downtime. On the other hand, process interruption in tomato processing can lead to 24 hour to 36 hours of downtime [95].

Some food productions are seasonal, with the survival of the entire plant depending on a short production season. This short production season increases the financial impact of power quality disturbances on the industry.

Typical sensitive equipment used in food processing plants include [95]:

- AC Powered Relays, Contactors, and Motor Starters
- Programmable Logic Controllers (PLC) - PLCs are the backbone of industrial automation and are used extensively in food processing.
- Adjustable Speed Drives (ASD)

Typical power quality disturbances include:

- RMS voltage variations, especially sags and interruptions
- Transients
- Harmonic Distortion

2.2.5 Pharmaceutical Plant

Maintaining a contamination-free process environment is one of the main priorities in the operation of pharmaceutical plants. To achieve this, process downtime due to equipment failure resulting from power quality disturbances has to be minimized [43].

A recent survey by the University of Manchester [43] involving seven participating pharmaceutical plants in India found that process outages due to voltage disruptions happen 1 to 5 times annually. It was suggested by 3 out of 6 respondents that voltage sags cause partial process disruption. On the other hand, only 1 out of 6 respondents suggested that voltage interruptions lead to complete process disruption, while 2 out of 6 respondents suggested partial disruption.

Programmable Logic Controllers (PLC) and Adjustable Speed Drives (ASD) were found to be the most sensitive devices, and are most likely to cause complete process disruption. Other sensitive equipment used in pharmaceutical plants include:

- Personal Computers (PC)
- Motor contactors
- Fuses
- Solid state relays.

Typical power quality disturbances include:

- Voltage and current harmonics
- Voltage sags
- Surges and transients
- Short and long (more than a minute) interruptions.

2.2.6 Textile Industry

The extrusion process in textile industry is very sensitive to power quality disturbances [96]. The process involves melting plastic chips, transforming it into filaments and finally wounding onto drums [96]. Many synchronized adjustable speed drives (ASD) are installed in the extrusion process, increasing its sensitivity to voltage sag conditions.

In the extrusion process, failure of one component trips the entire process [96]. Therefore, the sensitivity of the process is determined by the sensitivity of the weakest link. Normally, a production interruption following power quality disturbances would last for an average of one to two hours [96].

Typical sensitive equipments in the extrusion process of textile industry:

- ASD

Typical power quality disturbance:

- Voltage sag

2.3 High Tech Industries

High-tech industries have highly valuable production lines that often involve the manufacturing of high-tech electronic equipment with high level of process automation. According to [97], typical high-tech industries include the following categories:

- Semiconductor (SC): IC design, mask production, chip production, wafer foundry, IC packaging and testing, and IC's peripheral industry.
- Computer and Peripherals (CP): microcomputer system, input equipment, output equipment, storage equipment, network equipment, power supplier, connector, software and electronic component.
- Telecommunications (TC): communication switching equipment, local transmission equipment, user equipment and wireless communication equipment.
- Optoelectronics (OE): battery, flat panel displays, optical information system and optical component system.
- Precision Machinery (PM): precision components system, automatic equipment system, precision machinery, and special materials.
- Biotechnology (BT): orthopedic equipment, medical instruments and artificial kidneys.

Generally, high-tech industries require a higher quality of power service and have higher interruption cost than traditional industries [97].

In the semiconductor industry, electric power reliability for wafer fabrication operations has to be 99.999% reliable. The definition of 99.999% is interpreted as a one-hour power outage out of 100000 hours of operation. That is one hour in 11.4 years [98].

In terms of susceptibility to voltage sags, a study in Taiwan [97] involving 284 high-tech companies concluded that 20% of the industry could not sustain voltage drops of less than 3% magnitude lasting for 5 cycles, and about 30% of the respondents could not survive a 3%~6% voltage drop of less than 5 cycles. For a voltage drop of 20%~30%, less than 12% of the respondents can sustain for 5 cycles.

The financial consequence of a process disruption due to voltage sags and interruptions are tremendous. To reduce the losses, high-tech industries had to make sure that their manufacturing equipments comply with certain requirements of voltage susceptibility. The most commonly used voltage sag susceptibility curves include the following:

- SEMI F47 [29] – This curve is developed by the Semiconductor Equipment and Materials International as a specification for semiconductor processing equipment voltage sag immunity.
- ITIC/CBEMA [28] – The Information Technology Industry Council (ITIC) curve is a revised version of the former CBEMA curve. This curve applies only to single-phase information technology products with 120V/60Hz ac supply. The ITIC curve defines the tolerance level of information technology equipments to voltage sag, swells and interruption.
- Samsung "Power Vaccine" [99] – Developed by Samsung Semiconductor as specification for semiconductor manufacturing equipment. This curve is far more stringent than the usual power quality immunity specification for this type of equipments.

These sensitivity curves are illustrated and compared in Figure 2-1.

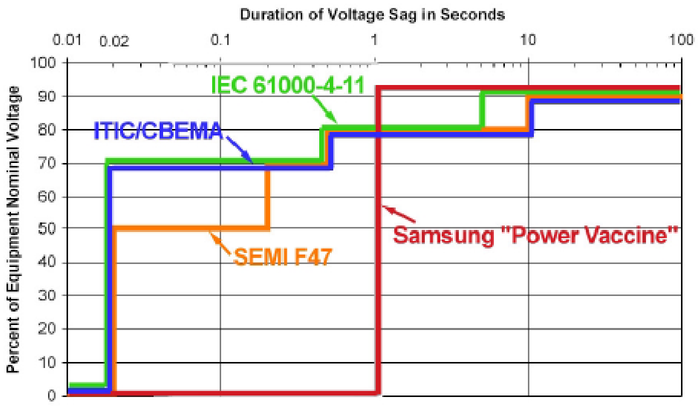


Figure 2-1 Various specification for equipment voltage sag immunity. Adopted from [99]

The susceptibility of high-tech processes may depend on the type of voltage sag susceptibility curve used as equipment specification. The supply quality can be more relaxed if the specification for equipment is more stringent. For instance, equipments that comply with the Samsung "Power Vaccine" curve can sustain an interruption of up to 1 second, which means that the power supplier is allowed for longer period of interruption.

Typical sensitive equipment for high-tech industries include [29, 100]:

- Power supplies
- Radio frequency generators and matching networks
- Ultrasonic generators
- Computers and communication systems
- Robots and factory interfaces
- AC Contactor coils and AC relay coils
- Chillers
- Pumps and blowers
- Adjustable speed drives
- Critical HVAC equipment (drives, PLCs)

The main problem with power quality disturbance is nuisance tripping of sensitive equipments listed above. The entire manufacturing process could be halted if critical equipments trip, resulting in very high financial losses.

According to a power quality study [101] in the United States involving semiconductor manufacturer Motorola, the potential cost impact of voltage sags extrapolated from historical events at several Motorola factories are shown in Figure 2-2. A typical Motorola fabrication factory may experience six events of voltage sags per year with sag magnitude of 75%-85%, which may cost between $25,000 and $75,000 per event. Sag between 60%-75% may appear three times per year, costing between $50,000 and $300,000 per event. Voltage sag below 60% of nominal voltage may occur once a year, costing between $100,000 and $2,000,000. The total cost risk is between $600,000 to over $3,000,000 per year for one factory.

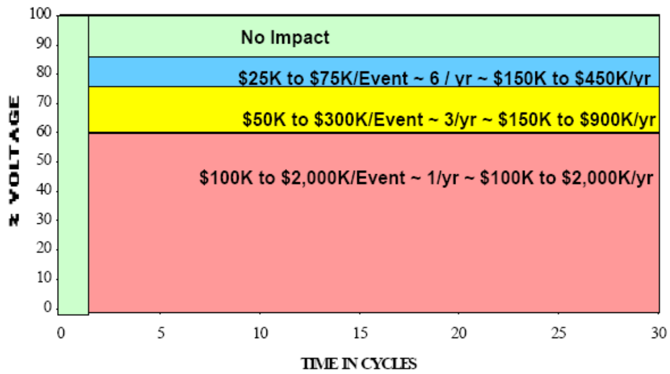


Figure 2-2 Potential cost impact for Motorola factories caused by voltage sags. Adopted from [101]

Typical power quality disturbance for high-tech industries include [97]:

- Short interruption
- Voltage sag
- Voltage swell
- Harmonics

According to the customer survey in Taiwan [52], short interruptions and voltage sags are the main power quality problems for most high-tech industries. Detailed percentages are given in Figure 2-3.

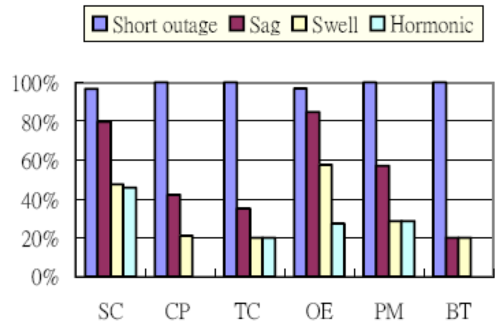


Figure 2-3 Percentage of power quality disturbances suffered by various high-tech industries. Adopted from [52]

2.4 Information Technology

Facilities that are considered in this area include data centres, research and development laboratories, and telecommunication-based industries. The massive penetration of electronically controlled devices and equipment in these facilities results in high sensitivity to minor power perturbations.

Typical sensitive equipment used include [102]:

- PCs and terminals
- Switch mode power supplies
- Microprocessor-based control and instrumentation devices
- Printers, copiers facsimile machines

The effects of power quality disturbances on sensitive IT equipments are summarized in Table 2-1 [102].

For telecommunication-based industries, high amplitude surges and fast ringing transients [100] are reported to cause various problems to the operation of the industry.

The effects of these disturbances on telecommunication-based loads are summarized in Table 2-2.

Table 2-1 Effects of power quality disturbance on IT equipments. adopted from [102]

Power Quality Disturbance	**Typical equipment problem**
Impulsive and oscillatory transients	Lock up Soft errors Hard disk crash Power supply failure Circuit board failure
Voltage sag	Soft errors Reset-reboot
Voltage swell	Soft errors Power supply failure Circuit board failure
Interruption	Hard disk crash Power supply failure

Table 2-2 Effects of transients and noise on telecommunication based loads, adopted from [100]

Effect on Telecommunication/electronic Loads	Impact of Disturbances		
	Transient 4x normal voltage	Transient 2x normal voltage	Repetitive Disturbance (noise)
Rectifier failure	Yes	-	-
Dropped Calls	Yes	Yes	Yes
Audible Noise	Yes	Yes	Yes
Lock Up	Yes	Yes	Yes
Parity Errors	Yes	Yes	Yes
Power Supply Failures	Yes	-	Yes
Circuit Board Failures	Yes	-	-

Main power quality disturbances include:

- Voltage sags
- Voltage swells
- Interruption
- Impulsive and oscillatory transients

2.5 Commercial Facilities

Typical sector activities include banking, retail, travel and communication [103]. The success of modern commercial facilities is reflected by the efficiency of data processing and communication. The operation of these facilities depend heavily on the use of microprocessor-based equipment, such as personal computer, local area networks (LANs), computer-aided design (CAD) workstations, and tele-video conferencing equipments [104].

The operational environment of commercial facilities needs to be carefully controlled to ensure that commercial data is not ‘corrupted’ due to power failure or signal distortion [103].

For banking sector, billions of dollars move around the world through countless financial transactions that rely on the banking sector’s ability to ensure that the computerized system never miss a payment. An interruption in power supply could cause major damage to a bank’s customer, and in serious cases could even affect the entire global economy [39].

Due to the threat posed by transient voltage, current surges and voltage sags, this sector invests largely in system backup and surge suppression, in the attempt to protect its business and electronic equipment [103].

Power quality disturbances could lead to unplanned and costly outages and failures of microprocessor-based equipment, such as network outages brought about by file server shutdown, lock-ups of mail server hardware, lock-ups of teleconferencing video equipment, catastrophic and repeated hardware failures of PC terminals [104].

Typical sensitive equipment in commercial facilities include [103, 104]:

- Microprocessor-based equipments
- Heating, ventilating and air-conditioning (HVAC)
- Lighting

Typical power quality disturbances include [104]:

- Voltage sags
- Harmonics
- Common mode disturbances (EMI)
- Voltage surges

2.6 Office Building

According to *Electric Light and Power* magazine, 30 to 40 percent of all business downtime is related to power quality problems [105].

Small commercial and office building power systems are largely composed of single phase loads. The large penetration of non-linear loads (personal computer and switch mode power supply) produces high levels of harmonics. The sensitivity of this equipment also increases the susceptibility of office buildings to power quality disturbances.

Studies [105] show that up to 80 percent power quality problems are caused by disturbances created inside the facility. Voltage sags and surges are often created by the switching of large loads, such as fans and air conditioning. These disturbances may affect other equipment in the building. Besides, lightning is another major source of disturbance, accounting for more than 10 percent of power disturbances [105].

Power quality also concerns the "human element" in the office environment. Basic requirements such as heating, air conditioning and lighting should not be affected by power quality disturbances [103].

Typical problems with power quality at office buildings includes tripping of electromechanical equipment (fans, pumps), frequent activation of uninterruptible power supplies(UPS), shutting down of personal computers (PC), Malfunction of elevators and HVAC equipments, and shutting down of fire command stations [106].

Following failure of equipments due to power quality issues, businesses in office buildings could suffer [105]:

- Lost productivity due to idled staff and equipment
- Lost profits from severed customer good will
- Lost transactions and unprocessed orders
- Revenue and accounting problems
- Customer and/or management dissatisfaction
- Overtime required to make up for lost work time

Sensitive equipment in office buildings include [106]:

- Personal computers (PC)
- Elevators
- HVAC

Typical power quality disturbance include [106, 107]:

- Surges
- Voltage sags
- Interruptions
- Harmonics

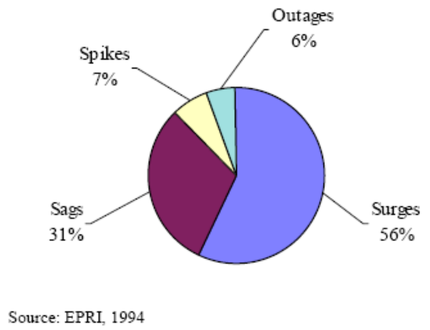


Figure 2-4 Types of power quality disturbances. Adopted from [105]

2.7 Medical Centre

The operation of hospitals and emergency services require completely uninterrupted power supply and protection from power quality disturbances. Power quality disturbance of even a slight fraction of a second, can be potentially life threatening in critical areas such as operating theatres and intensive care units [103].

The increasing dependence of hospitals on computers and microprocessor controls caused the facility to be susceptible to power fluctuation and short term interruption [108].

The Department of Health HTM (Health Technical Memorandum) 2007 – Electrical Services: Supply and Distribution (1993) [109], as well as IEC regulations awaiting ratification, require that a hospital electrical distribution system is designed to provide security of supply and flexibility and safety in operation.

It is reported that the seconds that lapse between a power quality event and the start of the stand-by engine generator pose serious issues for many systems in the healthcare environment [108].

Power quality events such as voltage transients may cause a microprocessor to read voltage levels incorrectly, resulting in incorrect data processing (ones being read like zeros) or altered stored data/settings. Other malfunctions in medical equipment caused by power quality events include: distortion of displays (due to distorted voltage, altered data); incorrect diagnostic results (due to EMI, grounding), equipment lockup (due to Voltage surges or sags), Control/alarm malfunction (due to Microprocessor malfunction) [110].

Sensitive equipment in healthcare facilities include [110-112]:

- Chiller
- Fan drives

- Microprocessor-based equipments
- Electronic medical equipments
- Lightings

Typical power quality disturbances include [110-112]:

- Voltage sags
- Harmonics
- Flicker

2.8 Automotive Industry

Automotive industry practices just-in-time production schemes, where flexible-automation and supply-chain management is essential for sustainability. Any process disruption at the main assembly plant or at the outsourced supplier's facility would result in loss of productivity and profit [61]. According to [61], a plant suffered over $700,000 losses due to a four-cycle voltage sag, which caused 72 minutes of downtime, shutdown of production, and extensive rework. Large penetration of robotics, programmable logic controllers and drive systems, coupled with a real time process environment, makes the industry very vulnerable to power quality disturbances [61].

The extensive use of resistance-welding in the automotive industry generates high levels of voltage fluctuations and flicker. Severe voltage variations reduce the power delivered to the welders, causing reduced heating and poor-quality welding joints [113]. The high-reactance welding transformer also creates a low-power-factor problem, while simultaneous operation of welders could cause voltage sags in the plant.

Typical sensitive equipment in an automotive manufacturing plant include [61] :

- DC and AC Drives
- Servo drives
- PLC
- AC contactors
- Computer numerical controller (CNC)

Typical power quality disturbances include [61, 113]:

- Flicker
- Voltage sags

2.9 Petroleum Terminals

Petroleum terminals provide temporary storage and distribution of petroleum products. Induction motors make up most of the electrical loads in a petroleum terminal. Many of the induction motors are operated by adjustable speed drives (ASD). ASDs are also used in vapor recovery systems and pumping operations. The use of ASD improves process control and energy efficiency [114].

Typical sensitive equipment in petroleum terminals include [114]:

- Adjustable speed drives (ASD)
- Programmable logic controllers (PLC)
- Metering systems
- Computers
- Fire alarm systems

Typical power quality disturbances include [114]:

- Voltage sags
- Transients
- Voltage and current harmonics

2.10 Residential Loads

Residential customers make up a large portion of the total customer for electrical suppliers. Traditionally, the effects of power quality disturbances in household environment are comparatively minor. Problems evolve around irritation caused by VCR and clock radios ‘flashing’, dimming or flickering lights and the loss of supply [103]. However, with the increasing use of sensitive electronics and IT products, and the trend of working from home (Tele-working), power quality requirements are becoming comparable to the commercial sector [103].

Common inconveniences caused by a power interruption include physical discomfort (loss of heating or air conditioning), inability to run kitchen appliances, loss or damage to equipment and laundry [115].

Typical sensitive equipment include [103]:

- Personal computers
- Household electronics

- Lightings

Typical power quality disturbances include [103, 116]:

- Interruptions (outage)
- Voltage sags
- Flicker

2.11 Summary

This chapter presented overview of major types of customers and their susceptibility to power quality disturbances. It is found that almost all major industries face power quality problems. The most important power quality disturbances include:

- Voltage sags
- Interruptions
- Harmonics
- Transients.

The most commonly identified sensitive equipment include:

- AC and DC drives
- Contactors
- Programmable logic controllers (PLC)
- Microprocessor based equipment
- Lighting

Chapter 3 The Cost of Voltage Sags and Interruptions

3.1 Introduction

Global evaluation (network or country based) of financial losses of industrial plants due to voltage sags and interruptions has been a subject of intense interest during the past decade. Over the years, researchers have developed many ways (i.e. deterministic, probabilistic and fuzzy logic) to tackle the problem [17, 18, 33, 37-39, 117]. The underlying issue faced in these evaluations, regardless of the method used, is the lack of a single most important value for realistic representation: the nominal loss value for a process interruption. The nominal loss value of an industrial process, also referred to as the "maximum loss value" [33], is the financial loss incurred due to process interruption during peak production period. This parameter is typically used as the basis for calculation of financial losses due to voltage sags and interruptions and it also often serves as the "typical" value of loss incurred by process interruption.

To estimate financial loss caused by voltage sag and short interruption, two main parameters are needed; the nominal loss value and process failure risk. The main equation for financial loss calculation as (3-1). This chapter focuses on overview of reported losses around the world due to power quality disturbances and in particular due to voltage sags and interruptions. It also lays foundation for determining the first part of the equation.

$$Expected\ Financial\ Loss\ per\ Sag = Nominal\ Loss \times Process\ Failure\ Risk \qquad (3\text{-}1)$$

3.2 Nominal Loss from Customer Survey

The nominal loss for existing customers in the network can be determined from customer surveys. For a distribution company prepared to invest millions in power quality management, conducting a customer survey in the network would provide the most accurate reflection of the existing level of losses.

To test the feasibility of customer surveys, a short survey questionnaire was prepared to determine the response rate of such surveys. The survey is conducted by UK distribution company on industrial customers that have previously complained about poor power quality. A total of nine customers were contacted over the phone. They comprise of 3 plants in automotive industry, 3 plants in food and beverage industry, 2 plants in plastic industry, and one each for a chemical plant and an IT service provider.

Out of the nine customers, only two responses were obtained, representing a 22% response rate. The response rate may not be representative due to the size of the survey, however, it reflects the difficulties faced in obtaining information from customer surveys, even though only the customers who explicitly complained were approached and the approach was made by the supplier directly.

3.3 Nominal Loss from Past Experiences

In cases where only rough estimates are required (e.g. studies at the very initial phase), obtaining the nominal loss from other surveys may be feasible. In the past decades, numerous studies were conducted around the world. The results of these studies can be used as the basis for subsequent sag assessments. This section summarizes the studies and their main findings. Reported customer damage due to long interruptions is also included as a reference.

3.3.1 Studies in Europe

A survey [45] conducted by UMIST, UK since October 1992 assessed the outage cost of various customer categories due to electricity supply interruption. The survey covered three regional electrical company areas and customer sectors are categorized as residential, commercial, industrial and large user. A customer interruption cost (CIC) was defined as the perceived individual customer or average sector customer costs resulting from electricity interruption. The customer interruption costs (CIC) obtained are shown in Table A-1, Appendix A.

A separate study by researchers of UMIST investigated the influence of process equipment composition on financial losses due to voltage sags [118]. Detailed formulae were proposed to calculate the direct and indirect damage costs associated with industrial process disruption due to voltage sags. The study was simulated on a generic distribution system consisting of 295 buses. Four types of sensitive equipments are considered, namely personal computers (PC), programmable logic controllers (PLC), adjustable speed drives (ASD) and AC contactors. It was observed that different load compositions at customer plant sites result in significant variation in sag costs.

In year 2000, researchers from Helsinki University of Technology, Finland conducted studies [15, 16] to estimate the annual frequency and cost of voltage sags for customers of five Finnish distribution companies (3 rural and 2 urban networks). Customers were divided into five categories of domestic, agricultural, industrial, commercial services and public services. The method of fault positioning was applied for the calculation of voltage sag frequency. Economic consequences were obtained by multiplying the sag frequency, the cost of a single voltage sag and the number of customers. The cost of a single voltage sag was taken from a survey in the mid 1990s in three Nordic countries. Different cost values were used for different customer categories. Results of the study are illustrated in Figure A-1, Appendix A.

Results obtained indicated much higher losses than expected. It was also suggested that more accurate results can be obtained by more precise representation of customers' sag-related inconvenience and actual economic losses.

A report by STRI AB, Sweden, [40] gives summary of voltage sag related cost in different industries. This summary is illustrated in Figure A-2, Appendix A.

Literature published in year 2000 by researchers from Italy [27] provided estimates of the costs associated to poor power quality. The estimation was built upon survey conducted by a semiconductor and pharmaceutical facilities construction company. The survey concerned around 30 industries located in Europe, USA and the Far East that do not have any means of mitigations against power quality disturbances. Having analyzed the results from the survey, three categories of voltage sag profile were determined as most meaningful for estimation of costs. The categories are:

- Category A – includes 10 or less voltage sags per year with residual voltage less than 40% of nominal and sag duration shorter than 100ms.
- Category B - includes 10 or less voltage sags per year with residual voltage less than 40% of nominal and sag duration shorter than 100ms, and 5 or less voltage sags per year with residual voltage less than 70% of nominal and duration ranging from 100ms to 300ms.
- Category C – includes 1 interruption with duration of 3 minutes or more.

Estimated costs for the industrial sectors considered in the survey are given in Table A-2, Appendix A. The cost is given in percentage value of the total yearly power cost.

In Italy, researchers performed a survey [23] in different areas of North-East Italy between year 1999 and 2002. The survey focused on 200 small industrial customers of various sectors. The costs due to voltage sags are presented in normalized cost per voltage sag per kW power to ease comparison between industrial sectors and sizes. Survey results are illustrated in Figure A-3, Appendix A. It was found that most sensitive plants have normalized cost per sag in the range of 0.25-1.5 Euro/kW.

Based on this survey, the same researchers proposed a method for computation of the interruption costs caused by supply voltage sags and interruptions in small industrial plants [26]. The assumption made is that industrial plants have only one shut-down model, and that each voltage sag or interruption that trips the process requires equal re-start time. This further implies that severe voltage sags and momentary interruption cause equal interruption costs. The error introduced by these assumptions is thought to be reasonably low.

A large portion of the report focused on producing equations for cost calculation. The costs considered include cost of lost production during supply disruption and restart time, cost of wasted materials, imperfect product, damaged equipment and extra maintenance resulting from the disturbance. Also considered are the savings on raw material, energy not consumed and recovery of lost production. Using this method, a production plant in the plastic sector was investigated [23, 26]. It was found that the cost of a nuisance voltage sag is 517.5 Euro. This value is about 66% of the losses due to a one hour unplanned interruption.

In 2007, Politecnico di Milano of Italy [119] conducted field survey on 50 customers in 13 manufacturing sectors, to determine the direct costs due to voltage sags and momentary interruptions (less than 1 second). Its key objective was to obtain cost indicators for sensitive manufacturing sectors. The indicators considered were: annual direct costs per kW, Direct cost per event per kW, annual direct cost per production plant, direct cost per event per production plant, and number of events in a year due to voltage disturbances. Main results are given in Table A-3, Appendix A.

While direct costs are obtained from surveys, indirect costs are approached through market-based analysis, whereby the annual amortization costs for mitigation (UPS) are used as an indicator of cost. The total annual cost for all sensitive sectors is found to exceed 780 million Euros. It is also found that the disturbance costs in sensitive sectors are more than 4 times higher than those in generic sectors.

Based on a report by the Copper Development Association sponsored by the copper producers and fabricators, [120], a 10-month study carried out by a major generator in Europe on 12 sites of low technology manufacturing operation logged a total financial loss of €600,000. Detailed losses are summarized in Table A-4, Appendix A.

In 2007, the Leonardo Power Quality Initiative (LPQI) team published results of a pan-European power quality survey [1] comprising of 62 face-to-face interviews across 8 European countries. A total of 16 industrial and services sectors were covered in the survey, which essentially represents 38% of the EU-25 turnover, and 70% of the region’s final electricity consumption. The cost of all major power quality disturbances (sags, swells, short and long interruption, harmonics, flicker, surges, transients, unbalance earthing and EMC problems) was obtained considering direct and indirect cost components. It was found that sags and short interruptions account for 60% of the overall cost for industrial samples and 57% for the total sample. Further regression analysis concluded that power quality cost is directly correlated to the annual turnover of the affected customer, with industrial and services customers wasting around 4% and 0.142% of their annual turnover respectively to power quality disturbances. Major findings of this study are summarised in Figure A-4 and A-5 of Appendix A.

3.3.2 Studies in US

An on-site survey of 299 U.S. large commercial and industrial customers was carried out in 1992 to determine the financial losses incurred by interruption and voltage sag events [107]. Interruption costs for the following scenarios were investigated:

- A 1 hour interruption starting at 3 p.m. on a summer afternoon without advance notice.
- A 1 hour interruption starting at 3 p.m. on a summer afternoon with 1 hour advance notice.
- A 4 hour interruption starting at 3 p.m. on a summer afternoon without advance notice.
- A 2 hour interruption starting at 7 a.m on a winter morning without advance notice.
- A 1 to 2 second momentary interruption on a summer afternoon in clear weather.
- A 10% to 20% voltage sag for 15 cycles.

Survey results are given in Table A-5, Appendix A.

In year 1993, Clemmensen [121] provided the first ever power quality cost estimate for US manufacturing sector. The estimate, derived that annual spending on industrial equipment due to power quality problem could sum up to $26 billion dollars for the US manufacturing sector. It was estimated that for every manufacturing sales dollar, 1.5 to 3 cents are spent to mitigate power quality problems.

Few years later in 1998, Swaminathan and Sen [121], in a Sandia National Laboratory report, estimated that US annual power interruption cost reaches $150 billion. This estimate was based on a 1992 Duke Power outage cost survey in US that manipulated industrial electricity sales as estimate basis.

Later in year 2001, EPRI Consortium for Electric Infrastructure to Support a Digital Society (CIEDS) [122] produced a report based on a Primen survey in the United States. The report identified three sectors of the US economy that are particularly sensitive to power disturbances. These sectors are:

- The Digital Economy (DE): telecommunications, data storage and retrieval services, biotechnology, electronics manufacturing and the financial industry.
- Continuous Process Manufacturing (CPM): paper, chemicals, petroleum, rubber and plastic, stone, clay and glass, and primary metals.
- Fabrication and Essential Services (F&ES): all other manufacturing industries, plus utilities and transportation facilities.

These three sectors collectively loss $45.7 billion a year due to outages and another $6.7 billion a year due to other power quality phenomenon. It is estimated that US economy losses between $104 billion to $164 billion due to outages and another $15 billion to $24 billion due to power quality phenomena.

In the mean time, EPRI Solutions (formerly EPRI PEAC) [123]conducted power quality investigations on continuous process manufacturing (CPM) sector of US industries to identify industry specific cost data resulting from power quality disturbances. CPM involves manufacturing facilities that continuously feed raw material at high temperature. Results of this investigation are summarized in Figure A-6, Appendix A.

According to [115], a consulting firm specializing in evaluating technology markets, estimated over $20 billion of annual voltage disturbance cost by US industries.

Estimated losses for various industries per voltage sag event are shown in Table A-6, Appendix A.

A comprehensive summary of outage cost is given in an EnerNex Corporation report [124] in year 2004. It includes outage costs obtained from different surveys as is shown in Table A-7, Appendix A.

3.3.3 Studies in Asia

Literature published [125] in year 2001 presented survey results of interruption costs for 284 high-tech industries in Taiwan. Six categories of high-tech industries were being studied and that include semiconductor (SC), computer and peripherals (CP), telecommunications (TC), optoelectronics (OE), precision machinery (PM) and biotechnology (BT). The obtained interruption costs are then compared to the interruption costs of other countries as summarized in Table A-8, Appendix A.

The results of this survey were also presented in a separate literature published in year 2006 [52]. The cost of interruption was given as customer damage functions as shown in Figure A-7, Appendix A.

The same literature also presented results for a power quality survey conducted on the same industries. Financial analysis for voltage sag used weighting factors for different voltage sag magnitudes. Besides, voltage sag sensitivity factors are derived based on the survey results and are shown in Table A-9, Appendix A. It is concluded that high-tech industries are sensitive to supply quality, and that semiconductor industry suffers the highest losses for interruption of less than three seconds.

In Korea, interview survey on 172 industrial customers [126] of various sizes and sectors resulted in successful estimation of interruption costs for the industries surveyed. Particularly, a Korean semiconductor factory reported losses of $20 million caused by a single event of short interruption. The industries surveyed are given in Table A-10, Appendix A, while the costs of interruption are summarized in Table A-11, Appendix A.

3.3.4 Other Reported Losses

Literature published in year 2004 describes a case study on two industrial plants in Egypt [24]. It was reported that each voltage sag costs 5800 dollars to a manufacturing plant (size of 1MVA) and 8060 dollars to 200kVA polyester factory.

Information gathered by ABB [127] concluded that the financial consequence of sensitive loads due to voltage disturbance can be summarized to the values in Table A-12, Appendix A.

Information obtained from EPRI's Power Quality Applications Guide for Architects and Engineers are summarized in Table A-13, Appendix A and those from U.S. Department of Energy [128] in Table A-14 and Table A-15, Appendix A.

3.3.5 Summary of Nominal Losses

Numerical data from all the studies presented is analyzed and compiled. The studies confirm high sensitivity to short interruptions and voltage sags in many processes, with particularly high losses in the production of electrical and electronic equipment, chemical products, food products, and motor vehicles. The nominal loss of various customer types due to voltage sag and short interruption are categorically summarized in the following Tables:

- Direct cost per kW of plant per disturbance (Table 3-1)
- Direct cost per kVA of plant per disturbance (Table 3-2)
- Direct cost per disturbance event (Table 3-3)
- Annual cost of disturbance (Table 3-4)
- Cost per hour of process interruption (Table 3-5)

Table 3-1 Direct cost per kW per event

Section	Division (NACE code)	Activities	Financial Loss	Currency	Disturbance Type
Manufacturing	General	Small Industrial (Canada)	2.55	US$	1-minute power interruption
		Industrial (England)	15.24	US$	1-minute power interruption
		Industrial (Nepal)	0.11	US$	1-minute power interruption
		Industrial (Greece)	2.55	US$	1-minute power interruption
		High-tech industry (Taiwan)	55.15	US$	1-minute power interruption
	Food products and beverages (10, 11)	Food products (Italy)	5.9	Euro	Very short interruptions and voltage sags
		Food	8	US$	General cost of power quality
		Food and Beverages (South Korea)	44.75	US$	1-minute power interruption
	Textiles (13)	Textiles (Italy)	3.2	Euro	Very short interruptions and voltage sags

		Textiles	11.7	US$	General cost of power quality
		Textiles (South Korea)	8.72	US$	1-minute power interruption
	Paper and paper products (17)	Paper (Italy)	0.9	Euro	Very short interruption and voltage sags
		Paper	1.7	US$	General cost of power quality
		Paper (South Korea)	1.67	US$	1-minute power interruption
	Coke and refined petroleum products (19)	Refined petroleum products (Italy)	13.3	Euro	Very short interruptions and voltage sags
	Chemical and chemical products (20)	Chemicals and man-made fibers (Italy)	0.5	Euro	Very short interruptions and voltage sags
		Chemical	20.6	US$	General cost of power quality
		Chemical and petrochemical (South Korea)	50.28	US$	1-minute power interruption
	Rubber and plastic products (22)	Plastic products (Italy)	2.2	Euro	Very short interruptions and voltage sags
		Plastic products	3	US$	General cost of power quality
	Non-metallic mineral products (23)	Glass and ceramic products (Italy)	0.9	Euro	Very short interruptions and voltage sags
		Glass products	8	US$	General cost of power quality
	Basic/fabricated metals (24, 25)	Primary metal	15.5	US$	General cost of power quality
		Basic/ fabricated Metal (South Korea)	18.71	US$	1 minute power interruption
		Metal products (Italy)	3.3	Euro	Very short interruptions and voltage sags
	Computer, electronic and optical products (26)	Electronic	58.3	US$	General cost of power quality
		Audio and Visual Equipment (South Korea)	12.71	US$	1-minute power interruption
		Electrical and Electronic Equipment (South Korea)	120.72	US$	1-minute power interruption
	Electrical equipment (27)	Electric Machinery (South Korea)	13.63	US$	1-minute power interruption
		Electrical equipment (Italy)	10.6	Euro	Very short interruptions and voltage sags
	Machinery and equipment (28)	Other Machinery and Equipment (South Korea)	15.95	US$	1-minute power interruption
	Motor vehicles, trailers and semi-trailers (29)	Auto and auto components (Italy)	2.9	Euro	Very short interruptions and voltage sags

		Motor Vehicles (South Korea)	36.68	US$	1-minute power interruption
	Other transport equipment (30)	Other Transport Equipment (South Korea)	12.86	US$	1-minute power interruption
Transport and storage	Transportation (49, 50, 51)	All transportation	10	US$	General cost of power quality
Information and communication	Communications (58-63)	Communications	28.6	US$	General cost of power quality
Financial and insurance activities	Financial service activities (64)	Business services	3.7	US$	General cost of power quality

Table 3-2 Direct cost per KVA per event

Section	Division (NACE code)	Activities	Financial Loss	Currency
Manufacturing	Textiles (13)	Textile	3 - 8	US$
	Rubber and plastic products (22)	Plastics	4 - 7	US$
	Non-metallic mineral products (23)	Glass	10 - 15	US$
	Computer, electronic and optical products (26)	Semiconductors	80 - 120	US$
	Motor vehicles, trailers and semi-trailers (29)	Automotive	6 - 10	US$

Table 3-3 Direct Cost per Event

Section	Division (NACE code)	Activities	Financial Loss	Currency	Disturbance type
Manufacturing	General	Large User (UK)	216000	£	1-minute power interruption
		Large industrial and commercial (US)	7694	US$	Voltage sag
		Industrial (UK)	1200	£	1-minute power interruption
	Textiles (13)	Textile Industry	10000 - 40000	US$	Process interruption
	Paper and paper products (17)	Paper manufacturing (US)	30000	US$	Voltage sag
		Paper industry	10000 - 30000	US$	Process interruption
	Chemical and chemical products (20)	Chemical industry (US)	50000	US$	Voltage sag
	Rubber and plastic products (22)	Plastic Industry	10000 - 50000	US$	Process interruption
	Non-metallic mineral products (23)	Glass industry (Europe)	250000	Euro	Voltage sag
		Glass plant (US)	200000	US$	Voltage sag
	Basic metals (24)	Steel works (Europe)	350000	Euro	Voltage sag
		Steel works (UK)	250000	US$	Voltage sag
	Computer, electronic and optical products (26)	Semiconductor (Europe)	3800000	Euro	Voltage sag
		Semiconductor (US, Europe and Far East)	2500000	US$	Voltage sag
		Semiconductor	10000-50000	US$	Process interruption
	Machinery and	Equipment manufacturing	100000	US$	Voltage sag

	equipment (28)	(US)			
	Motor vehicles, trailers and semi-trailers (29)	Automobile industry (US)	75000	US$	Voltage sag
		Automotive	15000	US$	Process interruption
Wholesale and retail trade	(45 - 47)	Commercial (UK)	11.7	£	1-minute power interruption
Information and communication	Telecommunications (61)	Telecommunications (Europe)	30000	Euro	Voltage sag
	Information service activities (63)	Computer center (Europe)	750000	Euro	Voltage sag
		US computer center (US)	600000	US$	Voltage sag
		Data processing	10000 - 40000	US$	Process interruption
Financial and insurance activities	Activities auxiliary to financial services and insurance activities (66)	Credit card processing (US)	250000	US$	Voltage sag

Table 3-4 Annual Cost

Section	Division (NACE code)	Activities	Financial Loss	Currency
Manufacturing	General	Manufacturing	0 - 1	% of total yearly power cost
	Food products and beverages (10, 11)	Food	0 - 2	% of total yearly power cost
	Coke and refined petroleum products (19)	Petrochemical	0 - 5	% of total yearly power cost
	Chemical and chemical products (20)	Chemical	0 - 4	% of total yearly power cost
	Basic pharmaceutical products and pharmaceutical preparations (21)	Pharmaceutical	0 - 5	% of total yearly power cost
	Basic metals (24)	Metallurgy	0 - 1.5	% of total yearly power cost
	Computer, electronic and optical products (26)	Semiconductor	0 - 10	% of total yearly power cost
	Motor vehicles, trailers and semi-trailers (29)	U.S. car plant	10,000,000	US$
Other	General	South Africa total	3,000,000,000	US$

Table 3-5 Cost per Hour of Interruption

Section	Division (NACE code)	Activities	Financial Loss	Currency
Financial and insurance activities	Activities auxiliary to financial services and insurance activities (66)	Brokerage operations	6,480,000	US$
		Credit card operations	2,580,000	US$
		Financial trading (Europe)	6,000,000	Euro
Information and communication	Telecommunications (61)	Mobile communications	41,000	US$
Wholesale and retail trade	Retail trade, except of motor vehicles and motorcycles (47)	Airline reservation	90,000	US$
		Telephone ticket sales	72,000	US$

3.4 Summary

The methods for obtaining nominal financial loss for voltage sag and interruption are discussed in this chapter. A thorough review of past surveys conducted around the world enabled the compilation of typical loss tables for various industries.

Though high losses processes are commonly identified in most surveys, the magnitude of the losses is rather inconsistent. For example, huge differences in losses can be seen in different surveys reported for chemical products and electrical products manufacturing. This disparity is due to the difference in circumstances while conducting the surveys. In particular, there are differences in the country in which the surveys are conducted, the categorization of industries, the type of disturbances included, the year of survey, the size of the industries involved, and the base currency used for loss representation. These differences prevent the surveys from being compared effectively and meaningfully.

With increasing need for accurate loss estimation for the industrial sector, a common standard in conducting surveys is crucial to ensure a consistent outcome in future surveys. In the meantime, a methodology capable of grouping and analyzing the surveys is required.

Chapter 4 Customized Customer Damage Functions

4.1 Introduction

In conventional financial loss evaluation studies, the nominal loss value is usually obtained from customer damage functions (CDFs) derived from survey results. These CDFs provide general indication of expected value financial loss. However, a "one size fits all" approach is not good enough when accurate assessment is crucial. There are huge differences reported in nominal financial loss values depending on the type of industry, size of industrial plant and the region of the world where survey was carried out. It is impossible to find a single survey result that would fit perfectly the requirements of a particular case study (unless the survey was actually done in the plant of interest). Ideally, evaluations of expected loss should therefore be based on multiple sources from as many survey results as possible.

To achieve this, a robust methodology that is capable of analyzing and combining past survey results from different regions of the world and of different time frames, and generating a customized CDF for the plant of interest is required. This section proposes one such methodology which represents the first original contribution of this thesis. It evaluates past survey results by comparing the characteristics of the assessed plant with the characteristics of the survey samples. The characteristics of interest include the type of industrial activity involved, the size of the assessed customer in terms of peak power demand (in kW) and the geographic location of the assessed plant. Once scaled and analyzed the characteristics of the past surveys are suitably merged to produce a new customized customer damage function (CCDF) for the customer/industry in question. The CCDF therefore represents a marked improvement compared to previous approaches and ensures more realistic assessment of financial losses incurred by process failure.

4.2 Data Preparation

The proposed methodology requires the input data in a particular format. The conversion of raw data into useable, formatted information involves procedures aimed at ensuring that the information from various sources are comparable. Raw customer loss data gathered from different sources are discounted/compounded to a common assessment time, converted to a common currency, and extrapolated to cover the same interruption durations.

4.2.1 Gathering Raw Data

Table 4-1 shows the input data required by the method. For the customer under assessment, information describing its business type, operation size and location is needed, as those are the main characteristics dictating the magnitude of customer financial loss [129, 130].

Business type is defined by the NACE system [131], which is the classification of economic activities in the European Community. NACE uses numerical codes to classify industrial activities. It is a level-by-level basis classification where each industry is assigned a unique six digit code.

The customer's peak demand determines the size of the plant, whereas the location of the customer depends on the country where its operations are based.

The same set of information needs to be extracted from the survey results, with additional data as shown in Table 4-1.

Table 4-1 Required Data from the Survey and The Assessed Plant

Customer under Assessment	Information of Surveys
NACE code, peak kW demand, location	Damage function for the industrial sector involved, NACE codes covered by the damage function, survey size, year of survey, average customer size, location/country performed, currency used

Table 4-2 Plant Under Assessment

Parameter	Value
NACE code	22.1.0 (Manufacture of rubber products)
Peak kW	15000
Location	Thailand

Table 4-3 Survey Information

Survey	1 [132]	2 [132]	3 [133]	4 [134]	5 [135]
NACE of sample	20, 22.1	20, 22.1	19, 20, 22	20	22.2
Four digit NACE (modified)	20.0.0 22.1.0	20.0.0 22.1.0	19.0.0 20.0.0 22.0.0	20.0.0	22.2.0
Survey size	23	65	127	No data	No data
Year conducted	2000	2000	2006	2001	1996
Location	Thailand A	Thailand B	South Korea	Greece	Nepal
Average customer size (kW peak)	No data	No data	12617	No data	No data
Own Currency	Thai Baht	Thai Baht	Korean Won	Euro	Nepalese Rupee
Currency Presented	Thai Baht	Thai Baht	US Dollar	US Dollar	Nepalese Rupee

To illustrate the method, the process of obtaining CCDF for an arbitrary industrial plant is demonstrated. The relevant plant information is given in Table 4-2. Five different surveys are used in this example, with information shown in Table 4-3. Figure 4-1 shows a typical customer damage function given in [135].

4.2.2 Modifying the Raw Data

The CDFs resulted from different surveys are usually given in different formats. The differences in data such as the business types involved, the currency in which the costs are expressed , and the year of survey have to be suitably modified prior to further evaluations. There are four steps involved in modifying original CDFs: currency conversion, discounting and compounding, conversion to a common currency, and extrapolation.

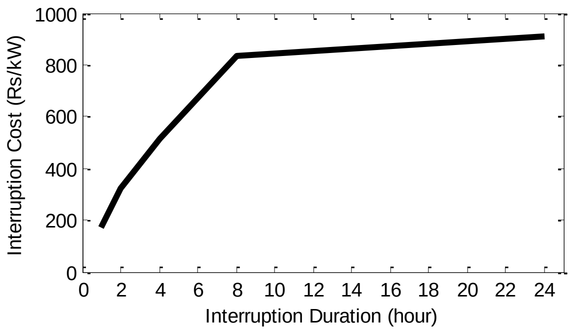


Figure 4-1 CDF from survey 5

4.2.2.1 Currency conversion

This methodology requires the use of the countries' own currency in evaluation. Therefore, all surveys with results presented in a foreign currency should have the cost values in the damage function converted back into their country's own currency. This must be done with the exchange rate used in the survey itself, at the time the survey was done.

4.2.2.2 Discounting and Compounding

Money has a time value. The same amount today was worth less a year ago, and will be worth more a year later. The former statement is the discounting effect and is described by (4-1), whereas the later is the compounding effect described by (4-2). PV and FV are present and future values, r is the discount/compound rate and n is the number of years ago/ahead.

$$PV = \frac{FV}{(1+r)^n} \tag{4-1}$$

$$FV = PV.(1+r)^n \tag{4-2}$$

For example, with r of 5% (r=0.05), using (4-1), 100 Euros today were only worth 95.2 Euros a year ago. With (4-2), 100 Euros today will be worth 105 Euros next year. This effect has to be incorporated into the methodology to conserve accuracy.

Using actual inflation rate based on consumer price index as the discount rate, for the countries where survey is conducted, the monetary values in the CDFs are converted into year 2005 values. For example, Survey 5 (Table 4-3) is conducted in 1996 in Nepal. The inflation rates over the years are given in Table 4-4. Because we are calculating future worth, (4-2) is used as follows:

$$FV_{2005} = PV_{1996} \times (1.081) \times (1.07) \times (1.067) \times (1.114) \times (1.034) \times (1.024) \times (1.029) \times (1.048) \times (1.04) = 1.633 PV_{1996}$$

The modified (treated) CDF is given in Figure 4-2. It can be seen that it has much higher values compared to the original CDF.

Table 4-4 Inflation Rate Based on Consumer Price Index

Year	Thailand	South Korea	Greece	Nepal
1996	5.87	4.93	7.87	8.10
1997	5.58	4.49	5.44	7.00
1998	8.08	7.51	4.52	6.70
1999	0.31	0.81	2.14	11.40
2000	1.55	2.26	2.89	3.40
2001	1.66	4.07	3.65	2.40
2002	0.64	2.76	3.92	2.90
2003	1.80	3.52	3.44	4.80
2004	2.77	3.59	3.02	4.00
2005	4.54	2.75	3.49	4.50
2006	4.64	2.24	3.31	8.00
2007	2.23	2.54	2.99	6.40
2008	3.52	3.40	3.50	6.40

Source: International Monetary Fund (IMF)

4.2.2.3 Conversion to Common Currency

The next step is to convert all currency values into a common currency. Instead of using market exchange rate as conversion rate, the purchasing power parity (PPP) exchange rate is used. Unlike market rate, “Purchasing Power Parities (PPPs) are currency conversion rates that both convert to a common currency and equalize the purchasing power of different currencies”[136]. PPP represents the “real” conversion rate where the difference in price level is eliminated during conversion [136] . In other words, it represents the actual value of money in different surveyed countries.

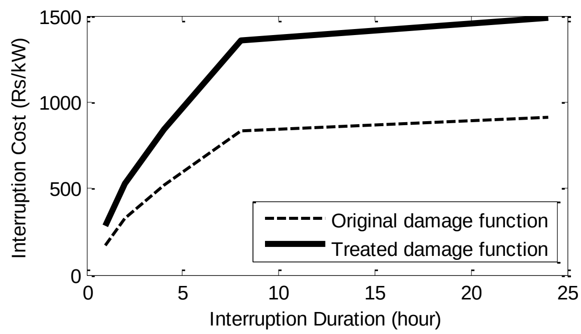


Figure 4-2 The original and treated CDF

The US Dollar is chosen as the platform due to ease of data acquisition. The most recent data that covered all surveyed countries are from [137], which reported PPP exchange rate of year 2005. Table 4-5 shows the conversion rates of the related currencies. Dividing the monetary values in CDFs developed in different countries with the given exchange rates will yield results in common US Dollar values, as shown in Figure 4-3.

Table 4-5 Purchasing Power Parity Exchange Rate

Currency	Equivalent to 1 US Dollar
Thai Baht	15.93
Korean Won	788.92
Euro	0.70
Nepalese Rupee	22.65

4.2.2.4 Extrapolation

Due to the fact that the duration ranges covered by the surveys are not the same, extrapolation techniques need to be applied to some of the functions (Survey 1 and Survey 2). The most straightforward method is linear extrapolation even though it may not be the most accurate one. The extrapolation method however does not invalidate the methodology used. Though it may affect the final result, it is always possible to "update" the extrapolation method if additional information that facilitate this are acquired. Figure 4-4 shows the CDFs after extrapolation.

4.3 Matching Index

A Matching Index is calculated for all surveys considered. It defines the level of similarity of the assessed plant with the plants assessed in surveys. In other words, it measures how well the assessed plant can be represented by the surveys. Calculation involves comparing characteristics of the assessed plant (Table 4-2) with the information provided by considered surveys (Table 4-3).

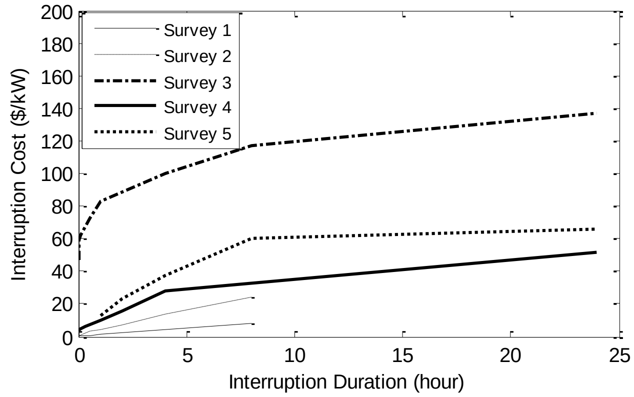


Figure 4-3 CDFs from different surveys expressed in US Dollars

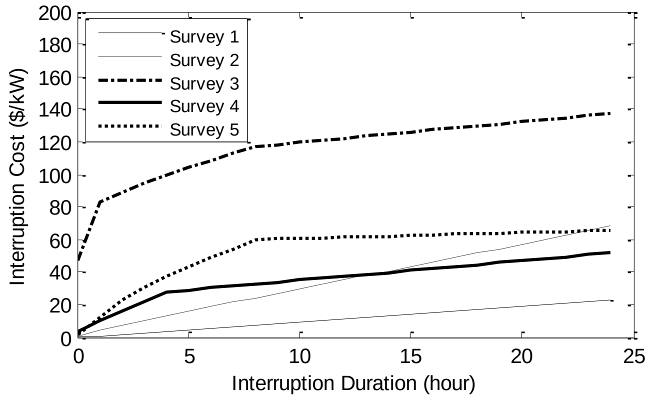


Figure 4-4 CDFs after linear extrapolation

4.3.1 Missing Data

To obtain realistic and accurate results, a complete set of data is necessary as input parameters. However, cases of incomplete data are quite usual. In the example used, some information regarding survey size and average customer size is missing (refer to Table 4-3).

Proper treatment of the missing data is essential for this assessment. Two methods for treating missing data are proposed here:

- Penalty – This treatment puts a penalty on the surveys where non-complete information is provided. A very low score (i.e. zero) is assigned to the sectors where information is missing. Hence reducing the influence of the surveys with missing data.
- Averaging – A score is obtained using the average value in the sector, derived from all other surveys used in assessment. This method preserves the influence of the survey with missing data.

4.3.2 Type Score

A survey can be used to represent the assessed plant if there are plants of the same industry type involved in the survey. Industry is identified using NACE codes. The proposed methodology uses the first four digits of the NACE to obtain a Type Score for the surveys according to their similarity to the assessed plant.

By comparing NACE codes of the surveys and the assessed plant, a score can be obtained. Type Scores are assigned based on the following rules:

1) Maximum score is 1.0.

2) A score of 0 if the first two digits do not match

3) A score of 0.5 if the first two digits match.

4) A score of 0.8 if the first three digits match.

5) A score of 1.0 if all four digits match.

6) Total score divided by the number of codes (sectors) covered by the particular survey.

For example, based on the four digit NACE from Table 4-3, Survey 1 will score 1.0 as one of its NACE code matches exactly that of the assessed plant. However, this score has to be divided by two as Survey 1 covered two NACE codes. The Type Score for all the surveys are given in Table 4-6.

4.3.3 Size Score

The magnitude of financial damage caused by power interruption is very much related to the size of the plant. Large plants lose more production and employee hours during interruptions compared to smaller plants. Therefore, it will not be realistic to represent a certain process with a survey that is based on very different sized samples.

The Size Score used in this methodology measures the closeness of the survey samples with the assessed plant. Scores are assigned by comparing the peak demand of the assessed plant with the average peak demand of the survey samples, based on the following rules:

1) Maximum score is 1.0.
2) A score of 1.0 for 10% or less difference in peak kW.
3) A score of 0.8 for 10% to 20% difference in peak kW.
4) A score of 0.6 for 20% to 30% difference in peak kW.
5) A score of 0.4 for 30% to 40% difference in peak kW.
6) A score of 0.2 for 40% to 50% difference in peak kW.
7) A score of 0 for more than 50% difference in peak kW.

These rules generated a score for each survey as shown in Table 4-6. The missing data in Table 4-6 are treated using the "penalty" method described in the previous section.

4.3.4 Location Score

The location of a plant has significant influence on its CDF due to power interruptions. This is mainly caused by the difference in material, labour and operation costs in different countries. The effect of plant location is considered using Location Scores, where a score of 1.0 is assigned to surveys within the same country of the assessed plant, and a score of 0 if the survey is done outside the country of the assessed plant. The Location Scores of the surveys are given in Table 4-6.

Table 4-6 Type, Size and Location Scores

Survey	1	2	3	4	5
Type Score	0.50	0.50	0.17	0	0.50
Size Score	0	0	0.80	0	0
Location Score	1.0	1.0	0	0	0

4.3.5 Relative Strength

A parameter called Relative Strength is introduced to define the “confidence” of a particular survey as a reference. This parameter is based on the number of plants participating in the survey (survey size in Table 4-3). Logically, the higher the sample size, the higher the “confidence”. Relative Strength describes this “confidence” as a comparison among all surveys involved in the evaluation. It is defined by (4-3) where the survey with the smallest survey size has a Relative Strength of 1.0 and all other surveys have Relative Strength larger than 1.0.

In (4-3), *RS* is the Relative Strength of survey *n*, while *s* is the sample size. *RS* for each of the five surveys of Table 4-3 is given in Table 4-7. In cases where survey size in not available, the "penalty" method is used such that a minimum score of 1.0 is given.

$$RS_n = 1 + log_{10}\left(\frac{s_n}{s_{min}}\right) \tag{4-3}$$

Table 4-7 Relative Strength of the Surveys

Survey	1	2	3	4	5
Relative Strength	1	2.04	2.71	1	1

4.3.6 Calculation of Matching Index

Based on Type Score, Location Score and Size Score, featuring in the Relative Strength of the surveys, a set of Matching Indices is generated using (4-4).

$$MI_n = TS_n(1 + a \cdot SS_n + b \cdot LS_n) \cdot RS_n \tag{4-4}$$

For survey *n*, *MI* is the Matching Index, *TS* is Type Score, *SS* is Size Score, *LS* is Location Score, and *RS* is Relative Strength of the survey. Parameters *a* and *b* are user definable weighting factors. The purpose of these factors is to allow some flexibility when the influence of location and size is not the same. For example, if the influence of location is higher than size, a higher value is assigned to *b*, so that the sum of *a* and *b* equals 1.

The Matching Indices for considered surveys calculated using equal weighting factors are shown in Table 4-8.

Table 4-8 Matching Index

Survey	1	2	3	4	5
Matching Index	0.75	1.53	0.63	0	0.5

4.4 Spring Theory

A customized damage function for the assessed plant can be calculated from the Matching Index of each survey utilizing the principles of Hooke's Law of elasticity

[138]. In this sense, each survey result (in the form of CDF) is thought to be behaving as a spring pulling the expected output towards it, with Matching Index being used as the spring constant that defines its stiffness.

Interaction of several surveys would generate an output when static equilibrium is achieved. This metaphor is pictured in Figure 4-5, where the position of the block is pulled by four springs (surveys). Equilibrium is achieved when the block is static and its position becomes the final output of the proposed methodology. At equilibrium, the net force on the block is zero and (4-5) applies. Values *d1*, *d2* and *d3* in (4-5) are obtained from the CDFs of individual surveys.

$$\begin{gathered} MI_1 \cdot x_1 + MI_2 \cdot x_2 = MI_3 \cdot x_3 + MI_4 \cdot x_4 \\ x_1 + x_3 = d_1 \\ x_2 + x_3 = d_2 \\ x_3 - x_4 = d_4 \end{gathered} \tag{4-5}$$

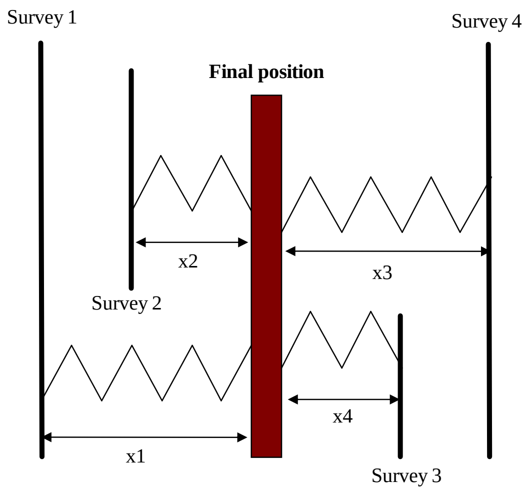


Figure 4-5 Final position of the block at equilibrium

Solving (4-5) for all interruption durations yields the customized CDF (CCDF) of the assessed plant. Figure 4-6 shows the results of applying the proposed methodology to the case study. The CCDF is a product of influences from all survey results, with more influence from the survey with higher Matching Index (Survey 2). The shape of the CCDF indicates that the influence of lower matching surveys (Survey 3 and Survey 5) are preserved.

The CCDF represents customized financial loss values due to both long and short interruptions. Voltage sag and short interruption incurred losses can be obtained at the initial point of the CCDF (interruption duration =0). The voltage sag losses obtained from the CCDF will serve as the "Nominal Loss" value described in Chapter 3.

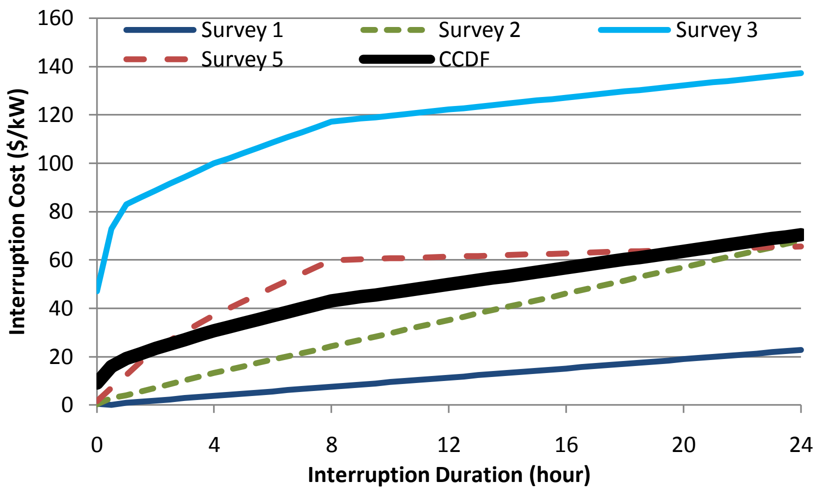


Figure 4-6 Customized customer damage function

4.5 Sensitivity to Weighting Factors

As described in Section 4.3.6, the methodology has two user-defined weighting factors; *a* and *b*. The size (*a*) and location (*b*) weighting factors are intended to improve flexibility of assessment so that the influence of plant size and location can be adjusted on a case by case basis. For example, weighting factors are useful when CCDF of a customer plant in France is assessed against the following surveys:

- Survey 1 conducted in France with 40% difference in plant size (between assessed plant and surveyed plants).
- Survey 2 conducted in Belgium with less than 10% difference in plant size (between assessed plant and surveyed plants).

Due to the difference in location, the CCDF will be dominantly influenced by Survey 1. In this case however, the similarity in plant size may be more relevant than plant location as plant owners in both countries are under comparable costs conditions (similar operation costs, similar financial losses). By selecting a low location factor in assessment (i.e. *b*=0), the two surveys will have equal influence on CCDF assessment.

The inclusion of user-defined weighting factors causes the final CCDF to vary when different weighting factors are used in assessment. For the plant under assessment (Table 4-2 and Table 4-3), the Matching Index for Survey 1, 2 and 3 changes when different size and location factors are used (Table 4-9). The Matching index for Survey

4 and 5 did not change and are therefore not shown in the table. It can be seen that increasing the size factor (*a*) increases the influence of Survey 3 while increasing the location factor (*b*) increases the influence of Survey 1 and 2.

Table 4-9 Matching Index with different weighting factors

Case	Size Dominant (a=1, b=0)			Base Case (a=0.5, b=0.5)			Location Dominant (a=0, b=1)		
Survey	1	2	3	1	2	3	1	2	3
Size Score	0	0	0.8	0	0	0.8	0	0	0.8
Location Score	1	1	0	1	1	0	1	1	0
Matching Index	0.5	1.02	0.81	0.75	1.53	0.63	1	2.04	0.45

Figure 4-7 shows the variation in CCDF with different weighting factors. In line with the changes given in Table 4-9, the CCDF moves closer to Survey 3 when size factor is increased, and closer to Survey 1 and 2 when location factor is increased.

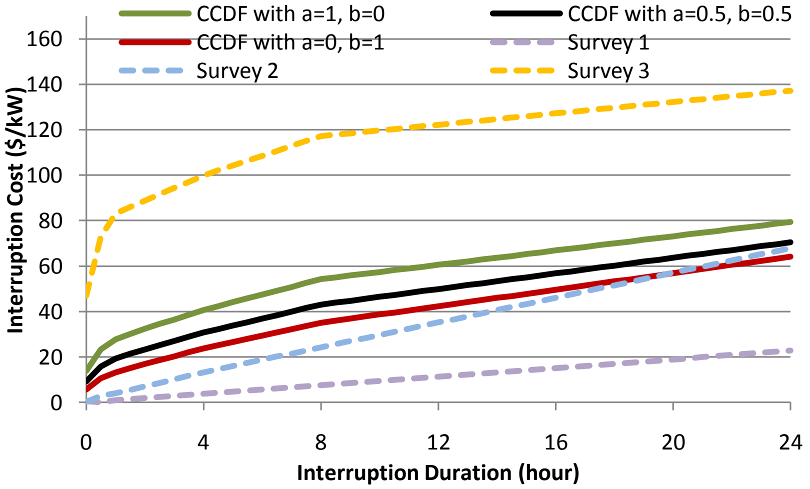


Figure 4-7 Variation in CCDF with different weighting factors

The variation in CCDF creates an area of uncertainty in assessment, where CCDF may take any value in the area depending on the weighting factors used in assessment. The area of uncertainty is bound by CCDF produced with two extreme weighting factor selections; size dominant (*a*=1, *b*=0) and location dominant (*a*=0, *b*=1). For the assessed case, the area of uncertainty is shown in Figure 4-8.

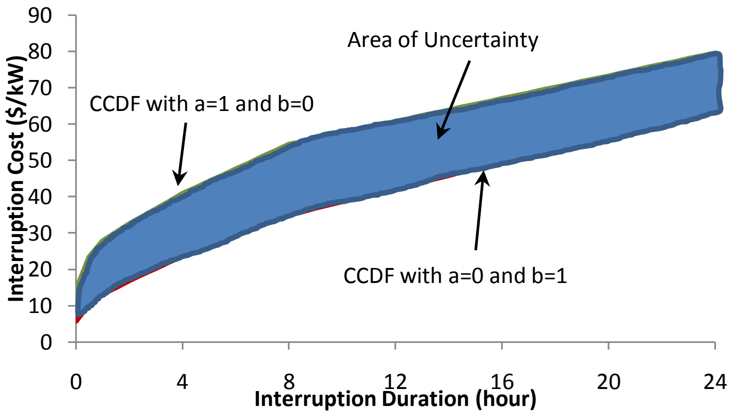


Figure 4-8 Area of uncertainty in CCDF assessment

4.6 Summary

A new methodology is proposed to derive customized customer damage function for individual industrial plant based on available data from surveys conducted at similar plants around the world. The existing customer damage functions (CCDF), developed based on past surveys, are suitably scaled and transformed into comparable platform using financial conversions. The methodology then considers all known factors that influence costs, including customer process type, size and location, and implements the well known Hooke's Law of elasticity to derive the appropriate CCDF.

The methodology can be used to obtain customer financial losses due to both long interruptions and voltage sags. It is intended to be used by distribution companies as an alternative to conducting customer survey on their network, as well as by industrial/commercial facility owners to benchmark their results by those reported at similar facilities around the world. The methodology proposed is "open ended" to a certain extent as it allows continuous updating of CCDF as more data (in number and confidence level) becomes available over time.

Chapter 5 Voltage Sag Risk Assessment

Voltage sags are inherently random in nature, in terms of time of occurrence, frequency and characteristics. Industrial plant or commercial process sensitivity to voltage sag depends on the type and sensitivity of equipment involved and production process cycle, which are all non-deterministic. Therefore, deterministic analysis of financial consequences of voltage sags is not the most appropriate way to account for all these uncertainties. A sound financial analysis requires proper representation of all the uncertainties involved.

As introduced in Chapter 3, the expected financial loss for an industrial process is determined by (3-1) reproduced here as (5-1).

.

$$Expected\ Financial\ Loss\ per\ Sag = Nominal\ Loss \times Process\ Failure\ Risk \quad (5\text{-}1)$$

Equation (5-1) can be expanded to cover the financial loss suffered in an assessment year, as given by (5-2).

$$Expected\ Annual\ Financial\ Loss = \sum_{n=1}^{N}(Nominal\ Loss_n \times Process\ Failure\ Risk_n) \quad (5\text{-}2)$$

Where n = sag event

N = total number of sag for the assessed year

Equation (5-2) exposes three variables for assessment:

- Process Failure Risk - this depends on the equipment immunity, process sensitivity and sag severity.
- Nominal Loss - Chapter 4 produced a constant "nominal loss" representing the maximum loss sufferable by the process due to a single voltage sag induced event. However, the "nominal loss" value varies with process cycle [44].
- The total number of sags, and their characteristics - The number of sags and sag characteristics vary every year and must be accurately estimated.

These three variables are the main risk factors influencing the assessment of sag induced financial loss. This chapter uses realistic examples to illustrate how each component can be probabilistically modeled, to account for associated uncertainties. This represents the second original contribution of this thesis.

5.1 Failure Risk Assessment

The response of industrial processes to voltage sags and short interruptions depends on sensitivity of equipment involved. In order to accurately evaluate the impact of voltage sags, sensitivity of equipment and processes has to be assessed.

Traditionally, failure risk assessments have been carried out by plant engineers to determine potential financial damage resulting from power quality disturbances in order to facilitate and inform investment decisions in mitigating solutions. More recently, market instruments, i.e., power quality contracts and services, have initiated more detailed failure risk assessments by the utilities. These assessments are needed for strategic planning and investment before any contracts and services could be offered.

Although both parties, network operators and industry, require similar risk assessments, conditions under which they are performed are different. Plant owners have detailed knowledge of their equipment, processes and operations, allowing them to design customized assessment models for accurate risk estimation of their plant(s). The utilities, on the other hand, for network planning purposes, have to run large scale assessments involving a number of industrial plants, with limited access to information about individual customer process operation. This requires the use of generic process models, which are flexible enough to be tuned to suit different industrial process types.

In real life, there are two possible outcomes after a voltage sag; Equipment/process will either “ride through” (normal operation) or “trip” (fail entirely or exhibit sub-optimum operation). The total equipment/process “trips” over a period of time determines the extent of the problem and the financial loss suffered. In failure risk assessment, the accuracy of a methodology is defined by its ability to estimate the total number of equipment/process “trips” as compared to the actual case.

Guidelines to assess financial losses at customer facilities due to voltage sags are available in IEEE Standard 1346-1998 [2] and in [44]. However, the standard did not consider the range of uncertainty in equipment tolerance when evaluating the number of disruptive sags. The interconnections between equipment and sub-processes that are thought to have significant impact on process operation were also not considered. This would surely have an impact on accuracy of assessment.

Over the years, numerous studies have investigated the effects of voltage sags on industry. Most of them [61, 96, 139], however, focused on detailed, process specific, modeling which cannot be used for other process types. Some of the most recently proposed methodologies [35, 38, 39] addressed the issue of generic assessment, however, they lacked the flexibility to be customized. Current industrial environment and a drive towards market based power quality regulation require a methodology that can be used for both detailed and general assessment.

This section expands the results of the author's previous work [33] and proposes generic models that incorporate full flexibility in failure risk assessment, and take into account more sag characteristics than previous methodologies that influence equipment behavior. Referring to Table 5-1, the models developed in [33] have included the influence of sag magnitude, sag duration, point on wave of sag initiation and phase angle jump in assessment. In this section, the theories behind the model development will be reiterated, before new models that take into account unbalanced sags are presented.

Table 5-1 Impact of sag characteristics on equipment immunity. Adopted from [12]

Sag Characteristics	**Sag Magnitude**	**Sag Duration**	**Point on Wave**	**Phase Angle Jump**	**Unbalance**
AC Contactors	Yes	Yes	Yes		
DC Contactors	Yes	Yes			
Induction Motor	Yes	Yes		Yes	Yes
AC Adjustable Speed Drives	Yes	Yes			Yes
DC Adjustable Speed Drives	Yes	Yes		Yes	Yes
Personal Computers	Yes	Yes			
Programmable Logic Controller	Yes	Yes			

5.1.1 Voltage Sag Severity Indices

Each device (equipment) responds uniquely to voltage sag and short interruption events. The effect of the sags on equipment cannot be estimated without information about the equipment’s voltage tolerance characteristic. Even if the voltage tolerance characteristic of a particular device type is known, it is difficult to generalize the effect of sag on other similar devices.

The concept of voltage sag Magnitude Severity Index (MSI) and Duration Severity Index (DSI) was introduced in [33] to tackle the problem. Instead of using physical sag magnitude and duration to assess equipment behavior, sag characteristics are first translated into corresponding MSI and DSI. As MSI and DSI are indices unique to each equipment type, for every voltage sag, different severity indices would be generated for different equipment types. From the equipment point of view, severity indices provide better representation of voltage sags as they are directly linked to equipment failure risk [33].

5.1.1.1 Duration and Magnitude Severities

MSI and DSI are derived based on the known fact that voltage sags with magnitude larger than V_{max} or duration shorter than t_{min} (area P in Figure 5-1) will not cause equipment trips, whereas sags with magnitude lower than V_{min} and duration longer than t_{max} will definitely cause equipment trips (area R in Figure 5-1) [35]. In these two regions, equipment failure risk is definite. In the area of uncertainty (area Q in Figure 5-1, MSI and DSI uses a scale of 0 to 100, with 0 as minimum severity and 100 as maximum severity, to represent equipment behavior when subjected to voltage sags [33].

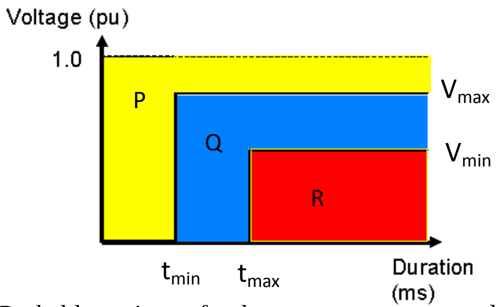


Figure 5-1 Probable regions of voltage sag occurrence, adopted from [33]

DSI has a value of 0 (minimum) at t_{min} and all sag durations shorter than t_{min}, and a value of 100 (maximum) at t_{max} and all sag durations longer than t_{max}. In between the two boundaries, DSI increases linearly with the duration of the sag. MSI behaves similarly with lower and upper boundaries set by V_{max} and V_{min}.

Figure 5-2 shows a typical voltage tolerance curve. The shaded area represents the area of uncertainty in equipment behavior. DSI for this equipment is 0 (minimum) at t_{min} and all durations shorter than t_{min}, and is 100 (maximum) at t_{max} and all durations longer than t_{max}. In other words, DSI is minimum along the lower boundary of the voltage tolerance curve (t_{min}), and maximum along the upper boundary of the curve (t_{max}). DSI increases linearly with the sag duration (*d*), from 0 to 100 as dictated by (5-3) and shown in Figure 5-3.

$$DSI = \begin{cases} 0, & d < t_{min} \\ (d - t_{min}) \times \left(\frac{100}{t_{max} - t_{min}}\right), & t_{min} \le d \le t_{max} \\ 100, & d > t_{max} \end{cases} \quad (5\text{-}3)$$

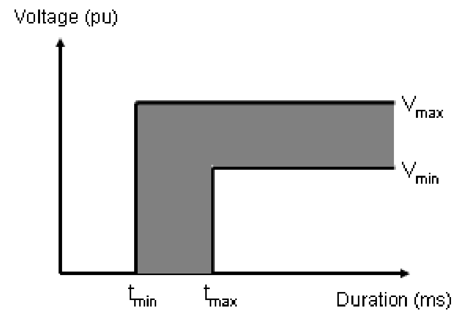


Figure 5-2 Area of uncertainty of equipment voltage tolerance, adopted from [33]

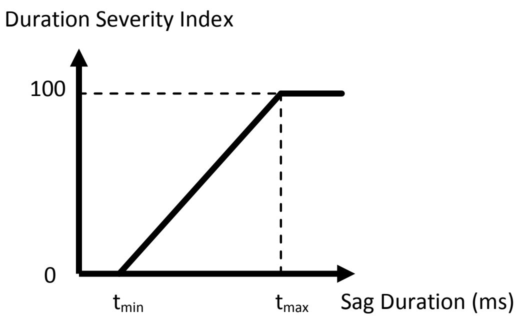


Figure 5-3. Relationship between sag duration and Duration Severity Index, adopted from [33]

On the other hand, MSI of the equipment is 0 (minimum) at V_{max} and all magnitudes above V_{max}, and is 100 (maximum) at V_{min} and all magnitudes below V_{min}. In other words, MSI is minimum along the lower boundary of the voltage tolerance curve (V_{max}), and maximum severity along the upper boundary of the curve (V_{min}). MSI increases linearly with the decrease of sag magnitude (*m*), from 0 to 100 as given in (5-4) and shown in Figure 5-4.

$$MSI = \begin{cases} 0, & m > V_{max} \\ (V_{max} - \mathrm{m}) \times \left(\frac{100}{V_{max} - V_{min}}\right), & V_{min} \le m \le V_{max} \\ 100, & m < V_{min} \end{cases} \quad (5\text{-}4)$$

5.1.1.2 Severity Indices of Industrial Equipment

Voltage sag appearing at equipment terminals should be first expressed in terms of DSI and MSI before equipment susceptibility is assessed. Since different equipment have different tolerance levels with respect to the same sag, each equipment type will have different set of severity indices when subjected to the same voltage sag. The sag "conversion procedure" for the most common sensitive industrial equipment as identified in Chapter 2, namely programmable logic controller (PLC), personal computer (PC), adjustable speed drives (ASD) and AC contactors (ACC) are detailed in the following sub-sections.

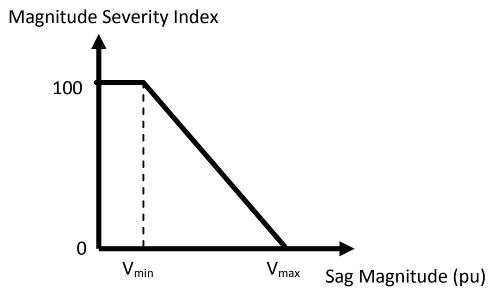


Figure 5-4 Relationship between sag magnitude and Magnitude Severity Index, adopted from [33]

5.1.1.2.1 PLC, PC and ASD

PLC and PC are single-phase equipment, and are therefore only affected by voltage sags on the phase that supplies them (assuming phase to neutral connection). On the other hand, ASDs are three-phase equipment that gives different response to different types of voltage sags.

Based on information gathered from previous studies [35, 140-142], voltage tolerance of PLC is compiled. Referring to Figure 5-1, t_{min} and t_{max} of PLC are 20ms and 400ms respectively, while V_{min} and V_{max} are 15% and 90% respectively of the rated voltage.

Test results from [32, 117, 140, 143] concluded that t_{min} and t_{max} for PC are 40ms and 459ms, while V_{min} and V_{max} are 22% and 72% of rated voltage.

Similarly, the range of voltage tolerance level of ASD is compiled based on equipment test results obtained from [30]. There are a total of seven types of voltage sags given in [6]. If the effect of phase shift during the sag (identified as insignificant in [30]) is disregarded, only five sets of tolerance levels need to be modeled. These are the balanced three-phase sags (type A), two-phase sags with third phase at rated (type C, E) and non-rated (type G) voltages, and single-phase sags with remaining phases at rated (type B) and non-rated (type D, F) voltages. It should be noted that two-phase sags and single-phase sags with the phase voltage of the "unsagged" phases below rated are unbalanced three-phase sags. These sags are here referred to as single/two-phase sags to simplify identification.

For balanced three-phase sags (type A), t_{min} and t_{max} are found to be 5ms and 20ms respectively, whereas V_{min} and V_{max} are 73% and 91% respectively of the rated voltage [30].

It was reported in [30] that ASD susceptibility to two-phase voltage sags, in terms of magnitude tolerance, depends on the voltage magnitude of the third phase during the sag. If the voltage in the third phase is at rated value (type C, E), t_{min} and t_{max} are 6ms and 20ms respectively, while V_{min} and V_{max} are 65% and 90% respectively of the rated voltage. If the third phase voltage is less than rated (type G), ASD magnitude tolerance (in %) is found to follow (5-5). Equation (5-5) is obtained through curve fitting of test results of ASD in [30], and it assumes a tolerance level of 100% when the third phase voltage is rated. The magnitude of the sag in the third phase, V_{sag} (in % of rated) decreases the magnitude tolerance of ASD. The duration tolerance, on the other hand, is not affected by the third phase voltage.

$$Magnitude\ Tolerance_{2\emptyset\ sag} = 94.944 - 3.665e^{-0.339V_{sag}} \times 10^{11} \tag{5-5}$$

Single-phase sags with voltages of non sagged phases at rated value (type B) have t_{min} and t_{max} of 5ms and 462ms, respectively and V_{min} and V_{max} of 5% and 85% respectively of the rated voltage. Analysis of ASD test results shows that sags with non-rated voltage at the remaining phases (type D, F) cause drop in both magnitude and duration tolerance of ASD. ASD tolerance levels (in %) are curve fitted from test results and described by (5-6). V_{sag} is the voltage magnitude (in % of rated) of the “unsagged” phases.

$$\begin{gathered} Magnitude\ Tolerance_{1\emptyset\ sag} = 97.362 - 2.263e^{-0.151V_{sag}} \times 10^{6} \\ Duration\ Tolerance_{1\emptyset\ sag} = -0.578 + 1.825e^{0.224V_{sag}} \times 10^{-8} \end{gathered} \tag{5-6}$$

Note that (5-5) and (5-6) are valid for tolerance values ranging from 0% to 100%. Magnitude and duration tolerance levels obtained from these equations are used to vary the upper boundaries (t_{max} and V_{min}) of equipment tolerance. Therefore, when subjected to sags with non-rated remaining phase(s) voltages, instead of having fixed boundaries, V_{min} and t_{max} vary according to the tolerance level, and follow (5-7) and (5-8).

$$V_{\min\,(G,D,F)} = V_{max} - (V_{max} - V_{min}) \times \frac{Magnitude\ Tolerance}{100} \tag{5-7}$$

$$t_{\max\,(D,F)} = t_{min} + (t_{max} - t_{min}) \times \frac{Duration\ Tolerance}{100} \tag{5-8}$$

The conversion graphs for PLC (all sag types), PC (all sag types) and ASD (balanced sags, neglecting phase shift) are shown in Figure 5-5 and Figure 5-6, respectively. Conversion graphs of ASD when subjected to three-phase unbalanced sags (magnitude unbalance) are given in Figure 5-7, Figure 5-8 and Figure 5-9.

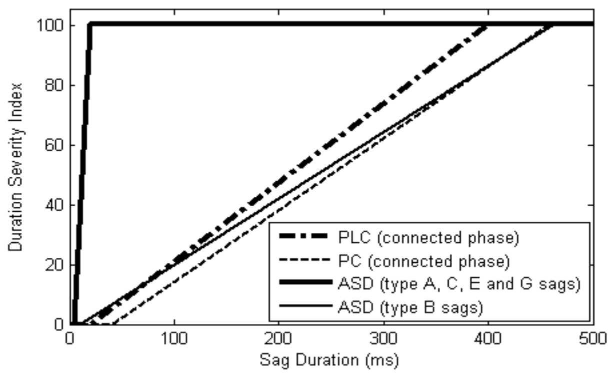


Figure 5-5 Sag duration to DSI conversion graphs of PLC, PC and ASD for balanced and type G sags

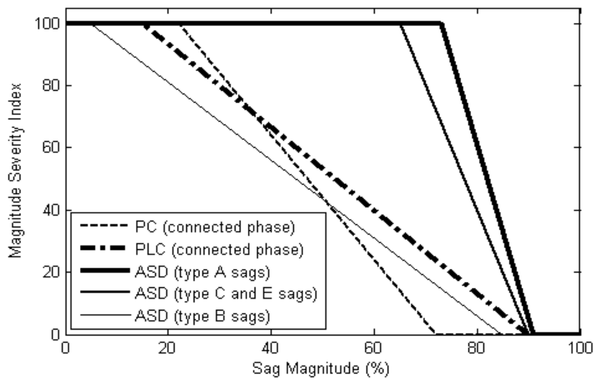


Figure 5-6 Sag magnitude to MSI conversion graph of PLC, PC and ASD for balanced sags

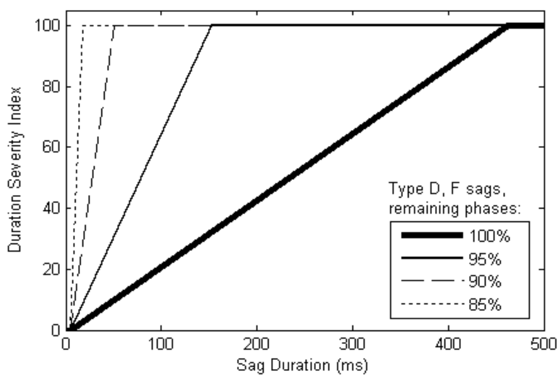


Figure 5-7 Sag duration to DSI conversion graph of ASD for type D, F sags

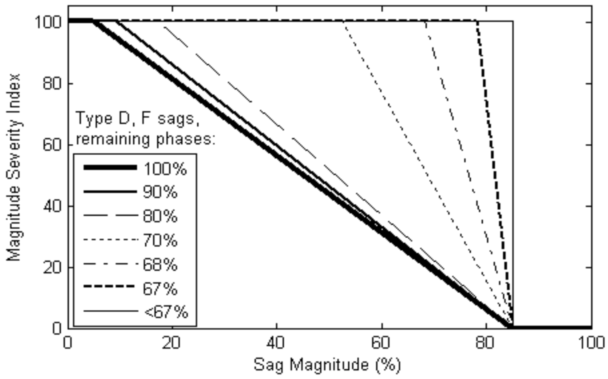


Figure 5-8 Sag magnitude to MSI conversion graph of ASD for type D, F sags

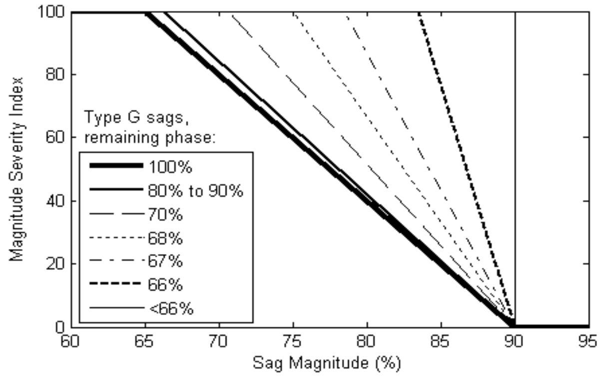


Figure 5-9 Sag magnitude to MSI conversion graph of ASD for type G sags

5.1.1.2.2 AC Contactors

Unlike other sensitive industrial equipment, AC Contactors do not have rectangular voltage tolerance curves [31, 117, 140, 144]. Laboratory tests conducted on AC contactors in [31] concluded that the tolerance curves have distinct shapes for 0º and 90º point on wave of sag initiation. Taking the tolerance curves of 0º and 90º points on wave as two opposite extremes, and superimposing them on a single figure, [33] obtained the boundaries of AC contactor tolerance, as shown in Figure 5-10.

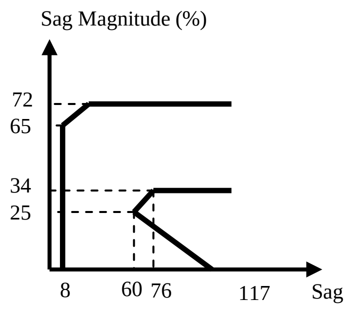


Figure 5-10 Boundaries of AC contactor voltage tolerance. Adopted from [33]

With a few modifications made in [33] on the starting point and cut-off points of severity indices, the MSI and DSI dependences on sag magnitude and duration are found to be as of Figure 5-11 and Figure 5-12.

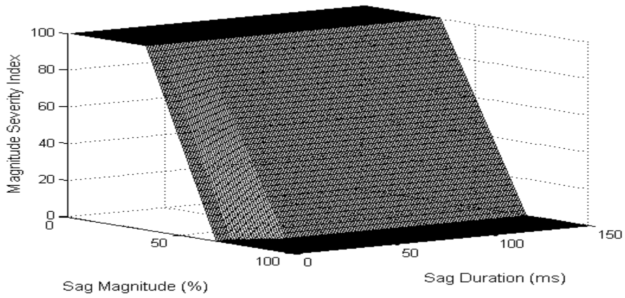


Figure 5-11 MSI conversion graph of AC contactor

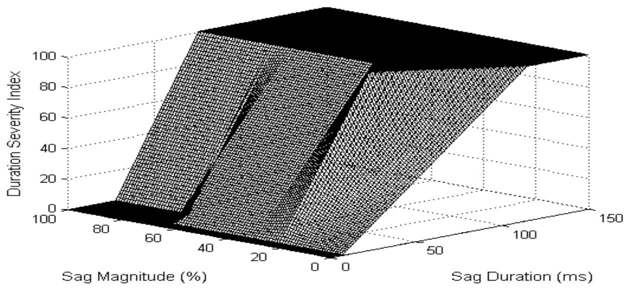


Figure 5-12 DSI conversion graph of AC contactor

5.1.2 Equipment Failure Risk Assessment

The goal of equipment sensitivity analysis is to estimate equipment behavior when subjected to voltage sags and short interruptions. For non deterministic issues as in equipment sensitivity analysis, equipment behavior is best quantified using failure risk values. Unlike conventional methods, the response of equipment to voltage sags and short interruptions is not confined to two states (trip or no trip). Instead, it is represented by the risk of equipment failure, with values ranging from 0 to 100. Failure risk of 0 represents certain ride through of equipment, whereas failure risk of 100 defines certain failure of equipment. The uncertainty in equipment response is represented by failure risks between 1 and 99. Knowing the failure risk of equipment for voltage sag events would help pinpoint weak links in processes, and facilitate the decision-making process for investments.

Two models are developed for determining equipment failure risk. These model would be subjectively compared with the fuzzy model developed in [33].

The simple MDSI method is designed for fast assessment, whereas probabilistic and fuzzy methods include statistical considerations to provide more accurate estimations. All three methods use MSI and DSI as basic input parameters, as shown in Figure 5-13.

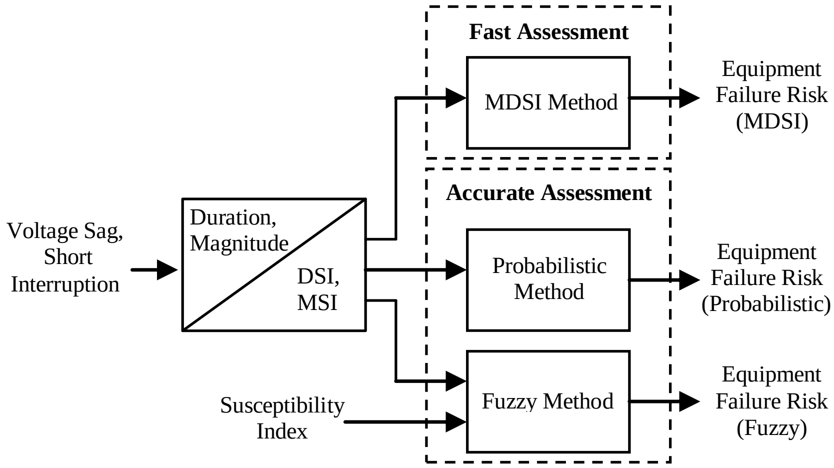


Figure 5-13 Equipment failure risk assessment models

5.1.2.1 Simple MDSI Assessment

The Magnitude Duration Severity Index (MDSI) defined by (5-9), integrates DSI and MSI into a single index to represent the impact of voltage sags and short interruptions as a function of both duration and magnitude severities. It translates physical sag characteristics into the level of severity posed by the disturbance. MDSI ranges from 0 to 100 and its value represents linear increase in equipment failure risk when subjected to voltage sag and short interruptions.

$$MDSI = \frac{MSI \times DSI}{100} \tag{5-9}$$

It can be used very efficiently to: i) Assess the impact of voltage sags and short interruptions on individual equipment type; ii) Compare the impact of voltage sag and short interruption events between different equipment types; iii) Identify the weakest link in an industrial process that has various equipment types; iv) Rank disturbance events based on their severity.

The application of MDSI is demonstrated, using arbitrarily generated balanced voltage sags. The behavior of AC contactors when subjected to voltage sags and short interruptions is predicted using MDSI. The sag characteristics of the generated voltage sags are summarized in Table 5-2.

Table 5-2 Arbitrarily created voltage sags

Sag	Sag Duration (ms)	Sag Magnitude (%)
A	100	75
B	96	23
C	400	67
D	75	85
E	43	73
F	321	53
G	28	33
H	125	0
I	230	37
J	360	87

MDSI allows comparison of the severity of different events. In Table 5-3 below, the events are ranked using MDSI, from the most severe sag "B", to the least severe sags A, J, D and E.

Table 5-3 Sag ranking with respect to contactor sensitivity

Rank	Sag	DSI	MSI	MDSI
1	B	100	100	100
=1	H	100	100	100
3	I	100	92.1	92.1
4	F	100	50	50
5	G	30.4	100	30.4
6	C	100	13.2	13.2
7	A	100	0	0
=7	J	100	0	0
=7	D	97.9	0	0
=7	E	31.3	0	0

Severity indices also enable comparison between different equipment types regarding sensitivity to voltage sags. By comparing the MDSI values, the most vulnerable equipment for any given sag can be identified. In this example, the most vulnerable equipment type for all generated sags is identified in Table 5-4.

This function can be further expanded to cover the entire range of sag characteristics. Figure 5-14 illustrates the most vulnerable equipment to a range of magnitudes and durations of voltage sags and short interruptions. With this information, industrial plant managers can easily identify weak links in a process.

The main advantage of MDSI method is that it is able to provide fast assessment without additional modeling or complicated calculations. However, the linear curve used by this model may prove too simplistic for assessments (e.g. financial assessment) that require accurate failure risk values.

Table 5-4 Equipment vulnerability to sags

Event	MDSI				Most Vulnerable Equipment
	PC	ASD	PLC	AC Contactor	
A	0.0	23.4	4.2	0.0	ASD
B	13.1	52.1	17.9	100.0	AC Contactor
C	8.6	65.7	30.7	13.2	ASD
D	0.0	5.6	1.0	0.0	ASD
E	0.0	9.7	1.4	0.0	ASD
F	25.5	100.0	39.1	50.0	ASD
G	0.0	10.9	1.6	30.4	AC Contactor
H	20.3	69.7	27.6	100.0	AC Contactor
I	31.7	100.0	39.1	92.1	ASD
J	0.0	8.6	3.6	0.0	ASD

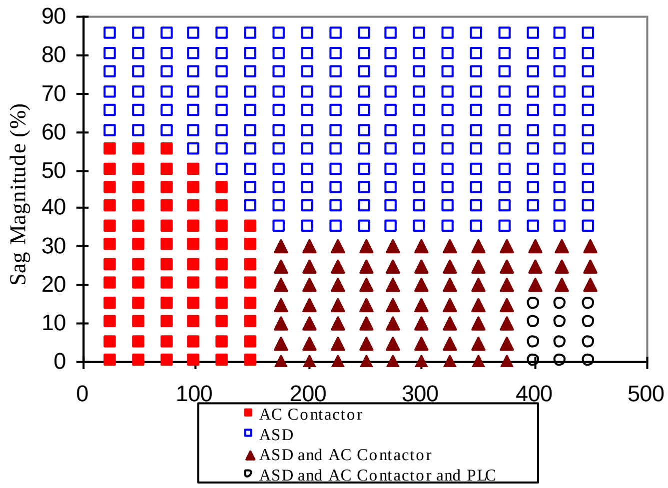


Figure 5-14 The most vulnerable equipment for a range of magnitudes and durations of voltage sags and short interruptions

5.1.2.2 Probabilistic Model

Probabilistic analysis is an accepted methodology used to assess equipment response to voltage sags. Basically, the area of uncertainty in equipment behavior is represented using probabilistic distribution functions obtained from equipment test results. Large amount of test information is required for probabilistic modeling. Therefore, the most widely tested and reported equipment, personal computer (PC), is used as a reference for modeling.

PC test results obtained from previous studies [32, 140, 143, 145] were gathered and statistically analyzed in [33]. A total of 38 voltage tolerance curves were used. All studies were independent and conducted on different PC types and ages. Hence, it is assumed that the test results are dominantly random in nature.

MSI, DSI, and MDSI are used to facilitate probabilistic modeling of PC behavior. From the 38 test results of PC, trip durations and magnitudes are converted into MSI, DSI and MDSI, and plotted against the cumulative failure probability of the tested subjects. The failure probability used is the combined failure probability (magnitude and duration failure) of the test subjects determined using (5-10) [35].

$$Combined\ Failure\ Probability = Failure\ due\ to\ Magnitude \times Failure\ due\ to\ Duration \quad (5\text{-}10)$$

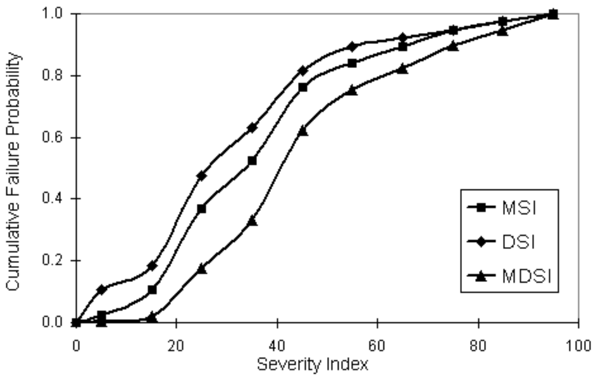


Figure 5-15 Cumulative failure probability of PC

The cumulative failure probability of PC with respect to *DSI*, *MSI* and *MDSI* are shown in Figure 5-15. These failure probabilities are then statistically fitted into probability distribution functions. The distribution functions for DSI and MSI are found to be Normal distributions with mean and standard deviation of 36.8 and 21.8 for DSI, and 40.4 and 20.9 for MSI.

The Normal distribution curve is used to represent the sensitivity of an average equipment. To incorporate more flexibility into the model, two more sensitivity levels (high and low) are modeled. The distribution functions for high and low sensitivity equipment behavior are represented using exponential and reverse exponential functions. These functions are modeled such that the DSI/MSI value that corresponds to 0.5 failure probability of the average curve gives failure probability of 0.85 for high sensitivity and 0.15 for low sensitivity, respectively. The mean values (μ) for corresponding exponential functions is found as follows:

- Duration: μ = 20 for high susceptibility, μ=33 for low susceptibility
- Magnitude: μ=21 for high susceptibility, μ=32 for low susceptibility

The resulting distribution functions are shown in Figure 5-16 and Figure 5-17.

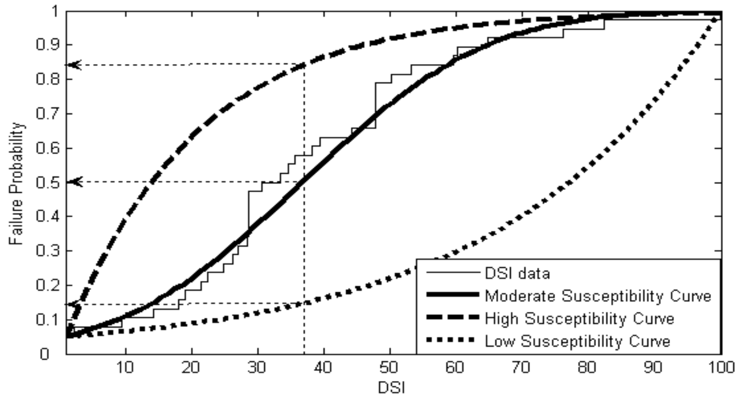


Figure 5-16 Probabilistic model representing duration failure probability

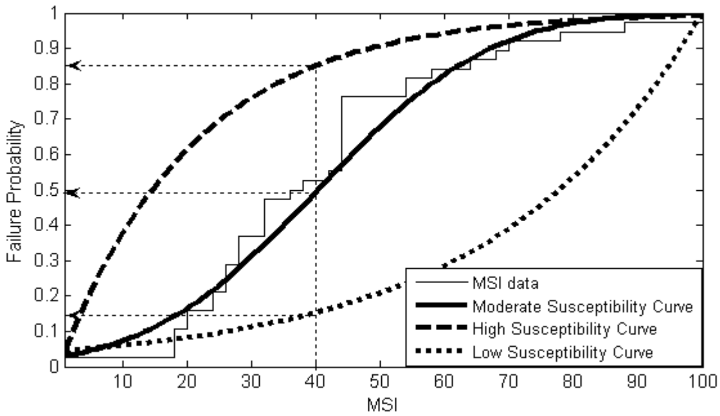


Figure 5-17 Probabilistic model representing magnitude failure probability

The procedure for determining equipment failure probability is as follows: First, sag duration and magnitude are translated into DSI and MSI. Next, using the fitted distribution functions, a duration failure probability and a magnitude failure probability is found. Finally, these probabilities are combined using (5-10), which gives the failure probability of the equipment considering both magnitude and duration. As different equipment types result in different MSI and DSI for the same voltage sag event, each equipment type would have a unique failure probability.

5.1.3 Comparison of Different Approaches

The simple MDSI models, the new probabilistic models, and the existing fuzzy models can all be used to assess equipment failure risk when subjected to voltage sags and short interruptions. To compare their characteristics in assessment, the most common sensitive equipment (PC, ASD, PLC, AC Contactor) are being modeled using all three methods. Each equipment model is being fed with 5000 balanced sags with random magnitude and durations.

5.1.3.1 Personal Computer

The output failure risks of personal computer (PC) for the first fifty randomly generated voltage sags are given in Figure 5-18 to Figure 5-20. It can be seen that all three methods follow a similar trend in transition from one voltage sag to another. The agreement in trend indicates that the models are modeled correctly. Though the trend is the same, the risk magnitudes differ substantially.

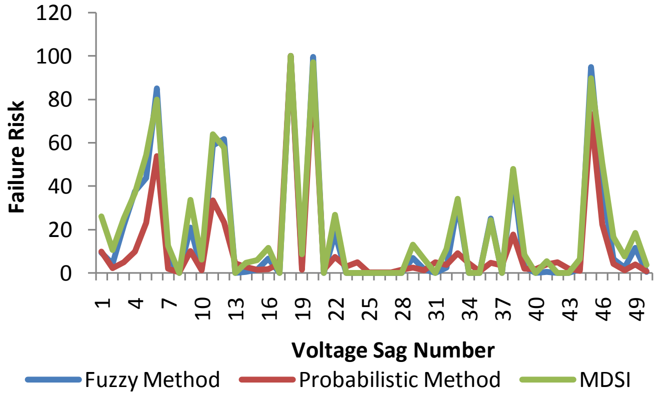


Figure 5-18 Failure risk of PC with low sensitivity for 50 random voltage sag events

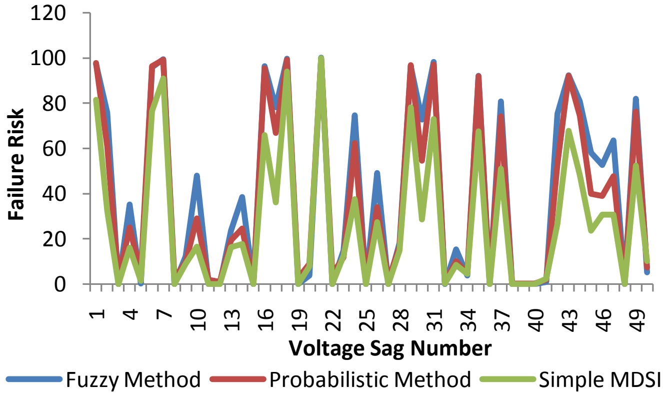


Figure 5-19 Failure risk of PC with moderate sensitivity for 50 random voltage sag events

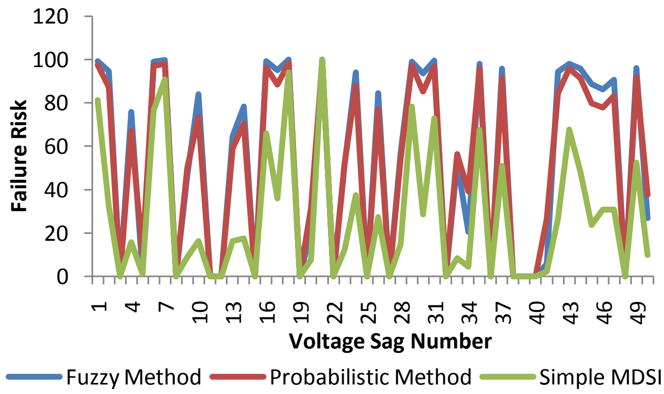


Figure 5-20 Failure risk of PC with high sensitivity for 50 random voltage sag events

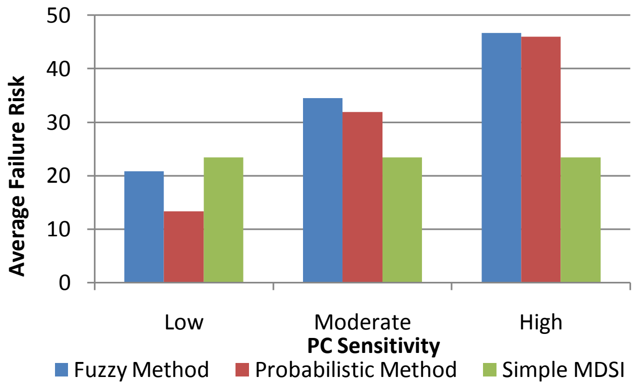


Figure 5-21 Comparison of fuzzy, probabilistic and simple MDSI methods in assessing failure risk of PC

Figure 5-21 shows the average failure risk of PC obtained from 5000 randomly generated voltage sags. It can be seen that the linear MDSI model cannot account for equipment sensitivity levels, producing a constant output for all sensitivity levels. On the other hand, both fuzzy and probabilistic methods consider equipment sensitivity in assessment and are flexible for different applications.

For all sensitivity level, fuzzy logic generates higher failure risk compared to probabilistic method, thus represents the more pessimistic outcome in risk assessment.

5.1.3.2 Adjustable Speed Drive

The output failure risks of ASD for the first fifty randomly generated voltage sags are given in Figure 5-22 to Figure 5-24. Again, all three methods follow a similar trend in transition from one voltage sag to another. Moreover, the risk magnitudes between fuzzy method and probabilistic method are very close to each other, indicating good agreement between the two methods.

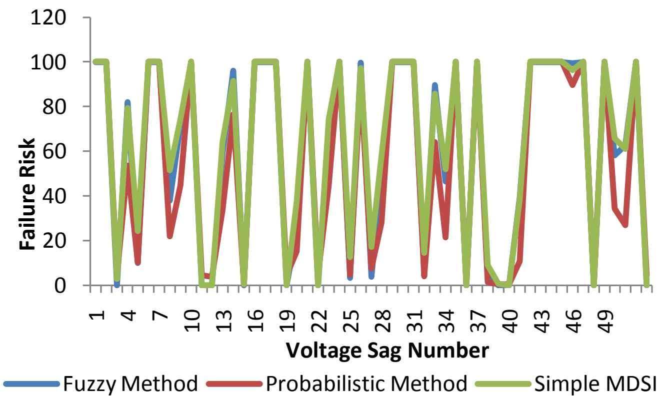


Figure 5-22 Failure risk of ASD with low sensitivity for 50 random voltage sag events

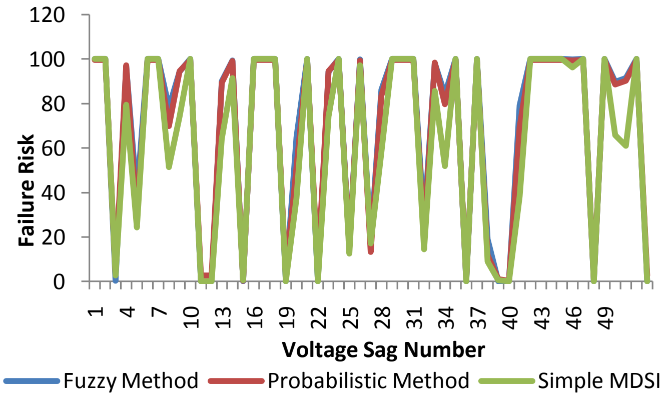


Figure 5-23 Failure risk of ASD with moderate sensitivity for 50 random voltage sag events

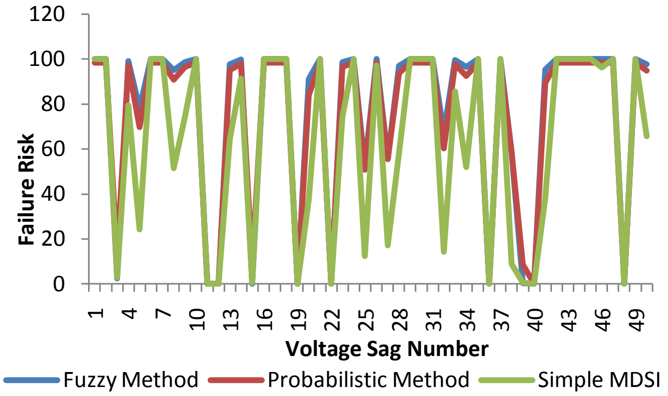


Figure 5-24 Failure risk of ASD with high sensitivity for 50 random voltage sag events

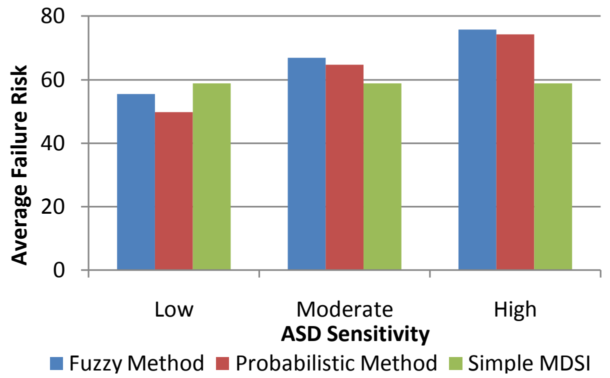


Figure 5-25 Comparison of fuzzy, probabilistic and simple MDSI methods in assessing failure risk of ASD

Figure 5-25 illustrates the average failure risk from 5000 randomly generated voltage sags. It can be seen that for ASD sensitivity analysis, the difference between fuzzy and probabilistic methods are minor for low ASD sensitivity and negligible for moderate and high ASD sensitivity.

5.1.3.3 Programmable Logic Controller

Figure 5-26 to Figure 5-28 shows the failure risk of PLC for the first 50 voltage sag generated. Again, all three methods agree on trend in transition from one voltage sag to another. Average failure risk of 5000 voltage sags is given in Figure 5-29. There are noticeable differences between fuzzy and probabilistic method for low and moderate sensitivity PLC. Negligible difference is found for high sensitivity PLC.

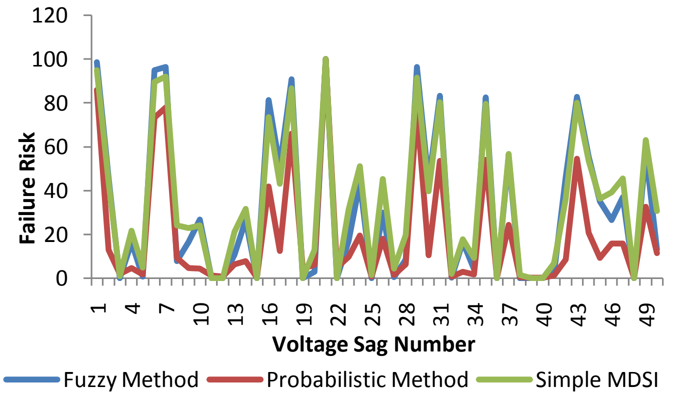


Figure 5-26 Failure risk of PLC with low sensitivity for 50 random voltage sag events

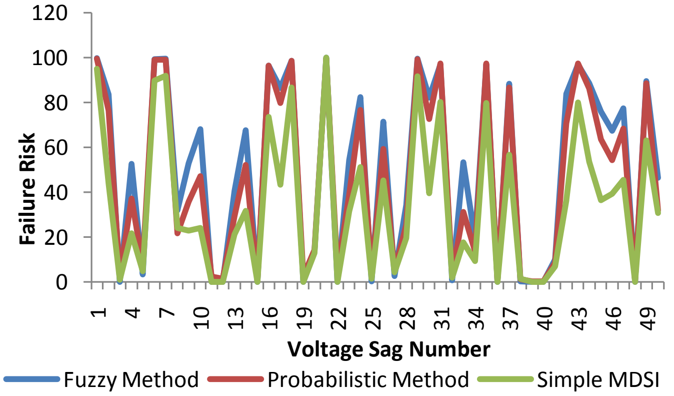


Figure 5-27 Failure risk of PLC with moderate sensitivity for 50 random voltage sag events

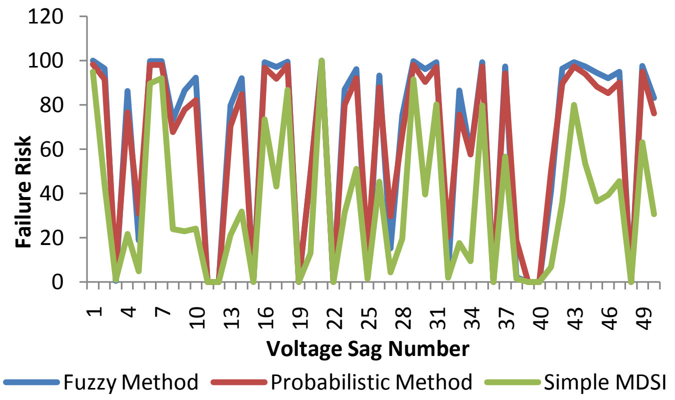


Figure 5-28 Failure risk of PLC with high sensitivity for 50 random voltage sag events

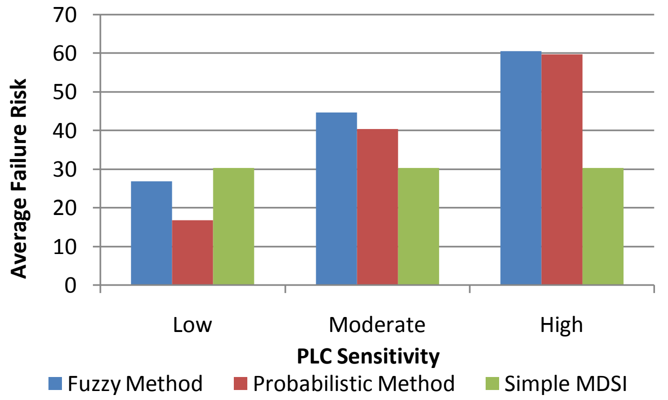


Figure 5-29 Comparison of fuzzy, probabilistic and simple MDSI methods in assessing failure risk of PLC

5.1.3.4 AC Contactor

Simulation results for the first 50 randomly generated voltage sags are given in Figure 5-30 to Figure 5-32. As expected, the transition trend from one voltage sag to another is consistent among the three methods.

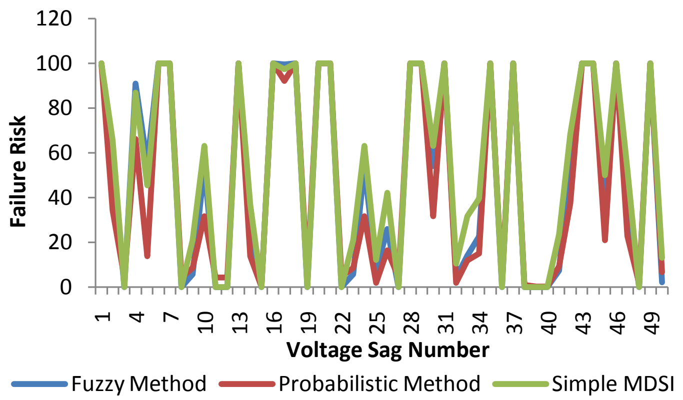


Figure 5-30 Failure risk of ACC with low sensitivity for 50 random voltage sag events

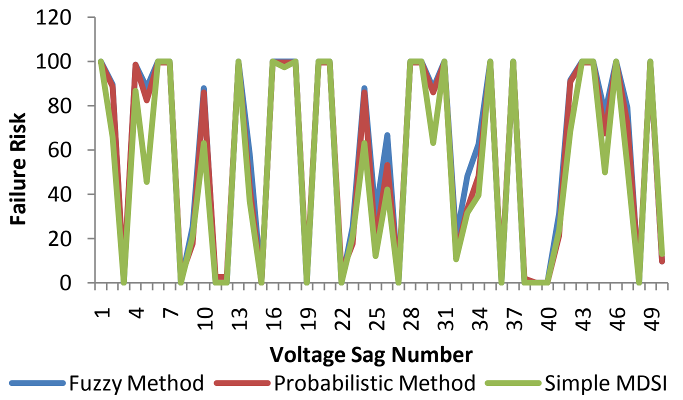


Figure 5-31 Failure risk of ACC with moderate sensitivity for 50 random voltage sag events

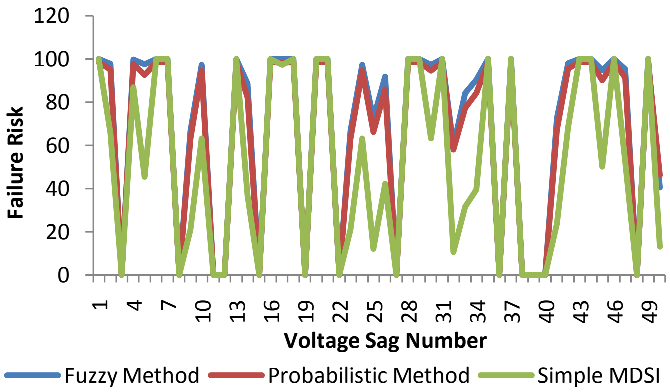


Figure 5-32 Failure risk of ACC with high sensitivity for 50 random voltage sag events

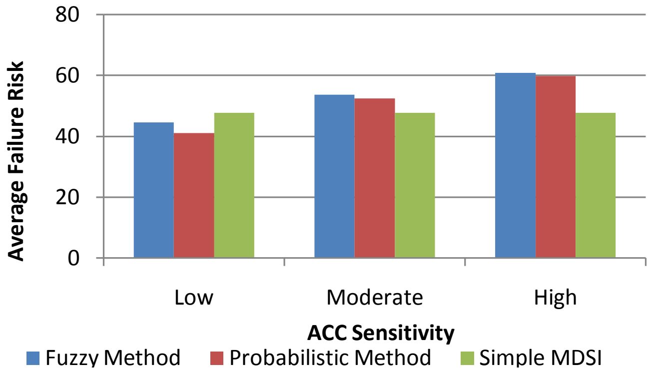


Figure 5-33 Comparison of fuzzy, probabilistic and simple MDSI methods in assessing failure risk of ACC

Figure 5-33 shows the average failure risk of ACC obtained from simulation of 5000 randomly generated voltage sags. It shows less than 5% difference in risk assessment for low sensitivity ACC, and less than 2% difference for moderate and high sensitivity ACC. Therefore, it is safe to say that both probabilistic and fuzzy methods are inter-changeable in ACC failure risk assessment.

Overall results confirmed that all three modelling methods produce consistent trend when assessing equipment. Simple MDSI method does not distinguish between different equipment sensitivity levels and is thus unsuitable for accurate assessment. Fuzzy method is the most conservative method as it gives the highest failure risk for all equipment types and sensitivity levels. Assessments using fuzzy models also requires significantly more computational time compared to probabilistic models. On the other hand, probabilistic models enable fast simulation time and good accuracy, most suitable for large scale assessments i.e. network level assessments involving hundreds of equipment and processes.

5.1.4 Influence of Transformer Winding

It is known that sag characteristics would change after travelling through transformers [6]. Though the effect of transformer winding connections on sag characteristics is described in detail in [146], the influence of winding connections on equipment failure risks has not been adequately addressed in the past due to the lack of proper equipment models. With the development of three-phase models for ASD, this effect can be now be quantified.

Table 5-5 below shows common transformer windings used in power systems and their effect on the sequence components of a voltage sag. It can be seen that Group 1 and Group 2 transformer filters the zero sequence component voltage during transformation. During sag, the elimination of zero sequence component voltage by the supply transformer will affect sag characteristics at customer busbar.

In this assessment, all single-phase equipment is assumed to be connected phase to neutral. One equipment is connected at each phase (e.g. 3 personal computers, 1 to phase A, 1 to phase B and 1 to phase C). Full three-phase representation for ASD is also used.

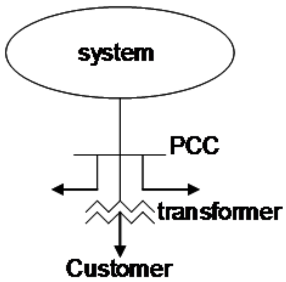


Figure 5-34 customer connection to the grid

The objective of this particular study is to determine the effect of transformer (Figure 5-34) winding connections on sag characteristics, and subsequently, the failure risk of customer equipment. It is assumed that the sags occurring at PCC still contains zero sequence components. An actual sag profile generated from fault positioning studies in [46] is used for the analysis. The study simulated faults across the network (refer to [46] for details) and generated 7852 voltage sags at PCC. Vast majority of the faults simulated (90%) were ground faults. Not all of them were severe enough to be classified as sags (voltage magnitude was>0.9p.u.). Those that were sags (voltage magnitude < 0.9p.u.) totaled 2800.

Table 5-5 Types of transformer windings and its effect on voltage sag

Transformer			**Output at secondary (Sequence Components)**		
Group	**Winding Type**	**Clock**	**Zero Sequence**	**Positive Sequence**	**Negative sequence**
1	Ygd	Ygd1	0	-30	+ 30
		Ygd3	0	-90	+ 90
		Ygd5	0	-150	+ 150
		Ygd7	0	-210	+ 210
		Ygd9	0	-270	+ 270
		Ygd11	0	-330	+ 330
	Yd	Yd1	0	-30	+ 30
		Yd3	0	-90	+ 90
		Yd5	0	-150	+ 150
		Yd7	0	-210	+ 210
		Yd9	0	-270	+ 270
		Yd11	0	-330	+ 330
	dYg	dYg1	0	-30	+ 30
	dY	dY1	0	-30	+ 30
2	YgY	Ygy0	0	no shift	no shift
		Ygy2	0	-60	+ 60
		Ygy4	0	-120	+ 120
		Ygy6	0	-180	+ 180
		Ygy8	0	-240	+ 240
		Ygy10	0	-300	+ 300
	Yyg	Yyg0	0	no shift	no shift
	Yy	Yy0	0	no shift	no shift
		Yy2	0	-60	+ 60
		Yy4	0	-120	+ 120
		Yy6	0	-180	+ 180
		Yy8	0	-240	+ 240
		Yy10	0	-300	+ 300
	Dd	Dd0	0	no shift	no shift
		Dd2	0	-60	+ 60
		Dd4	0	-120	+ 120
		Dd6	0	-180	+ 180
		Dd8	0	-240	+ 240
		Dd10	0	-300	+ 300
3	Ygyg	Ygyg0	Vp0	no shift	no shift
		Ygyg2	-Vp0	-60	+ 60
		Ygyg4	Vp	-120	+ 120
		Ygyg6	-Vp0	-180	+ 180
		Ygyg8	Vp	-240	+ 240
		Ygyg10	-Vp0	-300	+ 300

Figure 5-35, Figure 5-36 and Figure 5-37 show the effect of different groups of transformers on sag characteristics. It can be seen that there is a significant increase in the total number of sags for group 1 and group 2 transformer windings. The elimination of zero sequence voltages caused many sags to become deeper that 0.9p.u.. The total number of sags after propagating through a Group 3 type winding remains the same.

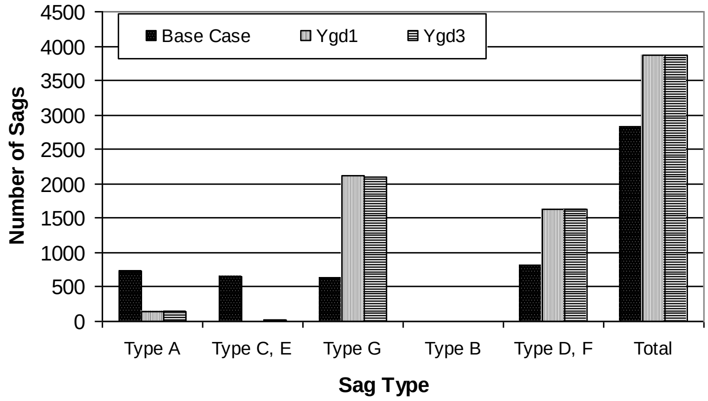


Figure 5-35 Influence of Group 1 transformers on the number of sags

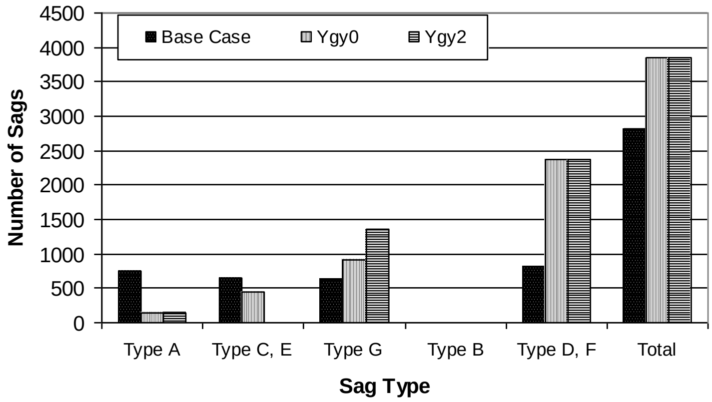


Figure 5-36 Influence of Group 2 transformers on the number of sags

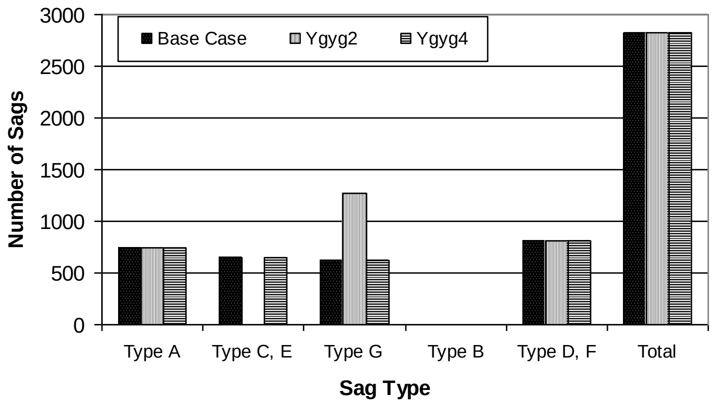


Figure 5-37 Influence of Group 3 transformers on the number of sags

Table 5-6 shows the change in equipment failure risk as a result of different transformer winding types. A significant increase of around 50% is observed for transformer group 1 and 2.

Extensive simulation confirms the significance of proper equipment modeling. Based on this analysis, the change in equipment failure risk due to the influence of different transformer groups is quantified. It should be noted that the assumption that sags at PCC contains zero sequence components does not usually apply as sags originating from different parts of the network would probably have passed through a number of transformers before reaching PCC.

Table 5-6 Change in equipment failure risk due to transformer windings

Transformer Group	Change in Risk (%)		
	Single-phase Equipment	Adjustable Speed Drives	Total
Group 1 Transformer	+52.2	+46.9	+50.8
Group 2 Transformer	+55	+51.2	+54.1
Group 3 Transformer	0	0	0

5.1.5 Process Failure Risk Assessment

Process failure risk assessment generally consists of two schools of modelling; single equipment process models and multi equipment process models. Single equipment process models assume that process operation depends on one main sensitive equipment. Tripping of this equipment will cause process disturbance. In multi equipment process models, process operation depends on several equipment types (or even sub-processes). Tripping of any equipment type will contribute the equipment's portion of risk to process failure.

Multi equipment process models are discussed in detail in [33]. An extra level of assessment involving sub-process assessment was also introduced. Basically, a sub-process is a group of equipment (different types and sensitivities) operating as part of a larger process. Equipment trips cause sub-process trips, which is followed by tripping of the process. Sub-process failure risk depends on its equipment types and their composition ratio. Assuming that higher equipment composition ratio translates to higher sub-process dependence on the equipment, the risk contribution of each equipment type is determined and summed together to form sub-process failure risk.

The failure risk of a process in turns depends on the failure risk of its sub-processes and was assessed using fault tree analysis. Figure 5-38 shows an example of the fault trees used. Sub-process failures are placed at the bottom of the fault tree. Using *AND* and *OR* gates, the relationship between sub-process failures is defined. *AND* operation (intersection of the subsets) is used when all sub-processes have to fail for the process to fail. On the other hand, O*R* operation (the union of the subsets) is used when failure of any one of the sub-processes shuts down the entire process (non-redundant system).

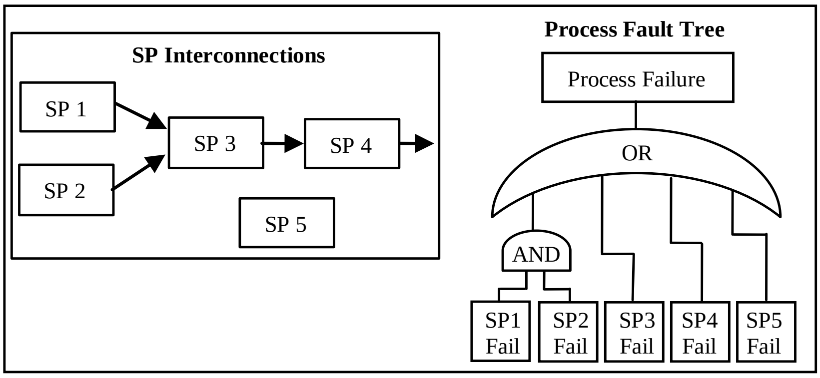


Figure 5-38 Fault tree analysis on a general process

Theoretically, multi equipment models are more precise in its approach to failure risk assessments. However, many parameters required by this approach, such as the importance level of equipment, would prove impossible to obtain or estimate in realistic situations. Despite the difficulty in parameter setting, multi equipment process models are still a viable alternative to single equipment process models.

Unlike multi equipment models, plant engineers often find that process operation depends only on one main equipment. Moreover, there is a buffer time, process immunity time (PIT), for which processes can continue to operate even though their main equipment has tripped. For example, temperature of chemicals in a processing plant would hold for a few minutes even when the main boiler has stopped working. Single equipment models provide an easy way of including this effect in assessments.

The time a process can continue operation after its main equipment tripped is defined as Process Immunity Time (PIT) constant [3]. On the other hand, the time required to restart a process's main equipment after it has been tripped is the Equipment Restart Time (ERT) of a process. Process will not be disrupted if equipment is restarted before PIT is reached.

PIT and ERT determines processes behavior when subjected to power quality disturbances. Given that the behavior of equipment is represented by failure risks, process will behave as follows:

- If PIT > ERT, process rides through and process failure risk is null.
- If PIT <ERT, process failure risk is equal to equipment failure risk.

Processes do not always operate independently. Some processes rely on the output of upstream processes while some supply downstream processes. The interdependence between processes can be specified in the form of a Process Dependence Matrix (PDM), as shown in Table 5-7. A PDM is way to translate complex process interdependence relationships into a machine friendly table easy to be read by a computer software.

Table 5-7 Process Dependence Matrix

PDM	Dependence				
Process		Process 1	Process 2	Process 3	Process 4
	Process 1	1	0	0	0
	Process 2	1	1	0	0
	Process 3	1	0	1	0
	Process 4	1	0	1	1

A plant with n processes is represented by an $n \times n$ PDM. PDM is populated by the inclusion of all direct and indirect dependence of each process to other processes. If i is the row number and j is the column number in a PDM, *1* means dependence of process i to process j, while zero signifies non dependence of process i to process j. The dependence relationship of processes for the PDM of Table 5-7 is illustrated in graphical form in Figure 5-39. It can be seen that a dependence relationship is formed for every "one" in the PDM. It should be noted that dependence relationships do not necessarily represent physical connections between processes.

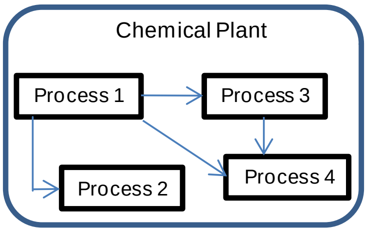


Figure 5-39 Dependence relationship between processes

Under the PDM scheme, a process has multiple sources of failure risk; risks caused by failure of equipment in the process (primary), and risks caused by failure (risk of) of processes it depends on (secondary). Total failure risk of a process can be calculated from (5-11).

$$Pi = (N_{i1} \times p_1) \cup (N_{i2} \times p_2) \cup (N_{i3} \times p_3) \cdots\cdots \cup \left(N_{ij} \times p_j\right) \quad (5\text{-}11)$$

Where P_i = total failure risk of process i

N_{ij} = value of PDM (1 or 0) at row *i* column *j*

p = primary failure risk of process

The PDM model also allows individual process cost factor to be added to each process to simulate the effect of load profile and process cycle modeling. This model will be used extensively in Chapter 7 for a full scale simulation of an actual network.

5.2 Sag Profile Estimation

The annual number of voltage sags and the characteristics of sags make up the voltage sag profile of a customer plant. This profile is the most important element in voltage sag analysis as it determines the severity of the problem faced, and directly influences the annual number of process trips and financial losses.

Voltage sag profile at customer busbar depends on many factors, from the electrical location of the customer, the strength of the network, fault rates of network components, to operational nature of neighboring establishments. Put simply, voltage sag profile at customer busbar is a unique combination of factors that vary from year to year. Therefore, modelling the voltage sag profile at customer busbar is a prerequisite to any further voltage sag analysis.

Typically, at least one year of sag monitoring record must be available, although longer monitoring period would yield more accurate sag profile. However, to expect monitoring record of more than a year at all buses of interest is unrealistic in most circumstances. Furthermore, spending too much time on monitoring and data acquisition could delay the deployment of mitigating solutions and cause unnecessary financial losses overtime. Therefore, it is important to find a balance between the monitoring duration and accuracy of estimation.

This section illustrates voltage sag profile estimation based on available monitoring records. It demonstrates how different methods and different durations of monitoring period affect accuracy of sag profile modelling. This represents the third original contribution of this research.

5.2.1 Reference Case

The general industrial process introduced in Figure 5-38 is used to illustrate the approach. In this case, multi equipment process model is used instead of the single equipment model, as the difficulty in parameter setting associated with the model does not exist here. The process has five sub-processes, with sub process interconnections and associated fault tree show in Figure 5-38. It is assumed that equipment restart time (ERT) is longer than Process Immunity time (PIT) for all equipment type, i.e. failure of equipment causes process failure. The equipment composition ratio used is given in Table 5-8. (Note: SP stands for sub-process; PC stands for personal computer; ASD for adjustable speed drives; PLC for programmable logic controllers; ACC for AC contactor).

Table 5-8 Equipment composition ratio of process model

Sub-process	Equipment Composition Ratio (%)			
	PC	ASD	PLC	ACC
1	0	50	0	50
2	0	40	30	30
3	0	40	30	30
4	25	25	25	25
5	80	0	20	0

5.2.2 Estimating Sag Characteristics

The parameter used to determine accuracy of sag profile modelling is the failure risk of the reference process resulting from the sags. In this case, the process financial loss is directly proportional to process failure risk. By comparing the process failure risk of estimated voltage sag profiles with the failure risk from the actual sag profile, the range of estimation error can be determined. Three parameters are considered in sag profile modelling; the annual number of sags, the sag durations, and the magnitude of sags.

The investigation uses an actual voltage sag monitoring record of a manufacturing plant in the United States. The sag profile is shown in Figure 5-40, while Figure 5-41 shows the number of voltage sags per year during the monitoring period. All sags are assumed to be three phase balanced sags to simplify assessment.

As can be seen in Figure 5-40, the monitored profile has the characteristics of a typical sag profile, with large concentration of relatively shallow (remaining magnitude of above 70% nominal) and short (sag duration of less than 0.5 seconds) sags. 13 years worth of monitoring record is used with a total of 183 recorded sags.

The annual number of sag varies from year to year. From Figure 5-41, the occurrence frequency of sags ranges from 8 to 20 sags a year, which is between 1 sag in 18 days to 1 sag in 46 days. Extrapolating from Table 5-9, the required monitoring periods to achieve 50% accuracy would be between 42 weeks to 2 years, whereas a 10% accuracy would require 18 to 42 years of monitoring, and 2% accuracy between 450 to 1150 years.

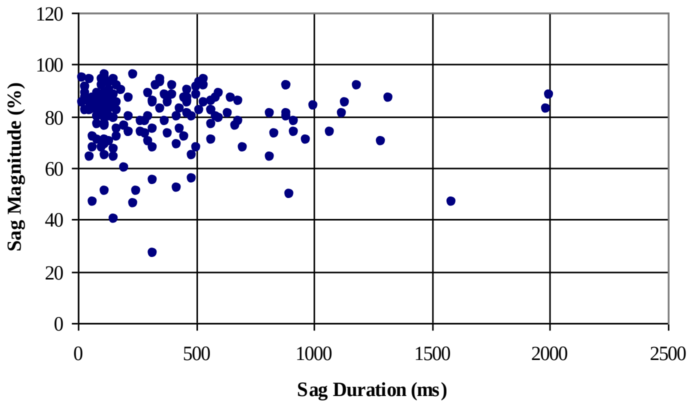


Figure 5-40 Actual 13-year voltage sag profile of a manufacturing plant

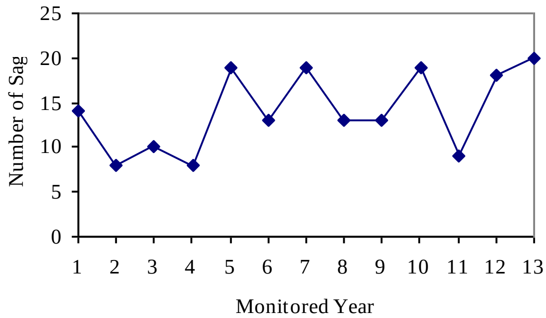


Figure 5-41 Annual number of sag in the 13-year period.

Table 5-9 Monitoring period and accuracy in estimation. Adopted from [22]

Event Frequency	Required Accuracy		
	50%	10%	2%
1 per day	2 weeks	1 year	25 years
1 per week	4 months	7 years	200 years
1 per month	1 year	30 years	800 years
1 per year	16 years	400 years	10000 years

Using the monitoring record as input to the reference model, process failure risk when subjected to each sag can be obtained. The total process failure risk, as the sum of failure risk for all 183 sags is calculated to be 7998 units. This value is then normalized to 1.0 and used as the reference to validate the accuracy of the following sag performance estimation methods.

The following analysis considers monitoring durations ranging from one year to 13 years. For each monitoring period, variable starting time of monitoring commencement is considered. For example, in the case where 3-year monitoring period is assessed, the first simulation considers monitoring starting at year-1. Hence, records for year-1, year-2 and year-3 are used to estimate sag performance of entire 13-year period. For the second simulation, monitoring is assumed to start at year-2, therefore, records of year-2, year-3, and year-4 are used. By varying the starting year of monitoring commencement, the entire 13-year period can be covered. It is assumed that the 13-year voltage sag profile is a cycle that repeats itself at the end of year-13. In this case, the 13^{th} simulation will use monitoring records of year-13, year-1 and year-2 for estimation.

Three sag characteristics need to be estimated; the annual number of sags, the sag duration, and the magnitude of the sag.

Probabilistic method estimates the annual number of sags using probability distributions obtained from monitoring records. As shown in Figure 5-42, a Poisson distribution with lamda of 14.08 is obtained through probability distribution fitting of the monitoring records. However, with limited sample for curve fitting, the resulting estimation can be misleading.

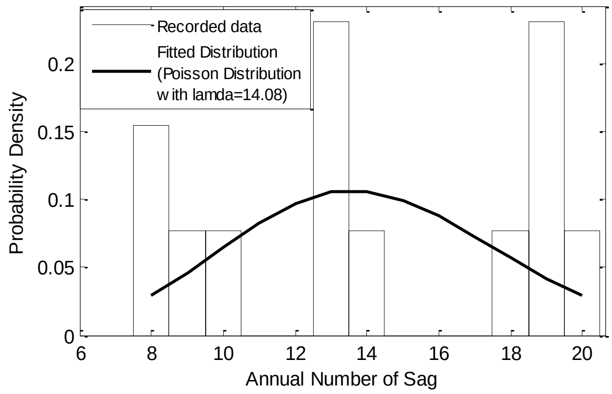


Figure 5-42 Distribution fitting of the annual number of sag

Therefore, A simple averaging technique is employed to estimate the annual number of voltage sags. For a given monitoring period, the annual number of sag is the average number in the period. This average annual sag number is then extrapolated to obtain the total sag number for the assessment period. Equation (5-12) gives the total number of estimated sags in the assessment period. From (5-12) N is the total estimated number of sags, num_t is the number of sags in year t, Y is the number of monitoring years, and P is the required assessment period, which is 13 years in the analysis.

$$N = \frac{\sum_{n=1}^{Y} num_t}{Y} \times P \tag{5-12}$$

To estimate sag magnitude and duration, three methods are investigated: simple averaging, linear extrapolation and probabilistic fitting. The estimated sag profiles of all three methods are fed into the reference process model to generate estimated process failure risk. These estimated failure risks are then normalized and compared to the actual failure risk to determine accuracy.

5.2.2.1 Simple Average

With the simple averaging technique, an “average” voltage sag is used to represent all sags that would occur. This “average” sag has its characteristics (magnitude and duration) derived from the average value of sag magnitudes and durations of all sags in the monitored period. For example, if there were sags recorded with sag magnitudes of 50% and 60% respectively, the “average” sag would have sag magnitude of 55%. This average sag is then reproduced until the total estimated number of sags in the 13-year period is reached. In other words, if there were 155 estimated sags, the “average” sag of 55% magnitude would be reproduced 155 times.

Figure 5-43, Figure 5-44 and Figure 5-45 shows the estimated total process failure risk with one, five and ten years worth of monitoring. It is obvious that estimation with one year of monitoring record does not represent the failure risk value of the actual case. The estimation improves with five years of monitoring, but still overestimates most risks. There is no obvious improvement when the monitoring period is extended to 10 years.

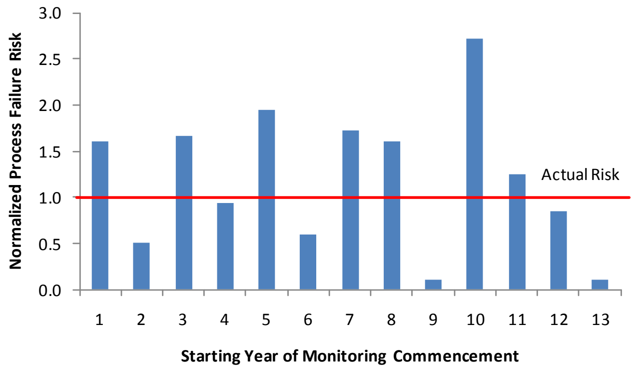


Figure 5-43 Performance estimation with simple averaging method, 1 year monitoring

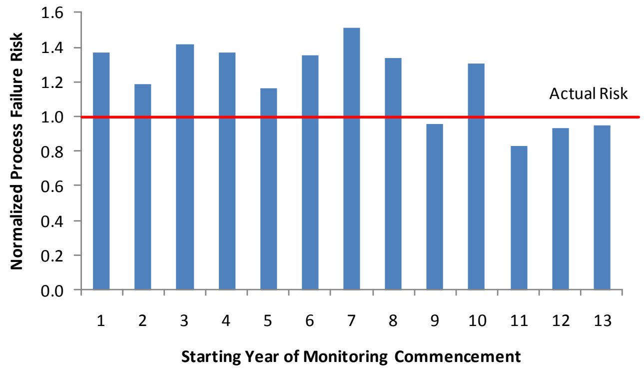


Figure 5-44 Performance estimation with simple averaging method, 5 year monitoring

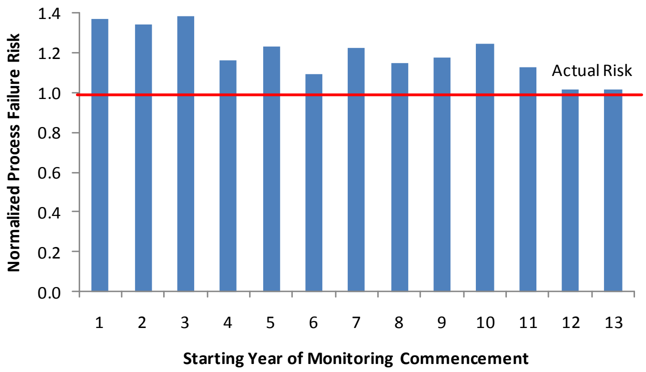


Figure 5-45 Performance estimation with simple averaging method, 10 year monitoring

5.2.2.2 Extrapolation

In the extrapolation method, monitored sags are repeatedly generated until it reaches the estimated total number of voltage sags. For instance, if the monitoring period is two years, the monitored sags in the two-year period will be generated 6.5 times to represent the entire 13-year assessment period.

The estimation results for one, five and ten years of monitoring are shown in Figure 5-46, Figure 5-47 and Figure 5-48 respectively. It can be seen that one year's worth of monitoring yielded better estimated compared to the simple averaging method (Figure 5-43), but still short of accuracy to represent the actual risk. Longer monitoring periods of five and ten years produced much more promising results with fairly accurate estimations.

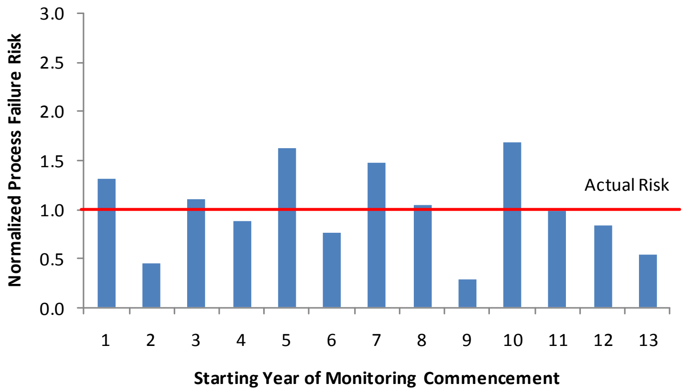


Figure 5-46 Performance estimation with linear extrapolation method, 1 year monitoring

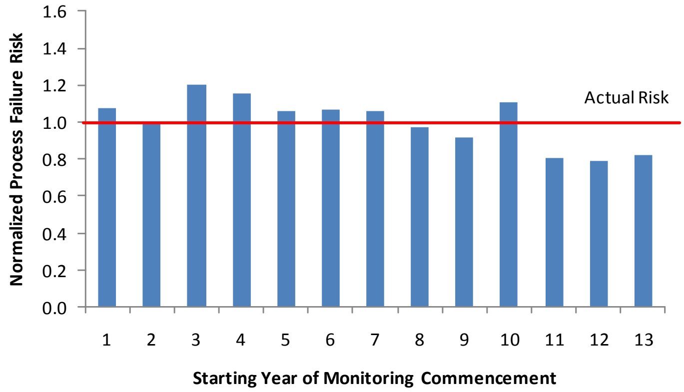


Figure 5-47 Performance estimation with linear extrapolation method, 5 year monitoring

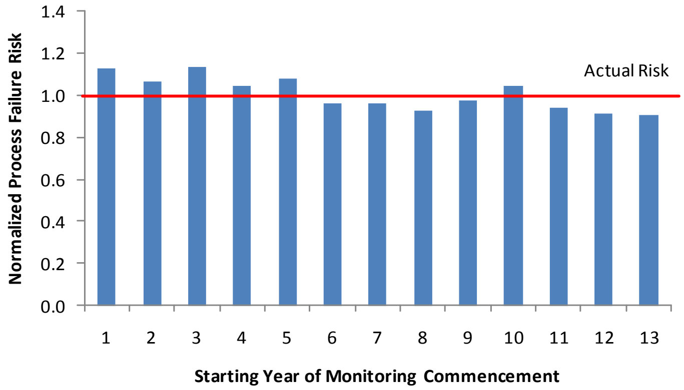


Figure 5-48 Performance estimation with linear extrapolation method, 10 year monitoring

5.2.2.3 Probabilistic Fitting

With probabilistic fitting, monitored sag characteristics are fitted to known distributions to represent their occurrence probability, as shown in Figure 5-49 and Figure 5-50. Using these probability distribution curves, the voltage sag profile with the estimated total number of voltage sag is generated. The profile is then assessed to obtain total process failure risk. In this assessment, 50 sag profiles are generated using the same distribution curves, and the mean failure risk of these profiles are taken as the estimated risk value.

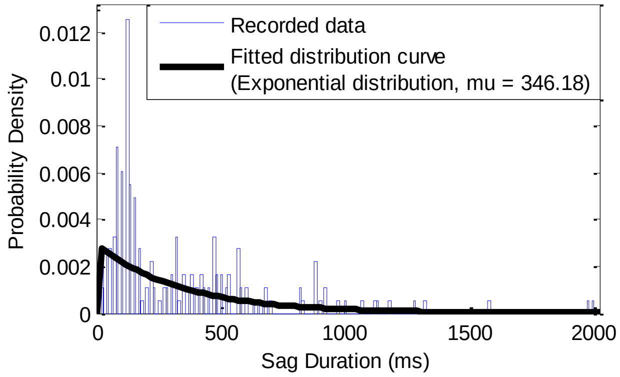


Figure 5-49 Distribution fitting of sag duration

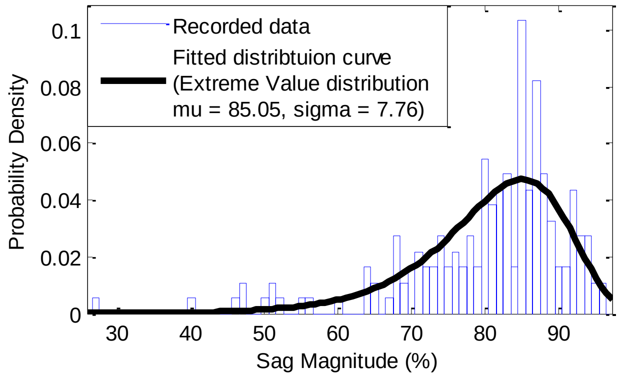


Figure 5-50 Distribution fitting of sag magnitude

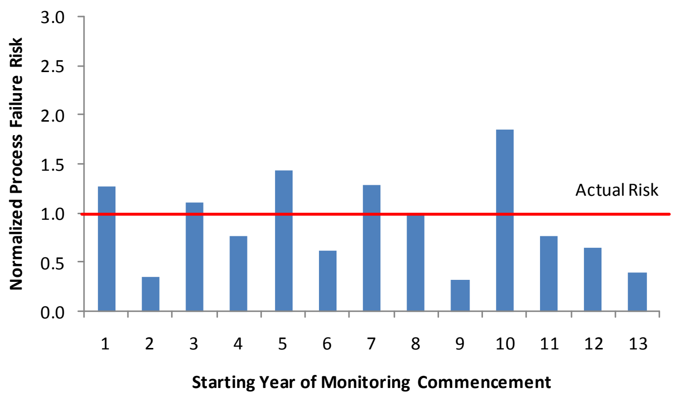


Figure 5-51 Performance estimation with probabilistic fitting method, 1 year monitoring

The estimation results with one, five and ten years of monitoring are shown in Figure 5-51, Figure 5-52 and Figure 5-53. While short (1 year) monitoring periods yielded results inconsistent with the actual case, estimation with longer monitoring periods can be quite reliable.

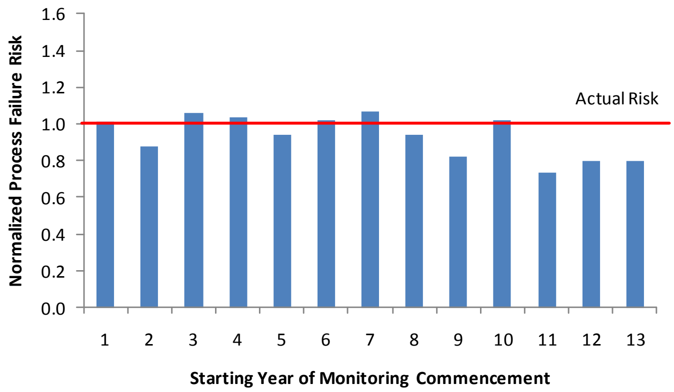


Figure 5-52 Performance estimation with probabilistic fitting method, 5 year monitoring

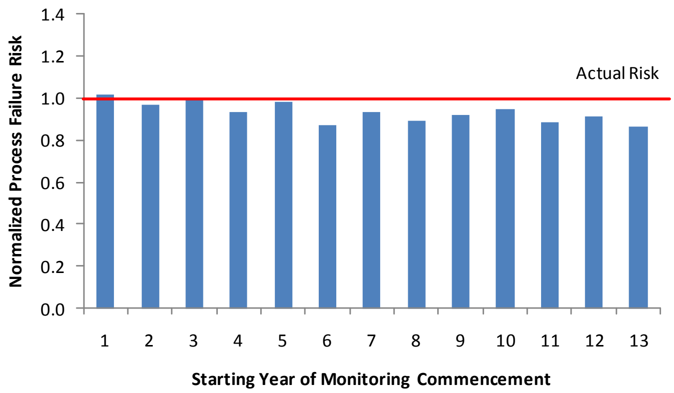


Figure 5-53 Performance estimation with probabilistic fitting method, 10 year monitoring

5.2.3 Discussions

The results shown in previous sub-sections confirmed that long term monitoring is a reliable alternative to fault positioning method in estimating customer voltage sag performance. Though longer monitoring period increases the accuracy of estimation, spending too much time on monitoring could delay the deployment of mitigation solutions, causing unnecessary financial losses. So, in reality, monitoring projects that last less than a few years could cause severe loss in accuracy of assessment

One way to overcome the situation is to factor in possible error produced in sag profile estimation, into subsequent financial assessment. The example in this assessment provided an insight into the level of accuracy to be expected from monitoring. Figure 5-54 gives the average estimation errors as a function of monitoring period. The estimation error obtained with averaging method is too high for any accurate assessment, while probabilistic and linear extrapolation methods result in more accurate assessment.

It is interesting to see that 80% accuracy (20% error) can be achieved in two years of monitoring. More excitingly, with four years of monitoring, average error is further reduced to 10% (90% accuracy).

Figure 5-55 shows a more pessimistic interpretation of the results, where the maximum error is considered. Surprisingly, accuracy of 70% is still achievable within two years of monitoring. Also, as oppose to earlier speculation of 18 to 42 years (extrapolation of Table 5-9), a 10 % accuracy is achieved with 5 years of monitoring.

In the mean time, it is worth noting that the best estimation using a one year monitoring period produced 35% average error and 70% maximum error. This implies that one year of monitoring is not sufficient for long term risk assessment. In this specific example, at least two years of monitoring are required to bring the error down to less that 20%. Probabilistic method and linear extrapolation method are similar in terms of accuracy; with the latter performing slightly better for shorter (<5 years) monitoring period.

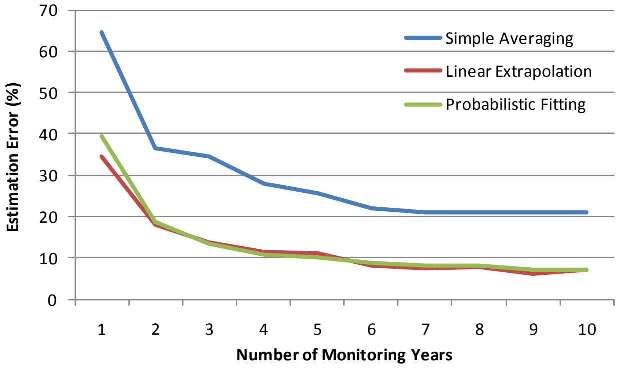


Figure 5-54 Average error in voltage sag profile estimation.

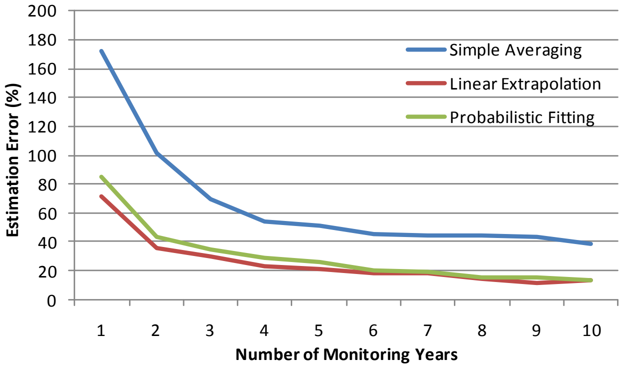


Figure 5-55 Maximum error in voltage sag profile estimation.

Robust conclusions cannot be expected from a single case study. However, this analysis provided evidences to support the following:

- Monitoring is a viable alternative to fault positioning method in estimating voltage sag performance for customers.
- Typical one year monitoring period is not sufficient to create accurate sag performance estimation. Results suggest that at least two years of monitoring is required for proper assessment.

5.3 Variation in Nominal Loss

Nominal loss is incurred when an industrial plant is forced to shut down during peak-time operation. It represents the worst case scenario as a consequence of voltage sag or short interruption. Voltage sags that occur during non peak-time operation incur only a fraction of the nominal loss.

In practical terms, the risk of nominal loss varies depending on the process activity when voltage sags occur [44]. Therefore, the operating nature of the industrial plant must be considered, as not all severe voltage sags affect plant operation (e.g. sags occurring at night where plant is not operating). Hence, it is important to include the variation in the loss value into risk assessment models.

This section introduces two methods of incorporating this variation in assessment. The first method uses load profile to represent process activity and subsequently the variation in nominal loss value. The second method models the operation cycle of processes, to obtain realistic link between process operation and variation in loss. Both methods represent variation in financial loss through probability of occurrence of different loss values.

5.3.1 Load Profile

The level of electricity consumption of an industrial plant is a reflection of process activity, which can be related to the financial loss of a plant. For example, during peak hour, industrial plant has the highest process activity where most equipment is involved in manufacturing of product (or providing the service). This heavy involvement of industrial equipment increases electrical consumption. Consequently, process trips during peak load are most expensive, as the plant suffers the most production losses, employee hours, and wastages as compared to other times of the day. On the other hand, during off-peak hours, process disruptions become less expensive as fewer process operations are running. Therefore, assuming direct relationship between electricity consumption, process activity and financial loss is logical.

Electricity consumption is available in the form of process load profile. Figure 5-56(a) shows a seven-day load factor (normalized load profile) of a continuously operating plant. Measurements are taken every 30 minutes for seven consecutive days. It can be seen that the electricity consumption of the plant is always above 0.6p.u.. This illustrates the working trend of the plant. In this particular case the plant is most probably active 24 hours, 7 days a week. On the other hand, the load profile in Figure 5-56(b) indicates a very different working trend; an "office-hour" type plant.

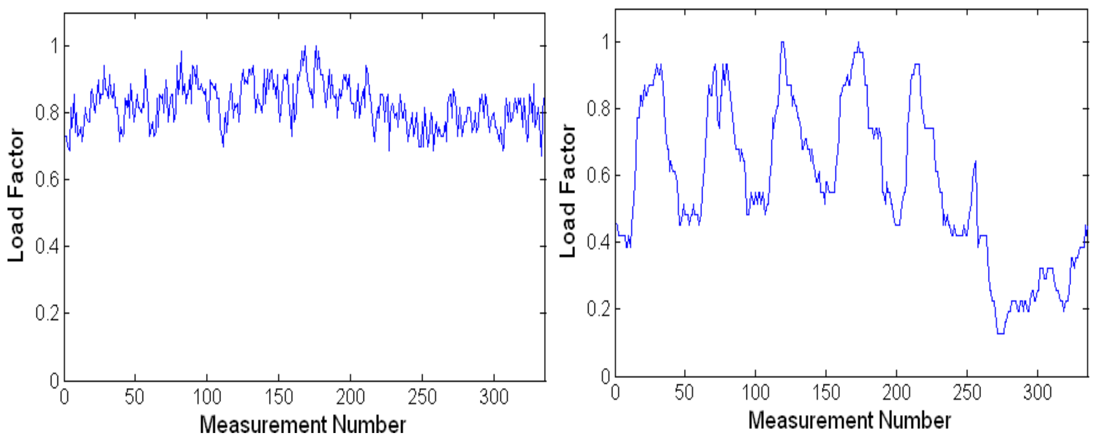


Figure 5-56 Normalized load profile of (a) continuously operating plant (b) office hour type plant

The load profiles can be converted into distribution functions to represent the cumulative probability of occurrence of each load value. Through distribution fitting, the resulting functions are obtained and shown in Figure 5-57 and Figure 5-58.

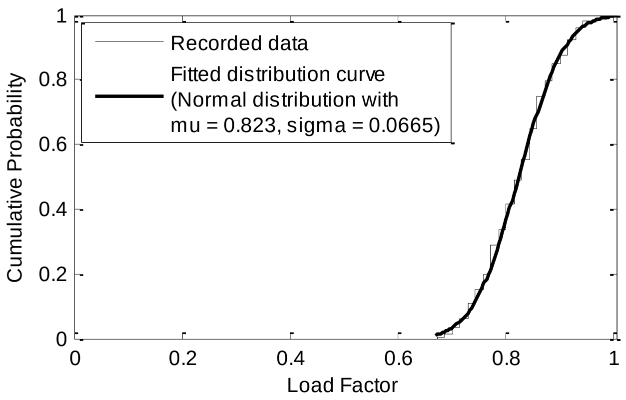


Figure 5-57 Cumulative probability function of continuously operating plant

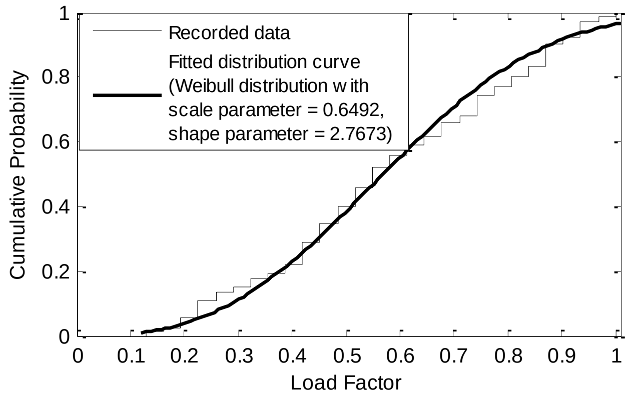


Figure 5-58 Cumulative probability function of office hour type plant

As the time of occurrence of voltage sag cannot be predicted, knowing the probability of occurrence of different load values helps clarify the risks involved. If load factor relates directly to the nominal loss value of an industrial plant, from Figure 5-57, all process trips have 100% chance of incurring more than 60% of the nominal loss of the plant, and all process trips have 60% chance of incurring less than 85% of the nominal loss. Therefore, with load profile modeling, the nominal loss value for a process trip is given by (5-13).

$$Nominal\ Loss = Nominal\ Loss_{max} \times Load\ Factor\ during\ Sag \quad (5\text{-}13)$$

For seasonal production processes where the product's demand/supply depends on season (e.g. fruit processing plant), at least one year of electricity consumption data is required to build probabilistic models. On the other hand, for non-seasonal production processes, a typical seven-day (one week) load profile is sufficient to represent the general production trend of a plant.

To investigate the effect of load profile on financial loss assessment, the reference process risk assessment model in Section 5.2.1 and sag profile in Section 5.2.2 are used. Monte Carlo simulation of 10,000 trials is run for a 10-year assessment period. Variables of the Monte Carlo simulation are shown in Table 5-10. The steps involved in the simulation are as follow:

1) Generate the number of sags for the 10 year period using the fitted distribution of Figure 5-42.
2) For each sag, generate a random sag magnitude and duration using the fitted distributions of Figure 5-49 and Figure 5-50.

3) Run sensitivity assessment for the reference plant with the generated sags as input. Calculate process failure risk for each sag.
4) Generate a random load factor for each sag event as required by (5-13), using the fitted distribution of Figure 5-57 for continuously operating process and Figure 5-58 for office-hour type plant. Load factor is set to 1 (nominal) for the case without load profile modelling.
5) Calculate the Nominal Loss due to Process Trip using (5-13)
6) Calculate Financial Loss using (5-1).
7) Repeat steps 1-6 for 10,000 trials to get a smooth financial risk profile for each case (Figure 5-59).

Table 5-10 Monte Carlo Simulation with Input from Load Profile Modelling

Objective	Random Variables
10-year financial risk of plant	Number of sags in the period, Sag magnitudes, Sag durations, Load factor during sag

Simulation results are summarized in Figure 5-59 and Figure 5-60. In Figure 5-59, one unit of financial risk is equivalent to the nominal loss value incurred by one process trip due to sags. It can be seen that different load profiles yield very different financial loss values, even though the processes involved are exactly the same. Generally, assessment without load profile modeling, where a nominal load factor is used for the assessment, produces higher estimated financial risk compared to those with load profile modeling. As shown in Figure 5-60, the estimated financial losses with continuously operating load and office-hour-type load models are only 82% and 58% respectively of those estimated through conventional models without load profile modeling. However, it is worth noting that there are also cases where assessment with load profile modeling gives higher failure risk estimation, as indicated by the overlapping of probability distribution functions in Figure 5-59. Hence, using average values may sometimes lead to misinterpretation of assessment results.

5.3.2 Process Cycle

The relationship between load profile and financial loss is a logical assumption. Although it could improve accuracy in general financial loss estimation, many technical factors of plant operation are being neglected. Therefore, when accuracy becomes important, detailed modeling of process cycle is inevitable.

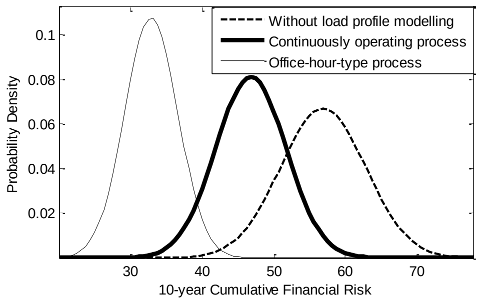


Figure 5-59 Financial risk estimation from different load profile modeling

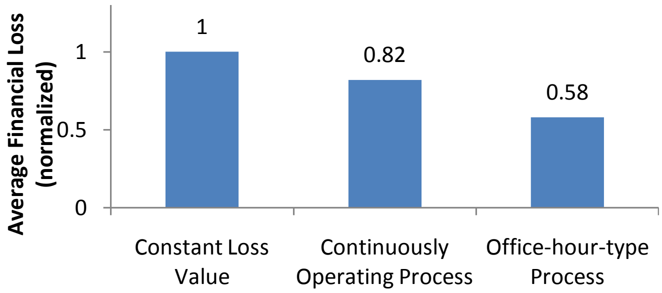


Figure 5-60 The influence of load profile on financial loss

Consider an industrial process with its process cycle divided into three stages involving different process activities in each stage, as shown in Figure 5-61. Obviously, with each stage having different active sub-processes, the failure mode in different stages is not the same. Thus, an individual fault tree should be built for each process stage, to represent individual failure mode. If equipment failure at different stages yields different financial loss values, individual cost index should be placed on each stage to represent the nominal loss value associated with that stage. Therefore, with process cycle modeling, the nominal loss value for a process trip is given by (5-14).

$$Nominal\ Loss = Nominal\ Loss_{max} \times Cost\ Index\ during\ Sag \quad (5\text{-}14)$$

To demonstrate the method, assume that the fault trees for the individual stages are as shown in Figure 5-62 and Figure 5-63. In this example, stage three is the most expensive stage where process disruption at this stage causes nominal financial loss. Therefore, the cost index for stage 3 is represented by nominal value, 1.0. The cost indices for stage 1 and stage 2 are arbitrarily set as 0.4 and 0.7, respectively. This means that process disruption at stage 1 will result in 40% of the losses incurred by disruption at stage 3, and disruption at stage 2 will result in 70% of the losses incurred by disruption at stage 3. Assuming that the plant is a continuously operating plant, the probability of sag occurrence at one stage equals the operation time of that stage divided by the total cycle time. In this example, the probability of occurrence of stages 1, 2 and 3 is 0.25, 0.5625 and 0.1875, respectively.

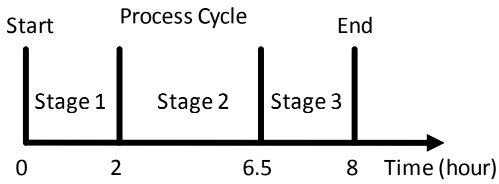


Figure 5-61 Operation cycle of an industrial process

The effect of process cycle modeling is investigated through simulation using the process risk assessment model in Section 5.2.1 and sag profile in Section 5.2.2. Monte Carlo simulation involving 10,000 trials for a 10-year assessment period is performed. Details of the simulation are shown in Table 5-11. The steps involved in the simulation are as follow:

1) Generate the number of sags for the 10 year period using the fitted distribution of Figure 5-42.
2) For each sag, generate a random sag magnitude and duration using the fitted distributions of Figure 5-49 and Figure 5-50.
3) Determine the active stage during each sag event using the probabilities of sag occurrence at each stage. Calculate the cost index (as defined by (5-14)) associated with the active stage.
4) The cost indices for constant stage 1, 2 and 3 processes are 0.4, 0.7 and 1.0 respectively.
5) Run sensitivity assessment for the reference plant with the generated sags as input, using fault trees given in Figure 5-62 and Figure 5-63. Calculate process failure risk for each sag.
6) Calculate the Nominal Loss due to Process Trip using (5-14).
7) Calculate Financial Loss using (5-1).
8) Repeat steps 1-7 for 10,000 trials to get a smooth financial risk profile for each case (Figure 5-64).

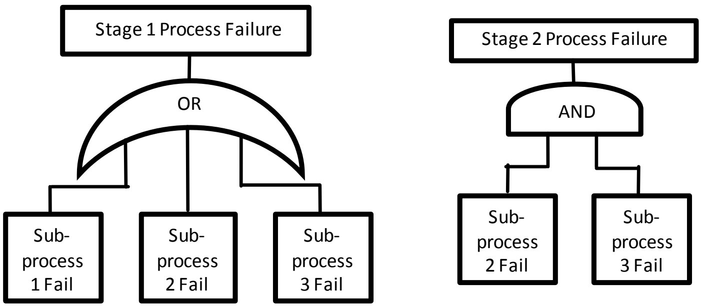


Figure 5-62 Process cycle stage 1 and stage 2 fault trees

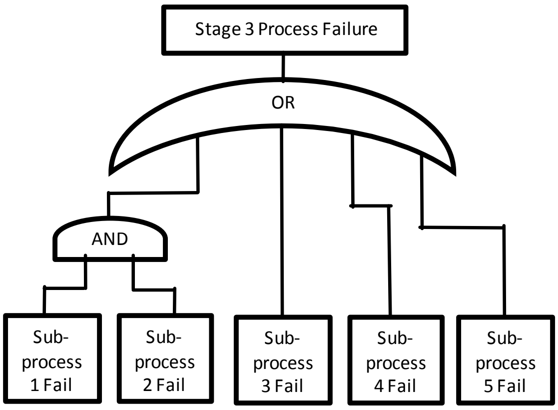


Figure 5-63 Process cycle stage 3 fault tree

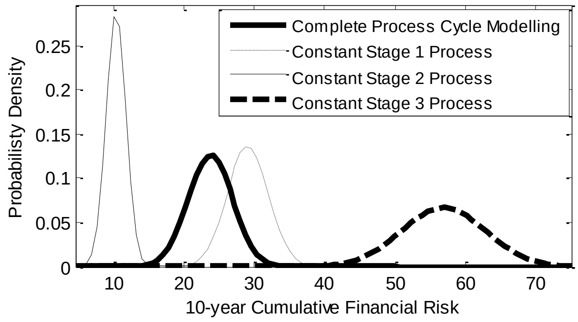


Figure 5-64 Financial risk estimation from different process cycle modeling

Table 5-11 Monte Carlo Simulation with Input from Process cycle modelling

Objective	Random Variables
10-year financial risk of plant	Number of sags in the period, Sag magnitudes, Sag durations, Process operation stage during sag

Simulation results are compared to cases where the process constantly operates at stage 1 only, stage 2 only and stage 3 only. Figure 5-64 shows the range of financial risk obtained. Again, huge difference in financial risk estimation is seen with different process cycle models. In this example, as shown in Figure 5-65, the constant stage representation could lead from 56% under estimation to 139% over estimation of average financial risk.

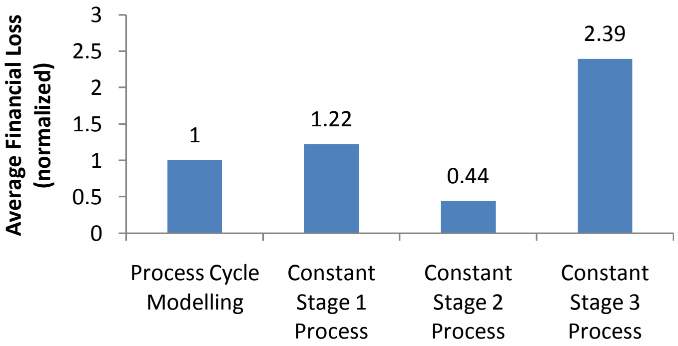


Figure 5-65 Influence of process cycle to financial loss

5.4 The Range of Financial Loss Value

Voltage sag could costs a fortune, hence, the use of proper financial analysis tool is vital. Due to the long-term nature of sag mitigation investments, the financial tool should be able to account for the time value of money. In the case of voltage sag financial analysis, the most suitable financial analysis tool is the Stochastic Net Present Value (SNPV) method [14]. SNPV is a modification of conventional Net Present Value (NPV) method that includes risk representation in analysis. This feature is important for the problem in hand due to the non-deterministic nature of various components involved in the analysis, such as equipment and plant sensitivities, voltage sag profile, and variations in losses due to load profile and process cycle.

SNPV method calculates the stochastic net present value financial loss using (5-15):

$$SNPV = -\sum_{t=1}^{T} \frac{\sum_{n=1}^{N} (p_n L_n)}{(1+r)^t} \tag{5-15}$$

Where:

T	=	lifetime of assessment in years
t	=	the year number
r	=	discount rate
N	=	total number of sags in year t
n	=	sag number
p	=	Process failure risk
L	=	Loss due to process trip, obtained from (5-1)

5.4.1 Financial Loss Assessment

Using the simulation results from previous sections, and assuming a nominal loss value during peak-time operation as £16,300 (average loss value for a 24 hour disruption for industrial customers according to [45]), the financial situation of the plant is obtained. Typical discount rate of 10% is used for the analysis. The random variables involved are shown in Table 5-12. The steps involved in the simulation are as follow:

1) Generate the number of sags for each year of the 10 year period using the fitted distribution of Figure 5-42.
2) For each sag, generate a random sag magnitude and duration using the fitted distributions of Figure 5-49 and Figure 5-50.
3) Obtain the active stage during each sag event using the probabilities of occurrence at each stage. Calculate the cost index (as required by (5-14)) associated with the active stage .
4) Run sensitivity assessment for the plant with the generated sags as input, using fault trees given in Figure 5-62 and Figure 5-63. Determine process failure risk for each sag.
5) Calculate the Nominal Loss due to Process Trip using (5-14), with Nominal $Loss_{max}$ per Process Trip set to £16,300.
6) Calculate SNPV using (5-15), while ignoring investment costs.
7) Repeat steps 1-6 for 10,000 trials to get a smooth SNPV profile. (Figure 5-67).

Figure 5-66 shows the distribution of SNPV of the initial financial situation for the plant with complete process cycle modelling. For most of the 10,000 trials, the SNPV is centered around -£240,000. This means that without mitigation, in the next 10-year period, this plant will lose an average present worth of £240,000 due to voltage sags.

It can be seen that in rare occasions, SNPV can be lower than -£150,000, or higher than -£300,000. Therefore, using average values to make financial decisions can be misleading, as the fluctuation in SNPV could seriously impact the viability of investment in mitigating solution.

Table 5-12 Monte Carlo Simulation to Obtain SNPV

Objective	Random Variables
Stochastic Net Present Value of Financial Loss for the next 10 years	Number of sags in the period, Sag magnitudes, Sag durations, Process operation stage during sag

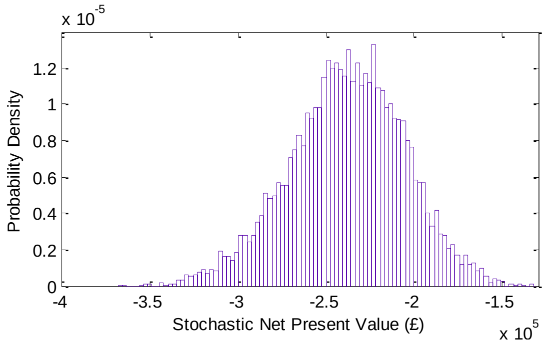


Figure 5-66 Distribution of SNPV from 10,000 trials with complete process cycle modeling

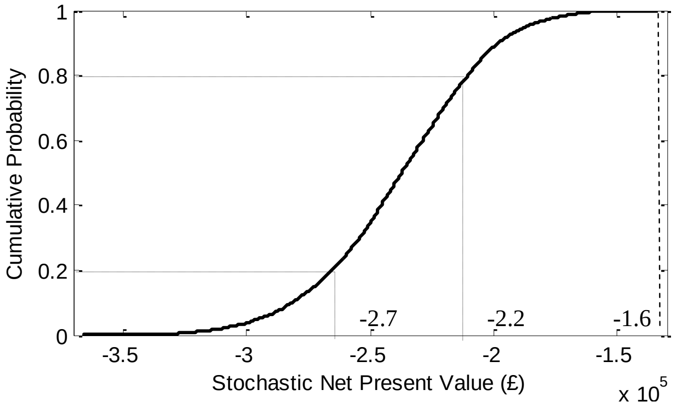


Figure 5-67 Cumulative distribution of SNPV from 10,000 trials with complete process cycle modeling

Due to the range of probable SNPV, probabilistic interpretation of information could help financial risk assessment. Figure 5-67 shows the cumulative probability of SNPV for the 10,000 trials. It gives the probability of losing more than a certain present worth of money. For example, in the next 10-years, the plant will have 100% chance of losing more than £160,000 present worth of money, 80% chance of losing more than £220,000 present worth of money, and 20% chance of losing more than £270,000 present worth of money. This interpretation of financial loss gives different risk values to individual loss value, and provides a clearer understanding of the situation in hand.

5.5 Voltage Disruption Cost Assessment Tool (VoDCAT)

A software assessment tool is developed for the industrial sponsor of this research, which is a distribution network operator in the United Kingdom. This is the fourth original contribution of this thesis. The tool (VoDCAT) is written in Visual Basic for Applications (VBA) language and implemented in Microsoft Excel environment. It enables practical implementation of the methodologies and models developed in Chapter 4 and Chapter 5. VoDCAT is developed to assist in strategic planning of network investments in reliability improvement and voltage sag mitigation. It includes the following functions:

Customized customer damage function - Development of customized customer damage function for individual plants based on generic damage functions compiled in past surveys (refer to methodology in Chapter 4). The function performs the following:

- Raw survey data is treated to a uniform format.
- A matching test to determine the similarity of survey to the assessed plant.
- Application of "Spring Theory" to build customized damage function

Failure risk and Financial Loss Assessment - Estimation of equipment and process trips frequency due to voltage sags and interruptions, and the consequent financial loss suffered by customer plants. The function performs the following:

- The impact of voltage sag is converted to Severity Indices (MSI & DSI).
- Probabilistic models of PC, PLC, ACC and ASD (full asymmetrical representation) described in Section 5.1.2.2 are used to convert severity indices into equipment failure risks.
- Plant failure risk is calculated from equipment failure risk using the single equipment process model with PIT described in Section 5.1.5.
- Customer financial loss is obtained as a product of nominal financial loss (obtained from CCDF) and plant failure risk.

Database - Keep an up to date database of general customer damage functions, as input for developing realistic customized damage functions.

Various built in features are included in VoDCAT so that it is as intuitive and robust as possible. This includes:

- Functional "push-buttons" for initiating assessments and viewing of assessment results.
- Built-in links that navigate to the relevant screen for the function chosen.
- Colour codes to assist user in data input and retrieving of results.
- Warning messages to notify user of the status of assessments.

- Updatable database of customer damage functions to allow for entry of newly available survey data, hence continuous improvement in accuracy of assessment.
- Updatable failure characteristics for the equipment model to ensure that the most realistic equipment tolerance curves are always used in assessment.

The Main page of the user interface of VoDCAT is shown in Figure 5-68 while Figure 5-69 and Figure 5-70 show the output screen for the assessments. Full description of VoDCAT is provided in Appendix B.

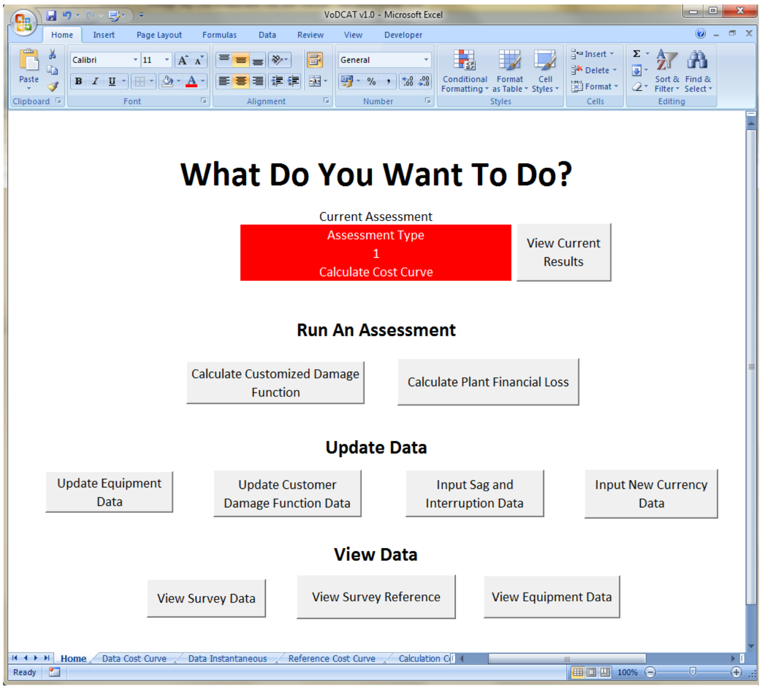


Figure 5-68 Main page of VoDCAT

5.6 Summary

The chapter proposed methodologies for modeling and assessment of equipment and industrial processes sensitivity to voltage sags and short interruptions. Simple MDSI and probabilistic models are developed to provide realistic equipment representation and to incorporate the capability to assess financial loss due to unbalanced sags. Extensive simulations showed that the proposed models yield good consistency in assessments compared to existing fuzzy method, with the added advantage of shorter simulation time.

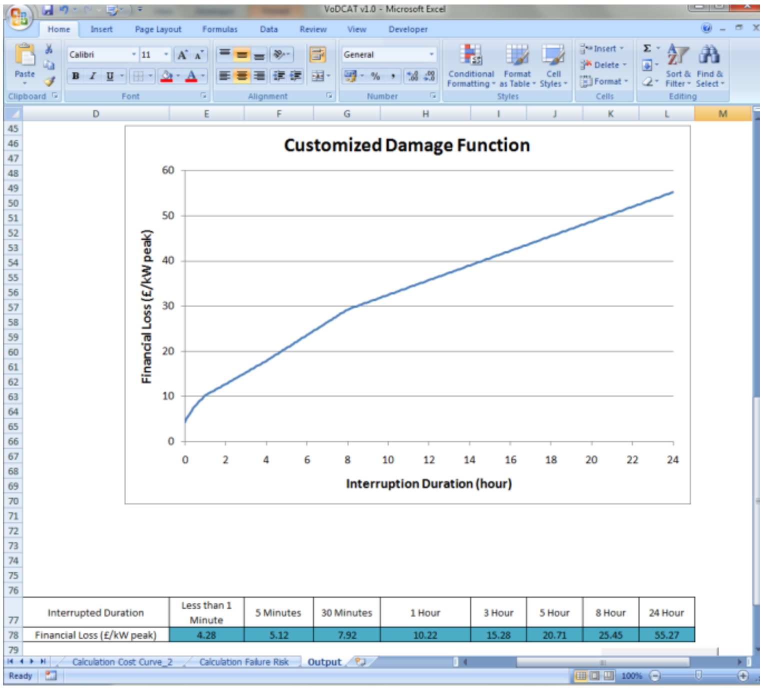


Figure 5-69 The output of Customized Customer Damage Function assessment

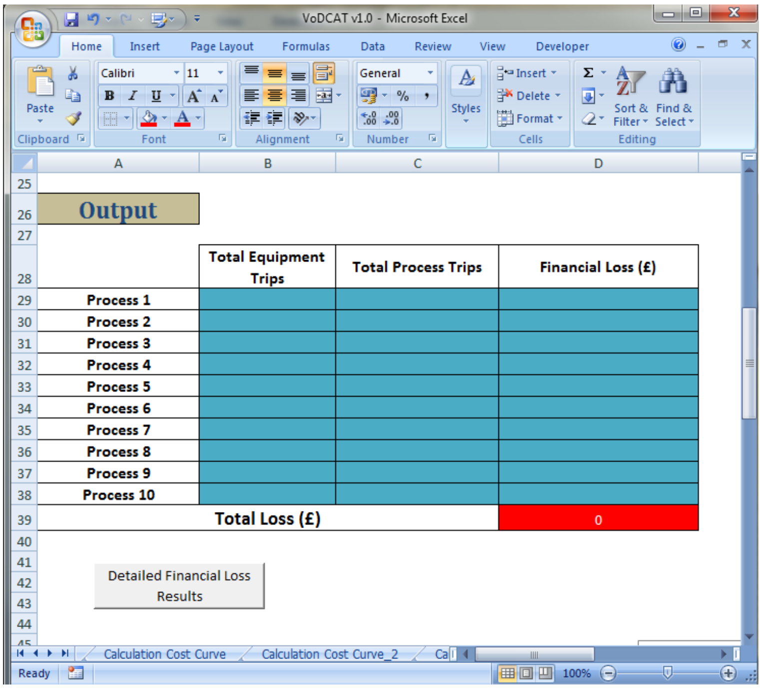


Figure 5-70 The output table for assessment of plant financial loss

The chapter also investigated the factors that influence the outcome of financial loss analysis in voltage sag studies. Parameters of the financial loss assessment, namely, limited availability of sag monitoring data, sag characteristics, process operation cycle and process load profile, that typically were not at all, or at least not simultaneously, considered in the past in this type of studies, were taken into account. Several different approaches were used for modelling each of the influential parameters and their merits were discussed and compared.

Next, the effects of the individual factors are analysed through Monte Carlo simulation. The results revealed that each of the parameters considered greatly affects the magnitude of financial loss estimation and that probabilistic modeling and risk based assessment are essential for meaningful conclusions regarding potential investments in costly mitigating solutions. Through the use of Stochastic Net Present Value (SNPV) method, the entire range of potential financial loss due to multiple varying risk factors can be found.

Finally, a software tool is developed for practical implementation of the developed methodologies and models. The software will be used by a UK distribution network operator to assist in strategic planning of network investments in reliability improvement and voltage sag mitigation.

Chapter 6 Modeling of Mitigation Devices and Solutions

6.1 Introduction

Power quality management is a multi dimensional problem where network condition and customer location play an inseparable part on top of customer PQ requirements. Previous investigations [46, 58, 59, 64] into custom power devices have identified that major financial savings can be achieved for plant owners with sensitive processes experiencing frequent trips. These findings strengthen the fact that for certain customers, some form of mitigation is inevitable.

However, current power quality mitigation practices are often dealt with on a plant by plant basis where over compensation is not unusual. This is especially true when plant owners invest millions in devices that are not necessarily optimal in terms of economic benefit for their plants.

When it comes to optimal mitigation, the distribution company has more control over supply quality in terms of the ability to identify network weaknesses and strengths, and the mitigation devices it could employ to improve supply quality. However, given that all devices are unique in terms of cost and effectiveness, without proper investigation, it is near impossible to converge to an optimal investment scheme. It is also true though that there is no incentive for distribution companies as yet, in general, to improve overall quality of electricity supply. The incentives are limited in most cases to reducing interruptions while other power quality phenomenon are mostly left unregulated.

With the development of customer models in Chapter 4 and Chapter 5, customer financial losses due to voltage sags, for any type of customers, become readily obtainable. This chapter presents required models for the mitigation side of the picture. The models developed will be used in Chapter 7 for detailed voltage sag economic assessments in the network and such pave the way for future global, network level approach to mitigation of power quality.

On top of device modeling, this chapter also presents a framework for general financial appraisal analysis to demonstrate the use of proper appraisal tools to obtain the best mitigation option taking into account the uncertainties of various assessment parameters. This framework presents another, the fifth, original contribution of this thesis.

6.2 Mitigation Device Models

A number of representative mitigation devices are modelled to investigate mitigation from different approaches. The devices modelled include power injecting mitigation devices, devices that reduce the number of faults in the network and devices that reduces the severity of faults.

The aim of the research is to to simulate the effect of the devices on process failure, rather than detailed technical modelling.

Before proceeding into device models, the costs of installing these devices need to be obtained. Table 6-1, Table 6-2 and Table 6-3 summarize typical device cost of the mitigation devices modelled. The currency used in Table 6-1 is Euro (€), while U.S. Dollar ($) is used in Table 6-2 and Table 6-3.

Table 6-1 Typical cost of power quality mitigation devices, adopted from [102]

Mitigation device	Typical Cost	
	Equipment Cost(€)	Operating and Maintenance Costs (% of initial costs per year)
Dynamic Sag Corrector (DySC)	184 per kVA	5
Low Speed Flywheel (15 seconds)	265-400 per kVA	5
High Speed Flywheel (15 seconds)	750 per kVA	7

Table 6-2 Cost of power quality mitigation devices for various levels of protection, adopted from [50]

Mitigation device	Typical Cost	
	Equipment Cost($)	Operating and Maintenance Costs (% of initial costs per year)
Facility Protection (2 - 10 MVA)		
Flywheel	500 per kVA	5
DVR (50% voltage boost)	300 per kVA	5
Static Switch (10 MVA)	600,000	5
Fast Transfer Switch (10 MVA)	150,000	5

Table 6-3 Cost of power quality mitigation devices, adopted from [147]

Mitigation Device	Typical Cost ($)
Solid State Transfer Switch	300 per kVA
Line Reactors	15 - 100 per kVA

6.2.1 Power Injecting Devices

Fundamentally, power injecting devices compensate the depressed voltage during sag by injecting real, reactive, or both powers into the network. The power injected is normally obtained from stored energy, or from other less affected lines in the network.

Three common power injecting devices are discussed here; dynamic voltage restorer (DVR) with real power storage, DVR without real power storage, and backup supply with flywheel energy storage.

6.2.1.1 Dynamic Voltage Restorer with Energy Storage

Dynamic voltage restorer (DVR) is a custom power device which is reasonably widely used for voltage sag mitigation. DVR is a voltage injecting device connected in series to the protected load. It is typically rated from 3 MVA up to 50 MVA [46] and is normally used for plant level protection against voltage sags. DVR usually have sufficient energy storage to compensate a 0.5p.u. three-phase voltage sag for up to 10 cycles, the period normally required for fault clearance [46]. DVR provides voltage support during voltage sags and momentary interruptions almost instantaneously (typically within 1/4 of a cycle). Figure 6-1 shows a connection of a DVR for plant protection.

To determine the effectiveness of DVR in sag mitigation, a DVR model has to be built. Two types of power injection capabilities are considered; DVR with only reactive power injection capability, and DVR with real and reactive power injection capability.

There are mainly three types control of strategies used for voltage compensation [148]:

- Pre-fault compensation
- In-phase compensation
- Energy saving compensation

The main difference between the methods lies in the reference voltage selected for restoration. Pre-fault compensation aims to restore voltages to the pre-fault value, with compensation of both sag magnitude and phase shift during sag [46]. On the other hand, in-phase compensation restores voltage magnitudes to pre-fault value while phase angles remain the same as during the sag [46]. For energy saving compensation, real power injection are kept as low as possible while compensating voltages, hence only partial restoration in phase angles is achieved [149].

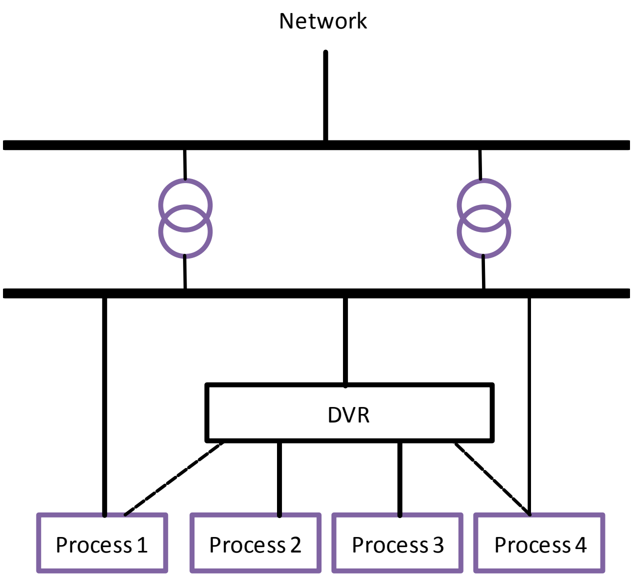


Figure 6-1 DVR at customer plant

In this study, DVR with pre-fault compensation control is modelled to restore both voltage magnitude and phase shifts during sag. Considering a DVR with real and reactive power injection capability, both voltage magnitude and phase angle in all three phases should be restored independently to pre sag values (or to a value above sag threshold, i.e., above 0.9 p.u.). The DVR is modeled to restore voltage magnitude to a user defined restorable value, $V_{restorable}$, while considering maximum restorable phase angle of ±30º.

A classical load model is assumed for the protected plant. To simplify complex load behavior under unbalanced sags, calculation for each phase is done separately. Load real and reactive power (Psag and Qsag) during sag for each phase is calculated using (6-1) and (6-2).

$$P_{sag} = P_0 \left(\frac{V_{sag}}{V_0}\right)^{n_p} \quad (6\text{-}1)$$

$$Q_{sag} = Q_0 \left(\frac{V_{sag}}{V_0}\right)^{n_q} \quad (6\text{-}2)$$

Where P_0 and Q_0 are pre sag real and reactive load powers respectively, n_p and n_q are real and reactive power exponents assumed to be 0.2 and 2, respectively (for illustrative purposes). The apparent power during sag, S_{sag} in each phase is then obtained using (6-3).

$$\underline{S}_{sag} = P_{sag} + jQ_{sag} \tag{6-3}$$

Load current during sag ($\underline{I}_{sag}$) for each phase can then be obtained using (6-4), with phase angle during load given by (6-5).

$$\underline{I}_{sag} = \frac{\underline{S}_{sag}^{*}}{\underline{V}_{sag}^{*}} \tag{6-4}$$

$$Angle(I_{sag}) = \theta \tag{6-5}$$

The ideal DVR voltage injection for each phase, $\underline{V}_{dvr\_ideal}$ is:

$$\underline{V}_{dvr\_ideal} = \underline{V}_0 - \underline{V}_{sag} \tag{6-6}$$

Assuming DVR operates to inject P and Q during sag, the reactive ($V_{dvr\_reactive}$) and active (V_{dvr_active}) voltage injections for each phase of the DVR are then:

$$Angle(V_{dvr\_reactive}) = |\theta| + 90^{\circ} \tag{6-7}$$

$$Angle(V_{dvr\_active}) = |\theta| \tag{6-8}$$

$$|V_{dvr\_reactive}| = |V_{dvr\_ideal}| \cdot sin[|\theta| + |Angle(V_{dvr\_ideal})|] \tag{6-9}$$

$$|V_{dvr\_active}| = |V_{dvr\_ideal}| \cdot cos[|\theta| + |Angle(V_{dvr\_ideal})|] \tag{6-10}$$

The required DVR real and reactive power injections for each phase are:

$$Q_{inject} = |V_{dvr\_reactive}| \cdot |I_{sag}| \tag{6-11}$$

$$P_{inject} = |V_{dvr\_active}| \cdot |I_{sag}| \tag{6-12}$$

Total required real and reactive powers for all three phases are therefore:

$$Q_{inject_{total}} = Q_{inject_A} + Q_{inject_B} + Q_{inject_C} \tag{6-13}$$

$$P_{inject_{total}} = P_{inject_A} + P_{inject_B} + P_{inject_C} \tag{6-14}$$

If the required real and reactive powers are within the capability of the DVR (P_{rated}>P_{inject_total}, Q_{rated}>Q_{inject_total}), full voltage restoration will be achieved. However, if Q_{rated}<Q_{inject_total} or P_{rated}<P_{inject_total}, voltage will not be fully restored. The new restored voltage must have balanced voltages in all three phases (equal magnitude and phase angle shifts) after mitigation. Therefore, if Q_{rated}<Q_{inject_total}, (6-15) is used to reduce the reactive power required by reducing the target voltage angle by 2 per step.

$$Angle(V_{restoration\_new}) = Angle(V_{restoration\_ideal}) - 2^{\circ} \tag{6-15}$$

On the other hand, if P_{rated}<P_{inject_total}, (6-16) is used to reduce the active power required by reducing the target voltage magnitude by 0.05 p.u. per step.

$$|V_{restoration\_new}| = |V_{restoration\_ideal}| - 0.05 \tag{6-16}$$

Equation (6-7) to (6-14) are repeated for every new target restoration point until $P_{rated} \geq P_{inject\_total}$ or $Q_{rated} \geq Q_{inject\_total}$. The final DVR injection and the resulting load voltage are then:

$$\underline{V}_{dvr} = V_{dvr\_active} + jV_{dvr\_reactive} \tag{6-17}$$

$$\underline{V}_{load\_stage1} = \underline{V}_{sag} + \underline{V}_{dvr} \tag{6-18}$$

It is assumed that real power of the DVR is stored in batteries, whilst reactive power is stored in capacitor banks. As the cost of batteries is considerably more than that of capacitors, to minimize device cost, real power (energy) storage is therefore the limiting factor in sag compensation. The energy storage is obtained through (6-19), where t_{max} is the maximum time that the DVR can fully compensate $V_{restorable}$.

$$E_{storage} = P_{rated} \cdot t_{max} \tag{6-19}$$

On the other hand, the energy (real) required to reach V_{load_stage1} is given by (6-20), with *d* as the duration of sag.

$$E_{required} = P_{inject_{total}} \cdot d \tag{6-20}$$

If the stored energy, $E_{storage}$ is more than $E_{required}$, V_{load_stage1} of (6-18) becomes the final load voltage after DVR compensation. However, if $E_{storage}<E_{required}$, when all stored energy is used, a two stage sag is formed where only reactive power is injected in the second stage, as shown in Figure 6-2.

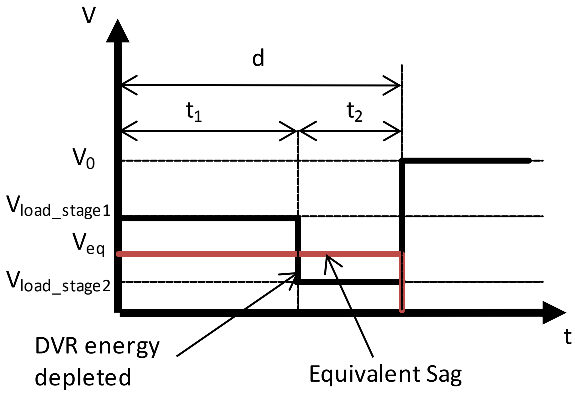


Figure 6-2 Two stage sag and its equivalent

The two stage sag is converted to an equivalent, single stage sag, to simplify modelling and simulations. The conversion is done using (6-21) to (6-24) based on methodology reported in [150].

$$t_1 = \frac{E_{storage}}{P_{inject_{total}}} \tag{6-21}$$

$$t_2 = d - t_1 \tag{6-22}$$

$$\underline{V}_{load\_stage2} = \underline{V}_{sag} + \underline{V}_{dvr\_reactive} \tag{6-23}$$

$$\left|V_{eq}\right| = \frac{\left|V_{load\_stage1}\right| \cdot t_1 + \left|V_{load\_stage2}\right| \cdot t_2}{d} \tag{6-24}$$

The final voltage to be used for risk assessment is the equivalent voltage V_{eq}. It should be noted that in this simplified model, P_{sag} and Q_{sag} are calculated only once at the start of the sag, neglecting subsequent changes in load voltage. This assumption will lead to underestimation of the required DVR injections and hence an optimistic assessment.

6.2.1.2 DVR Without Energy Storage

A separate DVR model with only reactive power injection is also used for assessments in Chapter 7. The simplified model uses the same equations as the full DVR model with active power injection set to zero.

6.2.1.3 Uninterruptible Power Supply with Flywheel Energy Storage

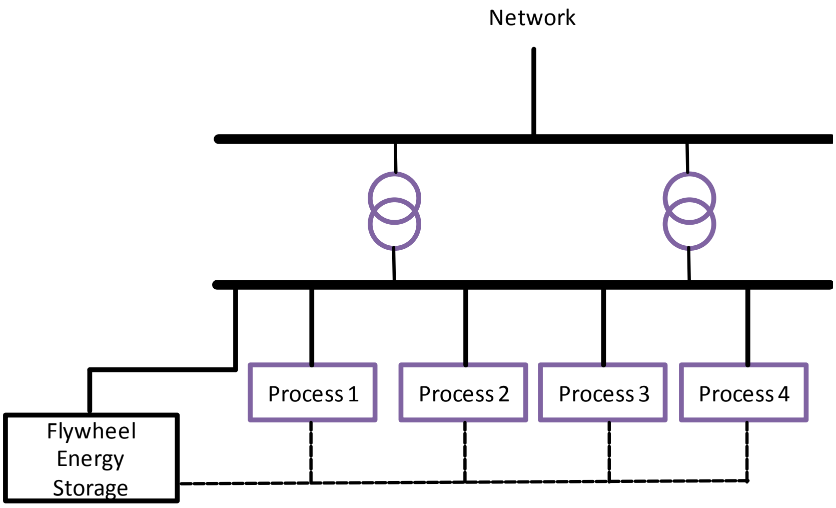


Figure 6-3 Flywheel energy storage at customer plant

A flywheel is a form of energy storage system that stores energy in a rotating mass. The kinetic energy stored in a rotating mass determines how long a flywheel system can support its protected load. The energy storage capacity of single rotors ranges from 0.25kWh to 6kWh [62]. In principle multiple rotor modules can be paralleled to form a flywheel energy matrix system [151]. For example, the system proposed in [151] consists of 54 rotor modules, capable of supplying a 13.5 MW load for 6 minutes.

In this study, the effect of a distribution voltage level UPS with solid-state switching and supported by flywheel energy storage is modeled. The flywheel system is shown in Figure 6-4. During normal operation, the sensitive load is supplied by the main supply from the grid. In the event of a voltage sag in the main supply, the static transfer switch isolates the main supply within 1/4 of a cycle [151], allowing the full load to be supplied by the flywheel system.

6.2.1.4 Device Costs

The total owning cost of the three considered power injecting and storage devices considered are summarized in Figure 6-5. The device costs are Net Present Values calculated using (6-25).

$$C_{device} = C_{initial} + \sum_{n=1}^{N} \frac{C_{annual}}{(1+r)^n} \quad (6\text{-}25)$$

Where C_{device} = Total owning cost of device in a period of N years

$C_{initial}$ = initial capital investment

C_{annual} = annual operating and maintenance costs

r = discount rate used for NPV calculation

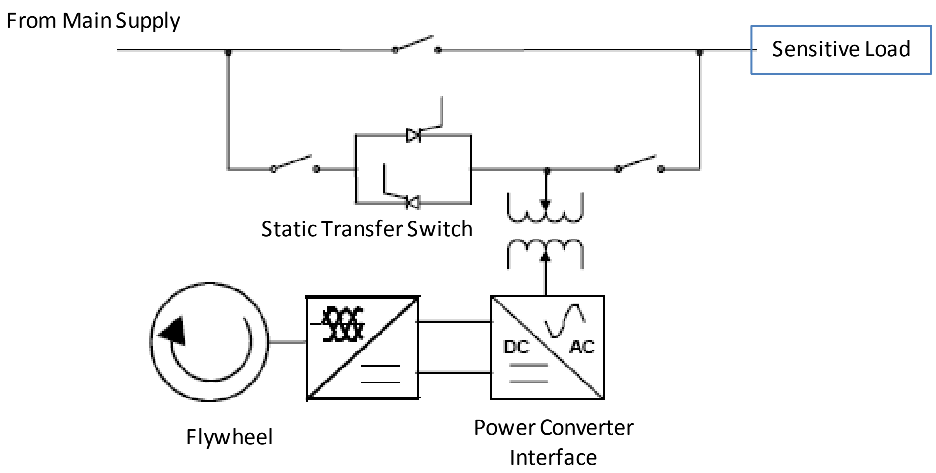


Figure 6-4 UPS with flywheel energy storage, adopted from [151]

DVR costs for the full model (real and reactive capabilities) are compiled based on [46], with C_{annual} = 10% of $C_{initial}$. The cost model for DVR with only reactive power capability is adopted from the cost model of another capacitor storage device, dynamic sag corrector (DySC) [152]. For DVR with reactive power capability only, C_{annual} = 5% of $C_{initial}$. This device comes with a maximum size of 2 MVA, thus explaining the ladder shape of its cost curve. The cost of a flywheel is determined by the energy storage capacity. Here an initial cost of £480/kVA plus 10% annual operation and maintenance cost is assumed for 5 second of full load protection. Flywheel costs are based on [13]. All device costs in this chapter are calculated assuming a typical discount rate, r of 6%.

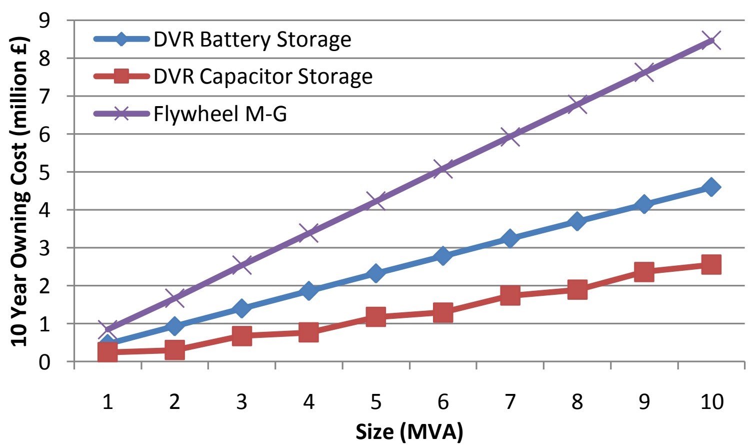


Figure 6-5 Ten year owning cost for DVR and Flywheel

6.2.2 Redundant Supply

A redundant supply system is illustrated in Figure 6-6. Basically, the industrial plant is supplied by a main feeder. When a sag occurs, supply switches using static transfer switch (STS) to the backup feeder within 1/4 to 1/2 of a cycle [71]. The industrial plant will such encounter a very short voltage sag invisible to the equipment.

There are instances though when both feeders may be affected by the same sag. For example, sags originated from transmission network. This could also happen if the electrical distance of busbars feeding the two supplies are not far enough. Therefore, before the static transfer switch operates, the voltage levels at the two feeders are compared. Switching to a backup feeder will only occur if the sum of voltage magnitudes of all three phases in the backup feeder is higher than in the main feeder.

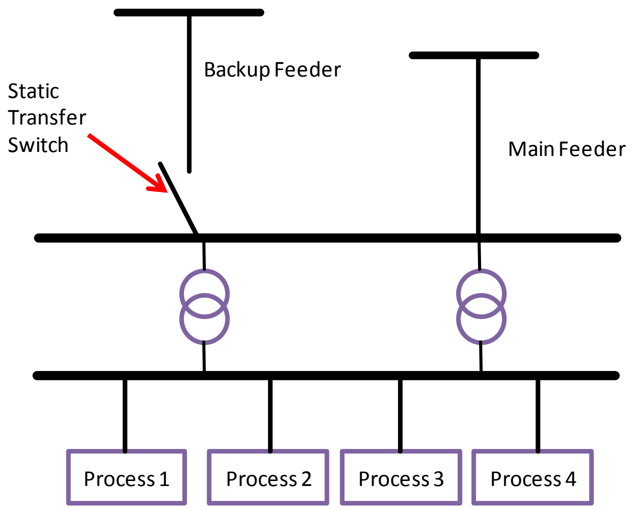


Figure 6-6 Static transfer switch at customer plant

In this case, this mitigation system requires a redundant feeder to be built. The cost of building the feeder would need to be included as part of the mitigation costs. Also, supplying the load through the backup feeder changes the power flow in the network. In some cases, power flow in the network might exceed thermal limits of lines, prompting an upgrade of the affected lines. When upgrade costs are included, the total mitigation cost becomes:

$$Cost\ of\ Redundant\ Supply = Cost\ of\ STS + Cost\ of\ New\ Feeder + Upgrade\ Costs \tag{6-26}$$

The cost model for the redundant system is summarized in Table 6-4. The cost of STS, based on [13] (conversion rate of £1=$1.5) is the 10 year owning cost calculated using (6-25), with annual operating and maintenance costs taken as 5% of initial costs. Cost of new lines at 11kV are based on overhead line construction costs in [87]. Costs of lines are assumed to double at higher voltage levels. Costs of transformer upgrades are based on typical values, including annual operating and maintenance costs, while costs of busbar upgrade are assumed to be the same as the cost of new lines.

Table 6-4 Cost model for redundancy in supply

Voltage Level (kV)	10 MVA STS (£/unit)	Lines (£/km)	Transformer (£/upgrade)	Busbar (£/upgrade)
11	525000	20000	75000	20000
33	525000	40000	75000	40000
132	525000	80000	150000	80000

6.2.3 Reducing the Number of Faults

Voltage sags observed in distribution network originate typically from short circuit faults in the transmission and distribution networks. The most typical causes of these faults are shown in Figure 6-7. The faults can be further categorized into faults involving short circuit of bare wires (contact faults), lightning induced faults (lightning faults), faults due to equipment failure, and accidental faults on underground cables (dig-ins). This section models mitigating solutions that reduce contact faults, lightning faults and accidental faults on cables.

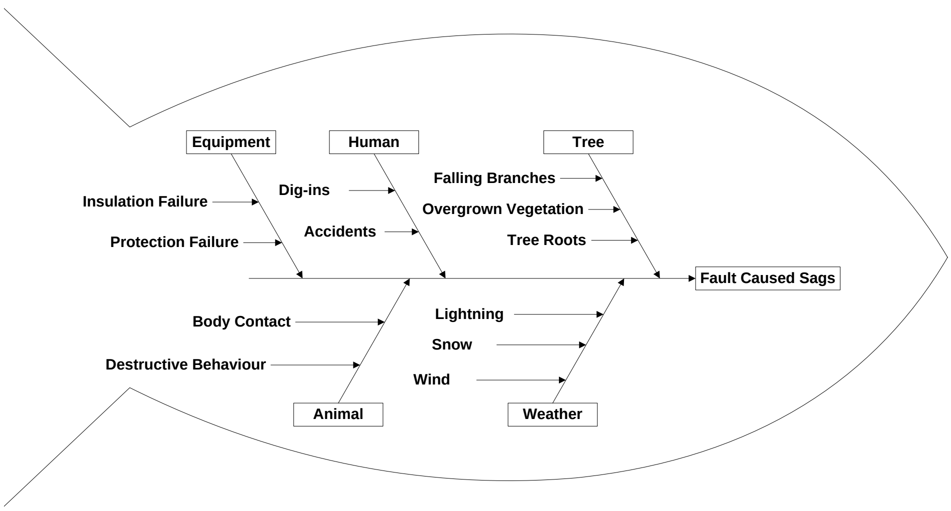


Figure 6-7 The causes of fault-caused sags and interruptions

Table 6-6 summarizes the faults to be investigated and the mitigation devices available. It can be seen that faults due to falling tree branches can be reduced by proper tree trimming schedule, covering overhead lines with insulation, and replacing overhead lines with cables.

Lightning faults can be reduced by converting overhead lines to underground cables, installation of shield wire and surge arresters, and by insulating lines.

Contact faults due to wind and animals can be reduced by converting to underground cables, insulating lines, and installing animal guards for animal caused faults.

To reduce accidental dig-ins due to construction work, better communication and data recording system is proposed. This involves investment in proper data storage of cable locations and making the information available prior to any construction work.

The cost and effectiveness of the mitigating solutions are given in Table 6-6. The information is mainly compiled from [81, 87, 153, 154]. In cases where the information was not available, a reasonable value was assumed. A sensitivity analysis to different cost and effectiveness values is carried out in Chapter 7 to account for the errors that might have been introduced by the assumed values.

Table 6-5 Reducing faults in the network

Causes	Fault Type	Affects	Mitigation Device
Tree	Contact	Overhead Lines	Tree Trimming Insulated Line Underground System
Lightning	Lightning	Overhead Lines	Underground System Shield Wire Surge Arrester Insulated Line
Wind	Contact	Overhead Lines	Underground System Insulated Line
Animal	Contact	Overhead Lines	Animal Guard Underground System Insulated Line
Dig-in	Accidents	Cables	Communication System

6.2.4 Reducing the Severity of Faults

The solutions to reducing severity of faults considered here include reducing fault clearing time and fault current limiting.

Table 6-6 Cost and effectiveness of reducing faults, figures compiled from [81, 87, 153, 154]

Improvement	Assumed Cost/km (£)	Effect on improved feeder
Undergrounding	100,000	Dig-in faults remains
Shield Wire	22,800	78% reduction in lightning faults
Surge Arrester	8150	78% reduction in lightning faults
Animal Guard	200	Assume 50% reduction in animal caused faults
Tree Trimming	200/trim	20% reduction in tree caused faults for every year earlier than 5 years
Insulated Line	10,000	75% reduction in lightning faults, 100% reduction in contact faults
Communication System	100	Assume 50% less dig-ins

6.2.4.1 Reducing Fault Clearing Time

Fault clearing time is the time required for circuit breaker to detect, respond and extinguish the arc caused by short circuit. Fault clearing time is an important parameter as it determines to a large extent the duration of voltage sags. In other words, reducing fault clearing time reduces duration of sags, and consequently equipment failure risk.

Fault clearing time can be reduced by reducing the response time of circuit breakers. From Figure 6-8, the duration of sag experienced by the sensitive customer due to Fault A would depend on the response time of the circuit breaker at fault occurring feeder. Theoretically, very short (<1ms) fault clearing times are achievable using state of the art solid state breakers [155]. However, due to high initial costs associated with the device, and the difficulties in coordination with lower level protection devices, instantaneous tripping is not considered in this research.

This research takes a more conservative approach on instantaneous tripping. Instead of investigating the impact of solid state breakers, the value of re-coordinating protections settings in the network is considered without installing new devices. It is assumed that slight reduction in fault clearing times is technically achievable in distribution networks with existing breakers. All costs involved therefore are those for the work carried out to reconfigure the protection system. The options to be considered and the assumed costs involved are summarized in Table 6-7. A sensitivity analysis to different cost and effectiveness values is carried out in Chapter 7 to account for the errors that might have been introduced by the assumed values.

.

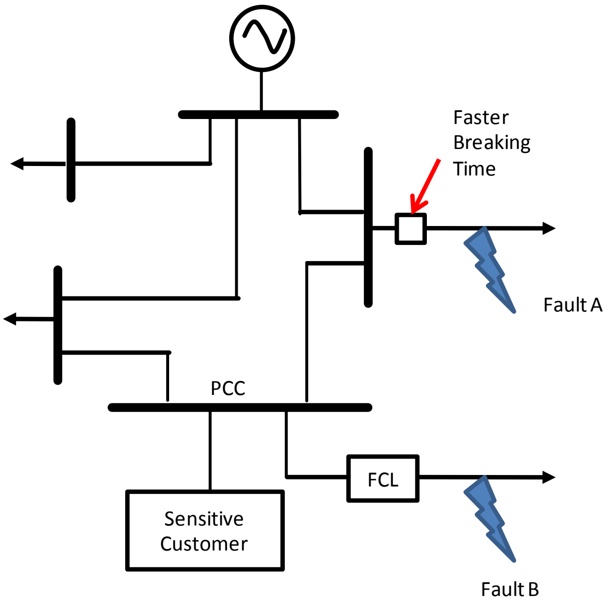


Figure 6-8 Application of fault current limiter and static breaker

Table 6-7 Options for reduction in fault clearing time

Improvement Options	Assumed Cost/feeder (£)
10% faster fault clearing	10,000
20% faster fault clearing	20,000
30% faster fault clearing	50,000

6.2.4.2 Fault Current Limiting

Referring to Figure 6-8, the voltage sag (p.u.) experienced by the sensitive customer due to Fault B can be roughly estimated by (6-27). This relationship indicates that higher Zf increases the magnitude of sags caused by faults in the feeder. Zf can be increased by placing a fault current limiter (FCL) at the feeder as shown in Figure 6-8.

$$V_{sag} = \frac{Z_f}{Z_f + Z_s} \quad (6\text{-}27)\ [6]$$

Where Z_f = impedance between PCC and fault,

Z_s = source impedance at PCC

Conventional way of fault current limiting is achieved by placing line reactors at feeders around the network. This approach, though inexpensive, causes unnecessary power losses and voltage drops during normal operation.

Modern fault current limiters employ solid state [76] technology and resonance circuits [77] that operate only during faults, and remain virtually invisible to the network during normal operation. In a fault condition, the FCL limits the fault current by introducing impedance across the line. This impedance becomes part of Z_f in (6-27), causing an increase in sag magnitude at PCC. The use of FCL has to be coordinated with circuit breaker settings so that the fault can be detected and cleared.

In this research it was assumed that modern FCLs can be placed across the network. A conservative reactance of 0.1pu. is used for each FCL which costs £100,000 a piece, to own and install. The cost model is the ten-year owning costs based on the cost of an Is Limiter [156] produced by ABB, with annual operation and maintenance costs at 5% of initial capital.

6.3 Financial Appraisal Tool

Though it is true that control of the network level power quality lies mainly in the hands of network operators, every action made, be it alteration to the network topology or installation of mitigation devices, has to be financially justified. This justification comes from potential financial savings gained from fewer process interruptions and improved operation predictability at customer plants. Therefore, for any successful power quality management projects, involvement from both network operator and the end user is necessary. Plant owners would need to provide information related to equipment and process sensitivity to power quality disturbances and the financial loss involved if process is tripped by a power quality event. With these information from several customers, mainly the largest and those with the most sensitive processes in the network, the network operator can perform suitable optimization to find potentially the best management scenario to employ.

Investment in sag mitigation is generally an expensive exercise. The use of proper financial analysis tool ensures that investment decision is properly made. Basically, sound economic analysis must include all costs and benefits associated with each mitigating solution for the entire life-cycle of the solution, and such provide a fair platform for comparison to be made.

The financial analysis tool best suited for this analysis has been introduced in Chapter 5. The SNPV method from (5-15) can be further expanded to include investment cost in mitigating solutions.

$$SNPV = -\left[\sum_{t=1}^{T} \frac{\sum_{n=1}^{N}(p_n L_n) + M_t}{(1+r)^t} + I\right] \quad (6\text{-}28)$$

Where:

I=initial investment

M_t=operation and maintenance cost in year *t*

In the case of voltage sag financial loss analysis, SNPV always have a negative value. This is because mitigating solutions can only reduce original plant losses, but they cannot generate profit for the plant. Therefore, the sum of voltage sag losses and mitigating solution costs will never become positive. With this method, the best mitigation option for the plant (or the network) is the one with the lowest magnitude of the negative SNPV.

6.3.1 Case Study

Voltage sags with different magnitude and duration severity can be grouped into different regions [10]. Figure 6-9 shows voltage sag regions that would theoretically depict the area of responsibility for sag mitigation. Sags in the "0"region (*K0*, *M0* and *L0*), of Figure 6-9, are under equipment manufacturers' responsibility and the equipment is supposed to be resilient to these types of sags [10]. Sags in the bottom region "2" (*K2*, *M2* and *L2*) are deemed too severe to be dealt with by conventional plant devices and therefore should be minimized at the network level [10]. The middle region "1" (*K1*, *M1* and *L1*) is the main focus of sag mitigation where a balance between customer and network investments in mitigation has to be found, to reach optimal plant resilience to voltage sags.

The reference case introduced in Section 5.2.1 is used here to illustrate sag mitigation approach. Probabilistic method is employed to assess equipment sensitivity. A total of 5000 random sags are generated for this example with the fitted probability distribution functions presented in Figure 5-49 and Figure 5-50. Generated 5000 voltage sags are equivalent to more 270 years of sag monitoring data.

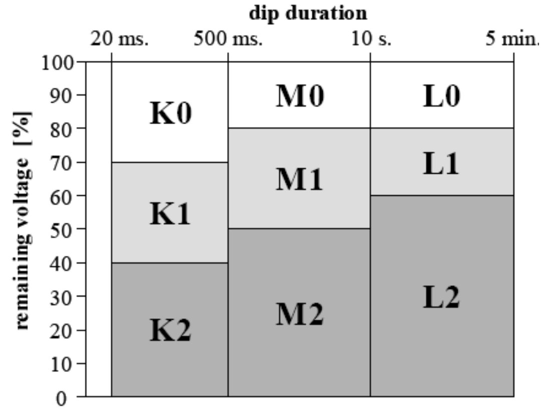


Figure 6-9 Voltage sag regions. Adopted from [10]

Before further analysis, the 5000 voltage sags are grouped into different regions corresponding to Figure 6-9. Figure 6-10 shows resulting sag distribution. A large portion (74%) of the sags are low severity sags that fall into region "0". Around 5% of the sags have duration of less than 20ms (1 cycle), and therefore fall in the undefined region, i.e., these event cannot be strictly classified as sags. Judging from sag distribution in each region in Figure 6-10 one can see that equipment immunity plays a dominant role in failure risk mitigation.

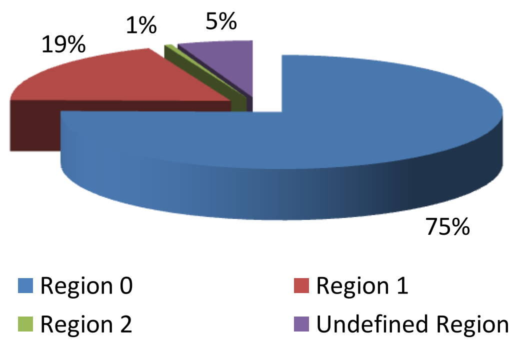


Figure 6-10 Sag distribution in each region

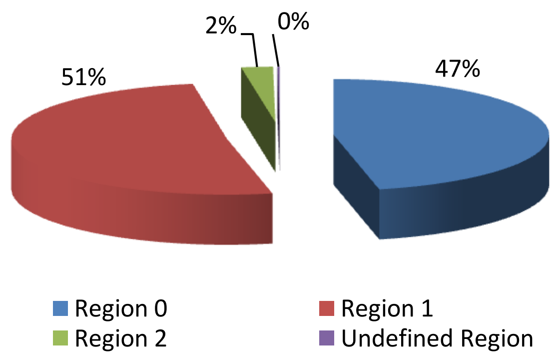


Figure 6-11 Failure risk distribution in each region

However, when the sags are fed into the risk assessment models, it is found that risk associated with sags in Region "1" is higher than that associated with sags in Region "0". Risk of failure attributed to the undefined region is negligible, while the risk associated with Region "2" is very low. Figure 6-11 shows risk distribution in each region.

The difference between actual number of sag and associated risk distributions is illustrated in Figure 6-12. The huge difference observed in particular for Regions 0 and 1, further emphasizes the need for full system modeling and simulation.

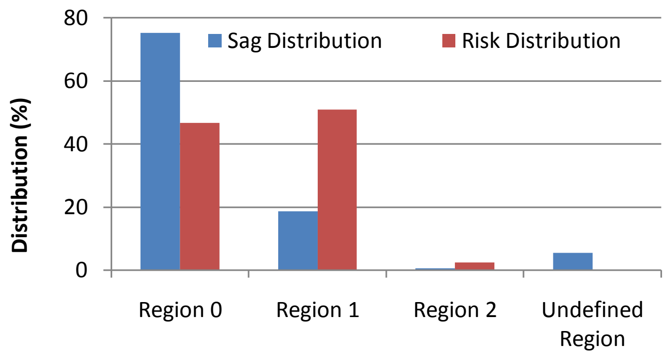


Figure 6-12 Difference in sag and risk distribution

6.3.1.1 The Options

The main purpose of this section is to demonstrate the effectiveness of the use of SNPV for reaching optimal decision regarding sag mitigation. Therefore, modeling of mitigating solutions (and associated costs) should be considered for illustrative purposes only, and does not represent the true benefit of the solution.

The cost effectiveness of sag mitigation at different levels/locations is investigated. The first option represents mitigation at equipment level. The second option considers the use of plant level power injecting device, and the final option depicts the "mitigating" potential of power quality targets set in power quality contracts.

6.3.1.1.1 Improving Equipment Immunity

Equipment level mitigation would theoretically minimize risks in Region "0". The first step is to determine which equipment to make more resilient, and the extent of required improvement. This however, depends on both, voltage sag characteristics and the type of equipment, as different sags affect differently, different equipment. The most sensitive equipment to given sag is the weakest link that should be considered first.

Figure 6-13 (same as Figure 5-14) shows the most sensitive equipment for different sag durations and magnitudes, while Figure 6-14 gives the probability distribution used to generate the voltage sag inputs for the simulation. Superimposing the two, results in Figure 6-15. Figure 6-15 illustrates how to prioritise sensitive devices (equipment) that need to be improved using sag magnitude-duration plane. Solid lines depict the boundaries of vulnerability areas for different equipment, and the contour lines represent probability density function of sag occurrence. It can be seen from the figure that the adjustable speed drives (ASD) are exposed the most to voltage sags recorded at the site and hence their ride through capabilities need to be improved first.

Improving equipment immunity would generally incur additional equipment (hardware), engineering and testing costs [3]. For example, it is found that the typical cost of the hardware required to improve equipment immunity in order to comply with SEMI F47 requirements was up to US$2,000, while the typical costs for testing and certification cost was about US$10,000 [3].

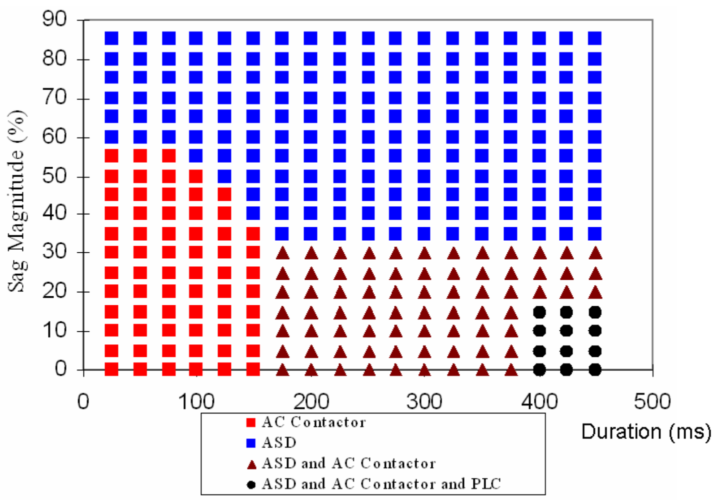


Figure 6-13 The weakest link in the process.

The technicality and the cost associated with improving the resilience of ASD to voltage sags is beyond the scope of this discussion. It is assumed that reasonable improvement can be made provided sufficient investment. That improvement in immunity would result in the modification in ASD voltage tolerance curve as shown in Figure 6-16, where sag magnitude threshold is reduced from 90% to 75%, while sag duration threshold is increased from 10ms (half cycle) to 60ms (three cycles). The consequence of this improvement in ride through capability is illustrated in Figure 6-17. The total risk of failure reduces to 50% of the original value, with the most obvious improvement in Region 0.

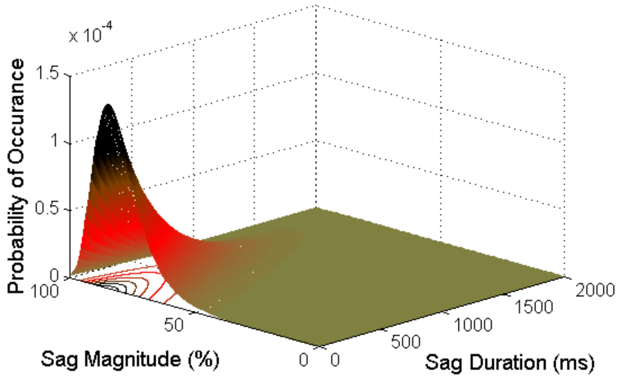


Figure 6-14 Probability of voltage sag occurrence

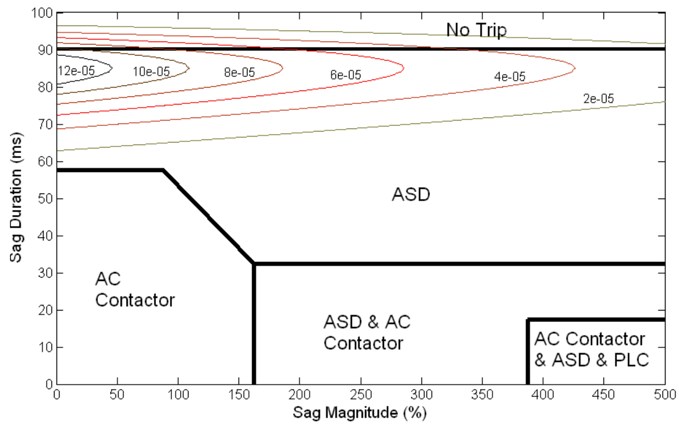


Figure 6-15 Determining of the most vulnerable equipment

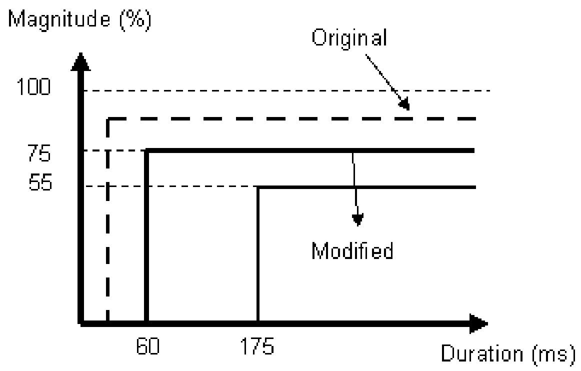


Figure 6-16 Modification of ASD tolerance curve after improvement

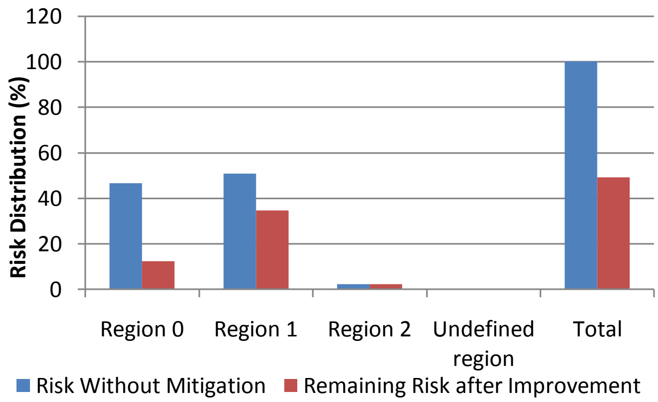


Figure 6-17 The effect of improving ASD resilience on process failure risk

6.3.1.1.2 Dynamic Voltage Restorer

The DVR model developed in Section 6.2.1.1 is used for simulations. The load information and DVR specification are given in Table 6-8 below. Four cases of $V_{restorable}$ are examined with a fixed t_{max} of 60 seconds.

Table 6-8 Load information and DVR specification

Load Information			DVR Specification	
Voltage level, V_l (KV)	Rated Power, S_{rated} (MVA)	Power Factor	$V_{restorable}$ (% of V_l)	t_{max} (seconds)
11	2.255	0.8 lagging	80, 70, 60, 50	60

The load power during different voltage sag events is varied using the continuous process load profile as shown in Figure 5-56(a) of Chapter 5. Power factor is assumed to be fixed, while all sags are assumed to have 30º phase angle lag.

Figure 6-18 shows the remaining risks in each region (risk in region 0 is completely eliminated) with various DVR capabilities. The difference in risks reduction capability is seen in Region 1 and Region 2 where higher DVR capability results in reduced risk of failure. E.g., a DVR with $V_{restorable}$=80% can reduce the risk of failure by up to 95% while a DVR with $V_{restorable}$=70%, 60% or 50% can reduce the risk of failure by up to 99%. Technically, DVR with $V_{restorable}$ =50% is the best choice as it removes the most of the risk. However, the price for DVR increases with its real and reactive power capability so it is essential to strike a balance between the DVR's risk reduction capability and its cost.

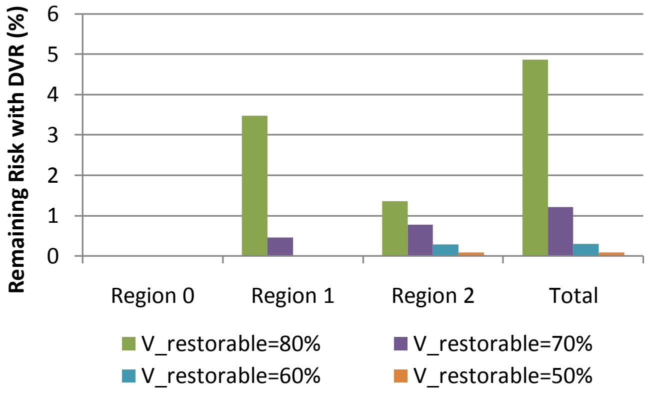


Figure 6-18 The effect of DVR on process failure risk

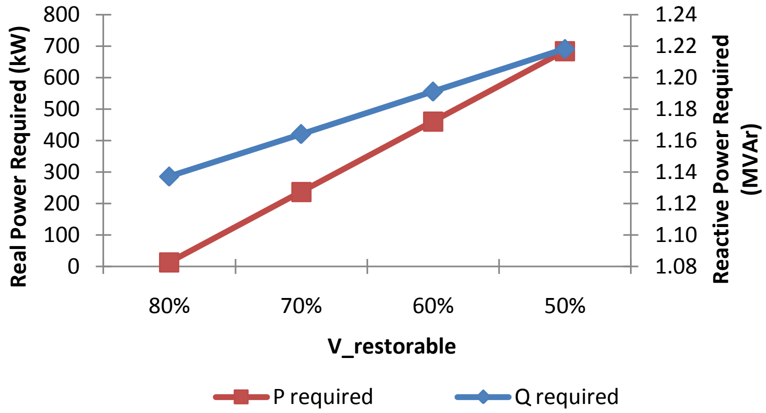


Figure 6-19 Real and reactive power requirement of DVR with different restoration capability

Figure 6-19 shows linear increase in real and reactive power required for different $V_{restorable}$ level. Figure 6-19 shows the real and reactive power storage size required for different DVR $V_{restorable}$ level. Both figures suggest that higher DVR capabilities lead to linearly increasing costs of the device.

Given that the difference in risk reduction capabilities between DVR with $V_{restorable}$ level of 70% and higher $V_{restorable}$ levels is not apparent, while price of DVR increases linearly, a DVR with $V_{restorable}$ =70% should be adequate for the industrial plant as it reduces the risk of failure by 99%. Therefore, for financial appraisal in following sections, DVR with $V_{restorable}$ level of 70% will be used.

6.3.1.1.3 Power Quality Targets

Network operators have the added advantage in power quality management with the flexibility to apply both plant and network level mitigating solutions. This example illustrates sag mitigation by setting an arbitrary target of sag reduction. Similarly to targets set in power quality contracts, the network operator employs various network level mitigation options to reduce the number of sags towards the target.

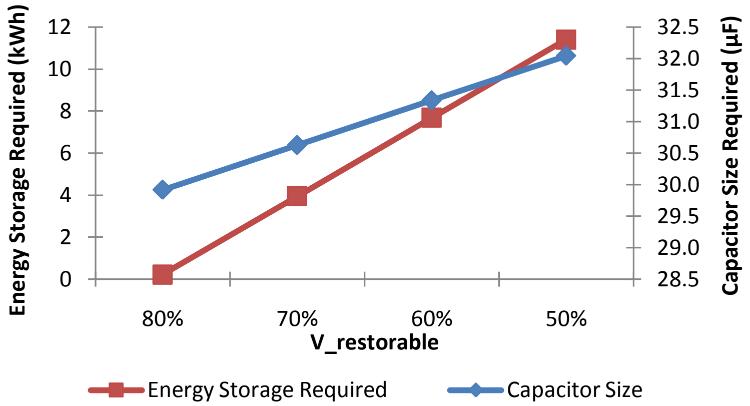


Figure 6-20 Energy storage and capacitor size required for DVR with different restoration capability

To demonstrate the effect of power quality targets, a simple example is given below. In this example, it is assumed that the network operator improves the power quality using all means of mitigation including installation of mitigation device at customer plant. The technicalities involved with each particular solution are not considered at this stage. The assumed power quality targets are given in Table 6-9. The value of this power quality contract, if the targets are met, is investigated in this example.

Figure 6-21 shows the remaining failure risk when the power quality targets are met, compared to the original case. It is found that a risk reduction of almost 80% can be achieved if the targets are met.

Table 6-9 Targets set in power quality contract

Sag Category	Region 0			Region 1			Region 2		
	K0	M0	L0	K1	M1	L1	K2	M2	L2
Target (sag per year)	2	1	0	0.5	0.3	0	0.1	0.05	0

6.3.1.2 Base Case Financial Loss

The first step in financial analysis is to determine the financial loss without mitigation. The base case SNPV of the industrial plant is calculated for a ten year period. The maximum financial loss for a single process trip during peak load is fixed at

£10,000. Typical discount rate of 10% is chosen for the analysis. The calculation is repeated for 10,000 trials.

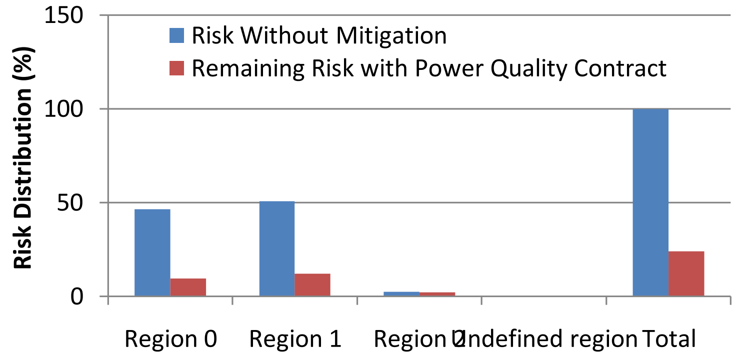


Figure 6-21 The effect of power quality contract on process failure risk

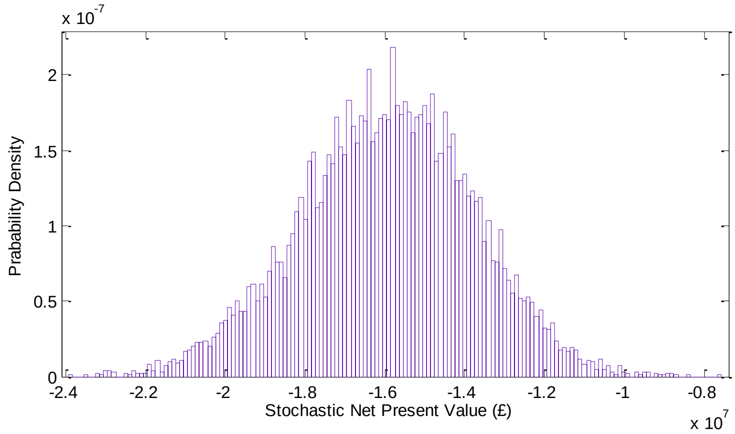


Figure 6-22 Probability distribution of SNPV for 10,000 trials

Figure 6-22 shows that for most of the 10,000 trials, the 10-year voltage sag SNPV is centered around -£16M. This means that without mitigation, in the next 10-year period, this plant will lose an average present worth of £16M due to voltage sags alone. The SNPV varies from £-8M, to as high as -£24M.

6.3.1.3 Remaining Losses with Mitigation

The effectiveness of the mitigation options is dictated by their capability to reduce financial losses. It is determined by comparing the financial losses remaining after employment of an option with the base case. Figure 6-23 shows the survivor functions of Stochastic Present Value (SPV) of remaining financial losses for different mitigation options as compared to the base case. Survivor function gives the probability of losing less than a certain present worth of money. This is an intuitive way of knowing the value of each mitigation option as a justification of investment. For example, if ASD immunity is improved, the plant has 90% chance of losing less than £10M.

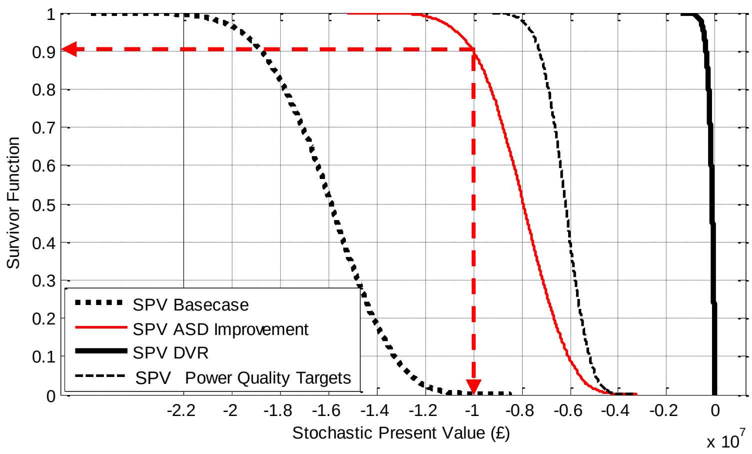


Figure 6-23 Stochastic present value of remaining losses

It can be seen that the losses reduce dramatically after employing any of the mitigation options. The most effective option is installation of DVR, followed by power quality contract and ASD immunity improvement. It should be noted that the Stochastic Present Value (SPV) shown in Figure 6-23 does not include the costs of mitigation options, hence cannot be used to decide which option is the best one for the plant. However, analysis of remaining losses does provide crucial information regarding the potential value of each investment. If a survivor level is chosen, the difference between SPV of a mitigation option and the base case SPV gives the potential value of that option. For example, if a survivor level of 90% is chosen, ASD improvement is worth £18M - £10M, £8M over the next 10 years. Therefore, if the cost of ASD improvement is less than £8M, this option is economically justified and can be accepted. On the other hand, if the cost is higher than £8M, the plant losses more money and therefore, ASD should not be improved.

6.3.1.4 Influence of Mitigation Cost and Nominal Loss Value

Mitigation cost is the costs involved in acquiring, installing, operating and maintaining a mitigation solution for the period of interest. It depends on various factors such as the type of mitigation, mitigation requirement, plant size, and the price set by supplier. The price of mitigation may differ greatly from one supplier to another.

On the other hand, as introduced in Chapter 3, nominal loss value is the maximum loss incurred by a single process trip during peak load. Determining this value is also not easy as it involves all losses during a process trip, from production loss, labour costs, and equipment damages. Moreover, this value is often considered sensitive thus cannot be easily obtained. Though a methodology is proposed in Chapter 4 to estimate nominal financial loss, considerable resources are still needed to build the database required for the methodology to be accurate enough for assessments.

Given the uncertain value of mitigation cost and nominal loss, it is necessary to develop general model that takes into account these values as variables, rather than constant values.

Figure 6-24 shows the variation in base case SNPV for different nominal loss value. It can be seen that SNPV has increasing negative values when the maximum loss value is increased. The shape of the survivor function also changes when nominal loss value is changed. It is found that base case SNPV follows equation (6-29), with x as survivor function of financial loss, and k_x as a multiplier at survivor function x.

$$SNPV_x = k_x \times Nominal\ Loss \tag{6-29}$$

To explain this relationship, consider the case where survivor function of 0.9 is required. If the nominal loss is £10,000, Figure 6-24 gives $SNPV_{0.9}$ of -£18.8M. Therefore,

$k_{0.9} = SNPV_{0.9}/Nominal\ Loss = -1880$

Then from (6-29), if Nominal Loss is £20,000, Base case $SNPV_{0.9}$ is given by:

$SNPV_{0.9} = -1880 * 20000$

$= -£37.6M$

Which is consistent with the value obtained from Figure 6-24.

SNPV of mitigation solutions also follows equation (6-29), as can be seen in Figure 6-25. In this figure, the SNPV of ASD is used as a general representation of mitigation option.

Next, the influence of mitigation cost is investigated. Figure 6-26 shows the change in SNPV for different DVR cost. It can be seen that for different DVR cost, the survivor function is moved without any change in curve shape. The magnitude of the displacement equals to the present value of DVR costs.

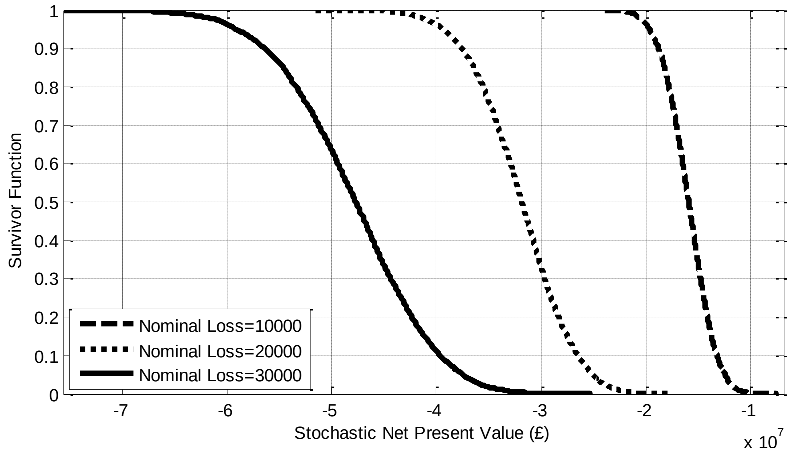


Figure 6-24 Influence of Maximum Loss value on base case SNPV

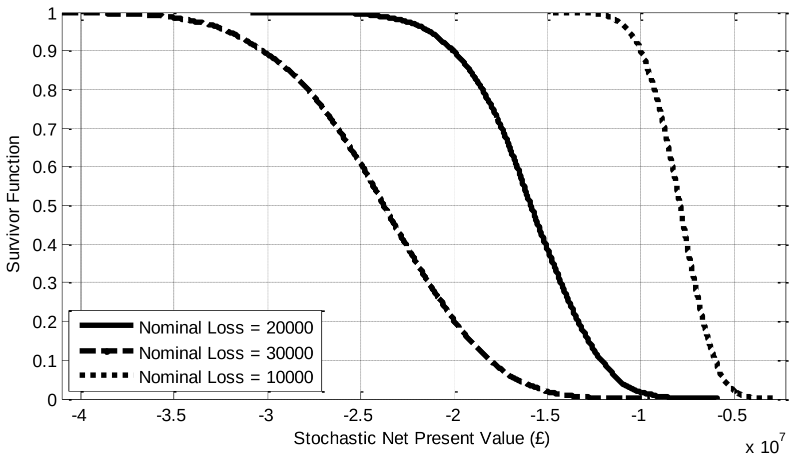


Figure 6-25 Influence of Maximum Loss value on SNPV of ASD

By including the effect of mitigation cost, (6-29) is extended into equation (6-30) and (6-31). Equation (6-30) gives the SNPV of the plant without mitigation, while (6-31) gives the SNPV of the plant with mitigation.

$$SNPV_x^{base\ case} = k_x \times Nominal\ Loss \tag{6-30}$$

$$SNPV_x^{mitigation} = (k_x \times Nominal\ Loss) - PV_{mitigation\ cost} \tag{6-31}$$

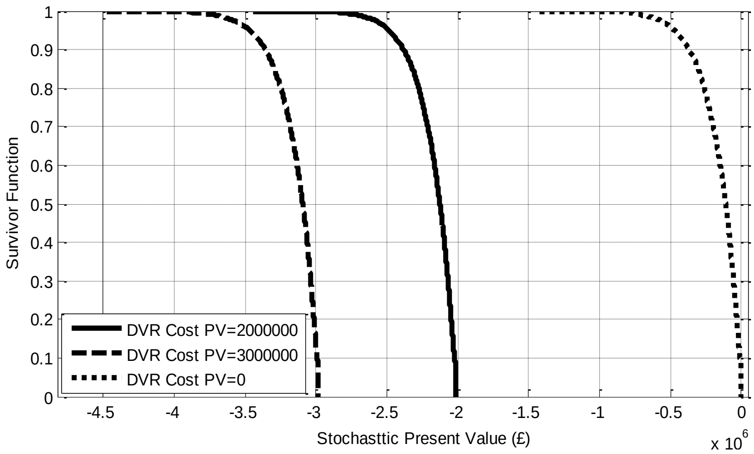


Figure 6-26 Influence of DVR cost on SPV of DVR

The present value of mitigation ($PV_{mitigation\ cost}$) is given by:

$$PV_{mitigation\ cost} = -\sum_{t=1}^{T} \frac{M_t}{(1+r)^t} - \mathrm{I} \tag{6-32}$$

Where:

T=project lifetime in years

t=the year number

I=initial investment

r=discount rate

M_t=operation and maintenance cost in year t

6.3.1.5 Generalized Solution

In order to use (6-28), one would need both technical (probability of process trip) and financial (maximum loss value) information about the analysed plant. Usually, consultants and engineers who deal with the technical part of the analysis may not have access to sensitive financial data, while on the other hand managers who have the financial data might not be concerned with the technical complexities. Therefore, it is particularly useful if the two parts can be assessed separately. A general solution considering the technical aspect of the analysis only is found first. This solution is given as a series of values called k factors:

$$k = \sum_{t=1}^{T} \frac{\left(\sum_{n=1}^{N}(-p)\right)_t}{(1+r)^t} \tag{6-33}$$

By running repeating simulations (trials) a series of k factors can be produced. In this example, 10,000 trials are run (T=10, r=0.1). Results are arranged in the form of survival function, x with k factors given in Table 6-10.

With k factors obtained, financial analysis can proceed using (6-31), with x as desired survival function value, i.e., probability of losing less than a certain amount of money. The development of (6-31) and (6-33) divides voltage sag financial loss analysis into separate technical and financial parts. PQ engineers and consultants will be therefore able to complete the risk and technical assessments without information on sensitive and uncertain financial loss values. The outcome of risk assessment and technical analysis shall be a list of k_x multipliers, as can be seen in Table 6-10.

Table 6-10 Generalized solution with multiplier k_x

Survivor Function (x)	Multiplier kx			
	Base Case	ASD Desensitization	DVR	Power Quality Contract
0.0	-757	-276	0	-380
0.1	-1320	-614	-0.6	-553
0.2	-1412	-675	-3.1	-588
0.3	-1477	-721	-5.4	-613
0.4	-1535	-763	-8	-635
0.5	-1589	-800	-11	-656
0.6	-1648	-841	-14.8	-676
0.7	-1713	-885	-19.6	-698
0.8	-1780	-937	-26.2	-725
0.9	-1880	-1011	-38	-763
1.0	-2244	-1303	-89.9	-895

On the other hand, plant managers will obtain maximum loss value through pure financial calculations, and mitigation cost value through quotations from mitigation solution providers. The optimal mitigation solution can then be obtained by selecting a survival function value (x), calculating k_x (multipliers from the Table 6-10), and plugging in the maximum loss and mitigation cost values into (6-31) and (6-32). For example, say the maximum loss value for a plant is *L=10K Euros*. If $PV_{mitigation\_cost}$ for improving ASD resilience, installing DVR and purchasing a PQ contract are 50K, 1300K and 185K Euros respectively, using (6-31), a survival value of 0.5 (50% chance of losing less than certain amount of money) will yield the following SNPV:

$$SNPV_{0.5}^{ASD} = (-800 \times 10{,}000) - 50{,}000 = -£8.05M$$
$$SNPV_{0.5}^{DVR} = (-11 \times 10{,}000) - 1{,}300{,}000 = -£1.41M$$
$$SNPV_{0.5}^{PQ\ contract} = (-656 \times 10{,}000) - 185{,}000 = -£6.75M$$

It is found that DVR produces the lowest negative SNPV, hence, installing a DVR would be the best option.

6.4 Summary

The technical effectiveness and associated costs of representative voltage sag mitigation solutions are modeled in this chapter. These models will be used in the following chapter to investigate potential value of voltage sag management.

The application of Stochastic Net Present Value method is also illustrated. The influence of nominal loss value and mitigation costs on financial analysis is investigated and resulted in the development of generalized formulae for comparison of mitigating solutions. The methodology proposed simplifies techno-economic assessment of voltage sag mitigating solution by enabling technical experts to deal only with technical problems, and financial experts to deal only with financial problems, while at the same time preserving the accuracy of the assessment.

Chapter 7 The Value of Voltage Sag Mitigation

7.1 Introduction

This chapter investigates the value of various mitigation solutions in reducing financial loss of industrial customers caused by voltage sags. Different types of power system faults are simulated on an actual UK distribution network model to obtain voltage sag profiles at various locations in the network. Using the customer process models developed in Chapter 5, and mitigation device models developed in Chapter 6, the effectiveness of various mitigation solutions for different customer processes at different locations of the network is assessed.

The sensitivity of the assessment to different input parameters, such as the type and size of customer plant, sensitive equipment type, customer process characteristics, financial loss resulting from process interruption, cost and effectiveness of mitigating solution and network fault rates are also investigated. Research findings would prove invaluable to both distribution companies and plant owners considering adopting power quality contracts. The results obtained represent the sixth original contribution of this thesis.

7.2 Network Model

A model of an actual UK distribution network is developed to facilitate the assessment. The network model consists of 158 buses; fifteen 132kV buses, ninety six 33kV buses, forty five 11kV buses and two 6.6kV buses. As illustrated in Figure 7-1, the network has a total length of 521km; 150km of 132kV lines and 371km of 33kV lines with mixture of cables and overhead lines. System short circuit power at the 132kV Main Station is 927MVA.

From the network, nine locations are selected for placement of customer plants. The locations are numbered in Figure 7-1 and are chosen such that different areas of the network are covered. Also, plants are either located close to (locations 1, 2, 3), far away from (locations 4, 6, 7) or in between (locations 5, 8, 9) bulk supply substations (33kV).

Due to the lack of information about some of the network parameters, those have to be based on typical values. Table 7-1 summarizes the parameters used in the assessment.

Table 7-1 Network parameters

Actual Data	Typical Values
All line and transformer data, including impedances, lengths, ratings and cable/overhead line ratios.	All fault data, including line and bus failure rates, fault causes and fault clearing times.

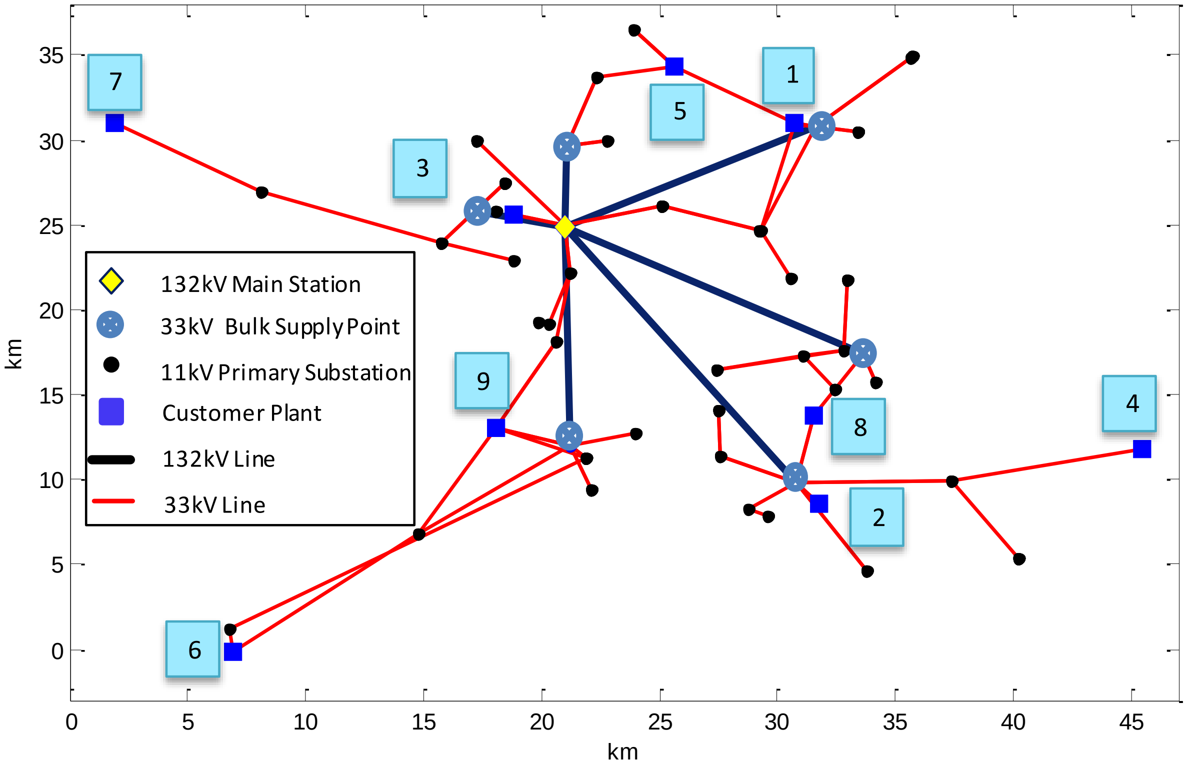


Figure 7-1 Network model

Network fault rates are based on typical values obtained from [87] and [46] and fault durations on typical fault clearing times obtained from [46]. Fault rates are calculated such that L-L-L, L-G, L-L-G and L-L faults are 4%, 73%, 17% and 6% of all faults for all components at all voltage levels [46]. Table 7-2 and Table 7-3 show the fault data used for fault calculation.

Table 7-2 Fault rates for network components

Component	Voltage Level (kV)	Fault Rate (per km/annum) or (per bus/annum)			
		L-L-L	L-G	L-L-G	L-L
Bus	11, 33, 132	0.0032	0.0584	0.0136	0.0048
Overhead Line	11, 33	0.0087	0.1588	0.0370	0.0131
	132	0.006	0.1095	0.0255	0.0090
Underground Cable	11, 33, 132	0.002	0.0365	0.0085	0.0030

To ensure realistic assessment, a fault occurrence factor is randomly assigned to all buses and lines, such that:

$$FR_{bus} = FR_{base\_bus} \times FF \tag{7-1}$$

$$FR_{line} = \left(FR_{base\_OH} \times l_{OH} + FR_{base\_Cable} \times l_{Cable} \right) \times FF \tag{7-2}$$

Where FR = Fault Rate
l = length
FF = Fault Occurrence Factor

Table 7-3 Fault clearing times

Component	Voltage Level (kV)	Fault Clearing Time (ms)
Bus	All	60
Lines	11	300
Lines	33	150
Lines	132	80

Fault occurrence factors are either Low (50% of FR_{base}), Normal (same as FR_{base}) or High (150% of FR_{base}).

The causes of fault are unique for different networks and therefore have to be assumed. For this study, the causes of fault for different network components at different voltage levels are summarized in Table 7-4 and Figure 7-2.

Table 7-4 Causes of faults for network components

Voltage Level	Cause of Faults (%)					
	OH Ratio	Lightning	Animal	Tree	Construction	Other
132	1	25	15	15	0	45
33	1	20	20	20	0	40
33	0.9	20	20	15	5	40
33	0.8	20	20	15	5	40
33	0.7	15	20	15	10	40
33	0.6	15	15	10	20	40
33	0.5	10	10	10	30	40
33	0.4	10	10	5	35	40
33	0.3	10	5	5	40	40
busbar	0	0	0	0	0	100

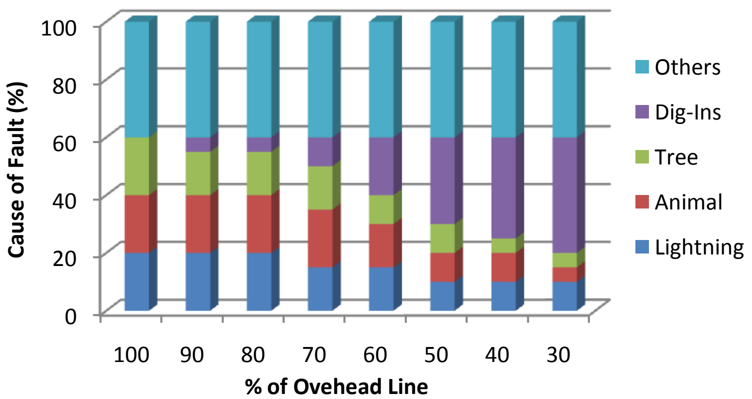


Figure 7-2 Causes of faults for 33kV line

To ensure that all relevant locations in the network are represented, nine locations have been chosen for placement of customer plants. Amongst the locations, three are near to 33kV bulk supply point (location 1,2 and 3) , three at the end of the 33kV line (location 4, 6 and 7), and three near the midpoint of the line (location 5,8 and 9).

Voltage sag performance at different busbars can be roughly estimated based on their Sag Score obtained using (7-3). Where R_n is the occurrence rate for each sag in each phase (Φ), and F is the sag severity factor, obtained using (7-4). The Magnitude Severity Factor (*M*) in magnitude class *i* is shown in Table 7-5, while Duration Severity Factor (*D*) in duration class *j* is shown in Table 7-6. Sag severity factors are intended as weighting factors for sags that fall into different severity classes. For example, a sag with 0.75p.u. magnitude and 200ms duration would have magnitude and duration severity factors of 0.3 and 0.5 respectively, resulting in sag severity factor, *F* of 0.8. Sag Scores for different locations of the network are shown in Figure 7-3.

$$Sag\ Score = \sum_{\varphi=1}^{3} \sum_{n=1}^{N} (R_n \times F) \quad (7\text{-}3)$$

$$F_{ij} = M_i + D_j \quad (7\text{-}4)$$

Table 7-5 Magnitude severity factor for each magnitude class

Sag Magnitude Class (*i*) [p.u.]	Magnitude Severity Factor (M)
>0.9	0
0.85-0.9	0.1
0.80-0.84	0.2
0.75-0.79	0.3
0.70-0.74	0.4
0.65-0.69	0.5
0.60-0.64	0.6
0.55-0.59	0.7
0.50-0.54	0.8
0.45-0.49	0.9
<0.45	1.0

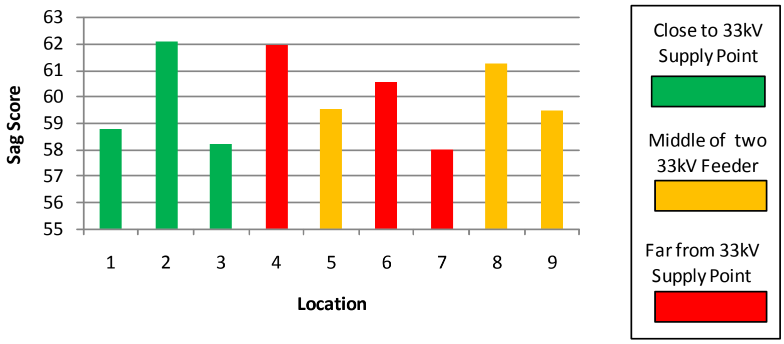


Figure 7-3 Sag Score at different network locations

Table 7-6 Duration severity factor for each duration class

Sag Duration Class (j) [ms]	Duration Severity Factor (D)
<10	0
10-49	0.1
50-99	0.2
100-149	0.3
150-199	0.4
200-249	0.5
250-299	0.6
300-349	0.7
350-399	0.8
400-449	0.9
≥450	1.0

Besides sags resulting from faults in the distribution network, sags originated in the upstream transmission network are also incorporated in the model. Transmission level sags used are randomly generated and given in Table D-6 in Appendix D. They contribute to around 10% of the total Sag Score in each location shown in Figure 7-3.

7.3 Customer Models

To ensure that main plant characteristics are covered, customer plants are divided based on process equipment type, process immunity, interdependence level and nominal financial loss. A total of 48 representative customer plants are modelled to include all combinations of process characteristics. Customer process characteristics and process models are summarized in Table 7-7 and Table 7-8. All plants have a fixed load of 3MW divided into four processes. The power factor is assumed at 0.7.

Table 7-7 Description of customer process characteristics

Characteristic	Code	Description	Model
Equipment Type	1	Predominantly microprocessors	At least 75% PC and PLC
	2	Predominantly drives and motors	At least 75% ASD and ACC
PIT vs Restart Time	1	High process immunity	<25% process failure due to equipment failure
	2	Low process immunity	>75% process failure due to equipment failure
	3	Moderate process immunity	25%<process failure<75%
Interdependence	1	Low interdependence between processes	all sub processes affect less than 2 other subprocesses
	2	High interdependence between processes	at least 1 sub process affects 2 or more other subprocesses
Nominal Loss	1	Low nominal loss	£10k/MW per disruption
	2	Moderate nominal loss	£35k/MW per disruption
	3	High nominal loss	£75k/MW per disruption
	4	Very High nominal loss	£100k/MW per disruption

Table 7-8 Customer plant models

Plant Identifier	Process Group	Main Sensitive Equipment	Process Immunity	Interdependence	Nominal Loss ('000 £)
1	1	Microprocessor Based Devices	High	Low	30
2	1		High	Low	105
3	1		High	Low	225
4	1		High	Low	300
5	2		High	High	30
6	2		High	High	105
7	2		High	High	225
8	2		High	High	300
9	3		Low	Low	30
10	3		Low	Low	105
11	3		Low	Low	225
12	3		Low	Low	300
13	4		Low	High	30
14	4		Low	High	105
15	4		Low	High	225
16	4		Low	High	300
17	5		Moderate	Low	30
18	5		Moderate	Low	105
19	5		Moderate	Low	225
20	5		Moderate	Low	300
21	6		Moderate	High	30
22	6		Moderate	High	105
23	6		Moderate	High	225
24	6		Moderate	High	300
25	7	Drive and Contactor Based Devices	High	Low	30
26	7		High	Low	105
27	7		High	Low	225
28	7		High	Low	300
29	8		High	High	30
30	8		High	High	105
31	8		High	High	225
32	8		High	High	300
33	9		Low	Low	30
34	9		Low	Low	105
35	9		Low	Low	225
36	9		Low	Low	300
37	10		Low	High	30
38	10		Low	High	105
39	10		Low	High	225
40	10		Low	High	300
41	11		Moderate	Low	30
42	11		Moderate	Low	105
43	11		Moderate	Low	225
44	11		Moderate	Low	300
45	12		Moderate	High	30
46	12		Moderate	High	105
47	12		Moderate	High	225
48	12		Moderate	High	300

The processes are grouped in a way that allows for easy comparison. Processes within the same Process Group are identical in all aspects except for their nominal loss value. On the other hand, Process Group 1 and Group 7 (or Group 2 and 8 etc.) are identical except for their main sensitive equipment.

7.4 Base Case Financial Loss

Base case financial loss is needed as the reference point for all assessments. Figure 7-4 gives the flow chart for assessment of base case losses. The procedure adopted for this assessment can be summarized as follows:

1. Simulate faults at all lines and buses in the network to obtain sag profile at buses of interest (customer plant buses). Detailed explanation of fault studies in available in [46].
2. Assess customer equipment failure risk with the probabilistic equipment models described in Chapter 5.
3. Assess customer process failure risk with the single equipment process model with PIT described in Chapter 5.
4. Assess customer financial loss from the failure risks, assuming constant nominal loss value (process cycle neglected).
5. Calculate total financial loss in an assessment period of ten years with the Net Present Value (non-stochastic) method.

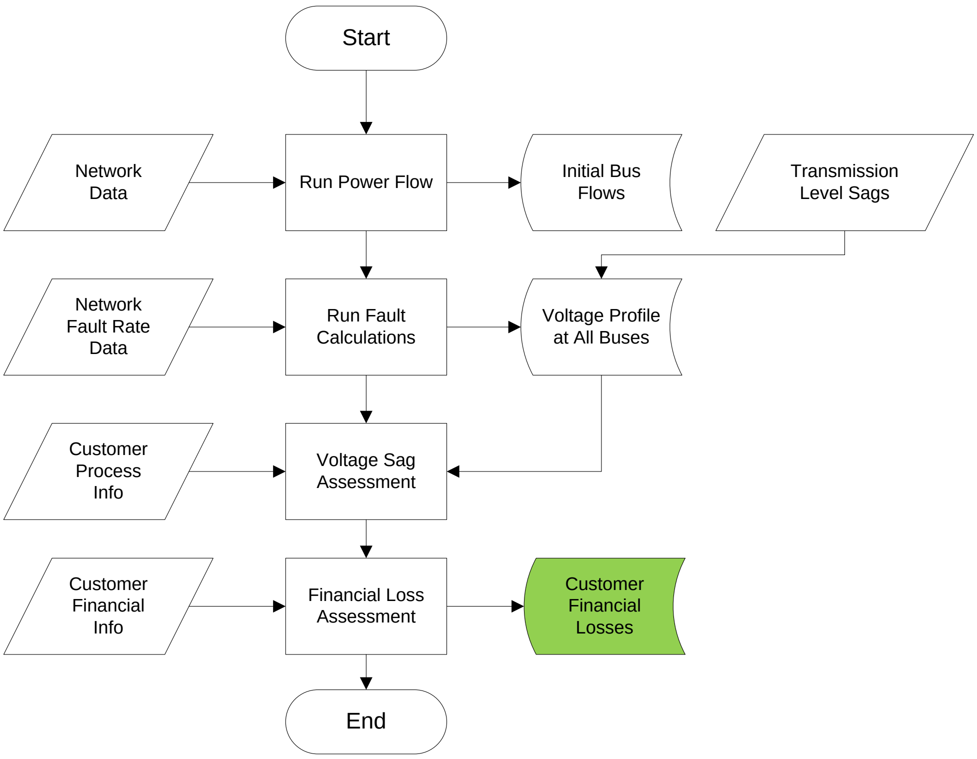


Figure 7-4 Base case financial loss assessment flow chart

Table 7-9 Process ranking based on total financial loss

Rank	Plant Identifier	Process Group	Equipment Type	Process Immunity	Interdependence	Nominal Loss (k£)	10 Year Loss (M £)
1	40	10	ASD	Low	High	300	23.8
2	48	12	ASD	Moderate	High	300	20.2
3	36	9	ASD	Low	Low	300	19.0
4	39	10	ASD	Low	High	225	17.8
5	44	11	ASD	Moderate	Low	300	16.3
6	47	12	ASD	Moderate	High	225	15.2
7	35	9	ASD	Low	Low	225	14.2
8	43	11	ASD	Moderate	Low	225	12.3
9	28	7	ASD	High	Low	300	11.4
10	32	8	ASD	High	High	300	11.4
11	27	7	ASD	High	Low	225	8.6
12	31	8	ASD	High	High	225	8.6
13	38	10	ASD	Low	High	105	8.3
14	46	12	ASD	Moderate	High	105	7.1
15	34	9	ASD	Low	Low	105	6.6
16	42	11	ASD	Moderate	Low	105	5.7
17	16	4	Microprocessor	Low	High	300	4.5
18	26	7	ASD	High	Low	105	4.0
19	30	8	ASD	High	High	105	4.0
20	24	6	Microprocessor	Moderate	High	300	3.6
21	15	4	Microprocessor	Low	High	225	3.4
22	12	3	Microprocessor	Low	Low	300	2.9
23	23	6	Microprocessor	Moderate	High	225	2.7
24	20	5	Microprocessor	Moderate	Low	300	2.6
25	37	10	ASD	Low	High	30	2.4
26	11	3	Microprocessor	Low	Low	225	2.2
27	45	12	ASD	Moderate	High	30	2.0
28	19	5	Microprocessor	Moderate	Low	225	1.9
29	33	9	ASD	Low	Low	30	1.9
30	41	11	ASD	Moderate	Low	30	1.6
31	14	4	Microprocessor	Low	High	105	1.6
32	22	6	Microprocessor	Moderate	High	105	1.3
33	25	7	ASD	High	Low	30	1.1
34	29	8	ASD	High	High	30	1.1
35	10	3	Microprocessor	Low	Low	105	1.0
36	18	5	Microprocessor	Moderate	Low	105	0.9
37	4	1	Microprocessor	High	Low	300	0.7
38	8	2	Microprocessor	High	High	300	0.7
39	3	1	Microprocessor	High	Low	225	0.5
40	7	2	Microprocessor	High	High	225	0.5
41	13	4	Microprocessor	Low	High	30	0.5
42	21	6	Microprocessor	Moderate	High	30	0.4
43	9	3	Microprocessor	Low	Low	30	0.3
44	17	5	Microprocessor	Moderate	Low	30	0.3
45	2	1	Microprocessor	High	Low	105	0.2
46	6	2	Microprocessor	High	High	105	0.2
47	1	1	Microprocessor	High	Low	30	0.1
48	5	2	Microprocessor	High	High	30	0.1

Table 7-9 ranks customer plants based on their ten-year financial loss calculated using the NPV method with 6% discount rate. It is found that financial loss could be as low as £0.1M or as high as £24M over ten years. Plants that depend on adjustable speed drives (ASD) and contactors tend to have higher losses compared to microprocessor-based processes.

7.4.1 Nominal Loss

Figure 7-5 and Figure 7-6 show the level of financial losses for different process groups, and the influence of nominal loss on base case financial loss. As expected, increase in nominal loss also increases base case financial loss. Modeling of process groups with different nominal loss is necessary as base case financial loss determines the possible range of mitigation solutions deployable for the process (e.g. mitigation solutions of higher costs are possible if the base case losses is high enough to justify the cost).

It is found that for the same class of nominal loss, Group 10 processes (ASD-based, low immunity and high interdependence level) have the highest base case financial losses, while processes in Group 1 (microprocessor-based, high immunity and low interdependence level) and Group 2 (microprocessor-based, high immunity and high interdependence level) have the lowest base case losses.

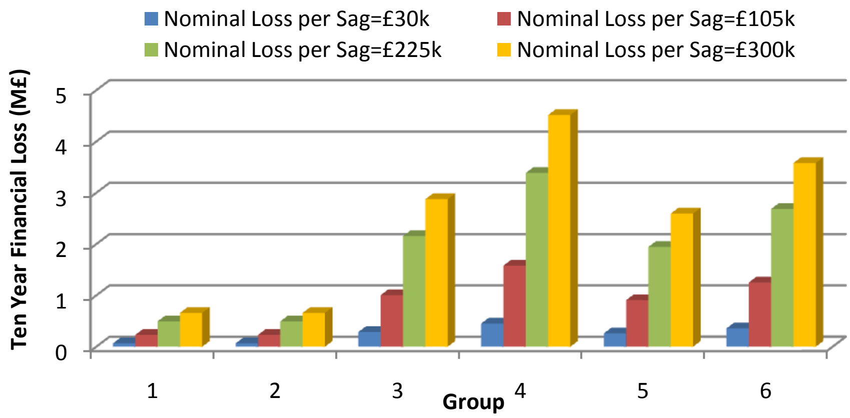


Figure 7-5 Base case financial loss for process group 1 to 6

7.4.2 Equipment Type

Table 7-10 groups processes into six classes for financial loss comparison based on the type of equipment used. Results (Figure 7-7) show that the average financial loss of ASD-based processes is five to seventeen times higher than the loss of microprocessor-based processes. Processes with high immunity showed the largest discrepancy in calculated financial losses with ASD-based processes a lot more costly than microprocessor based processes.

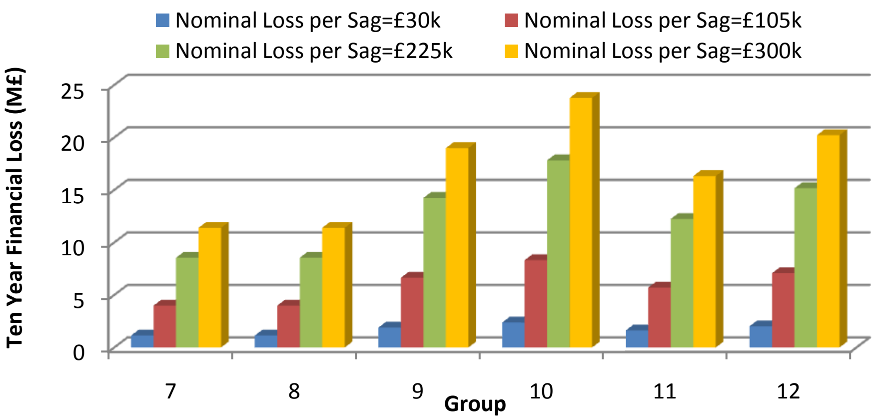


Figure 7-6 Base case financial loss for process group 7 to 12

Table 7-10 Description of process characteristics for equipment type comparison

Class	Process Immunity	Interdependence
1	High	Low
2	High	High
3	Low	Low
4	Low	High
5	Moderate	Low
6	Moderate	High

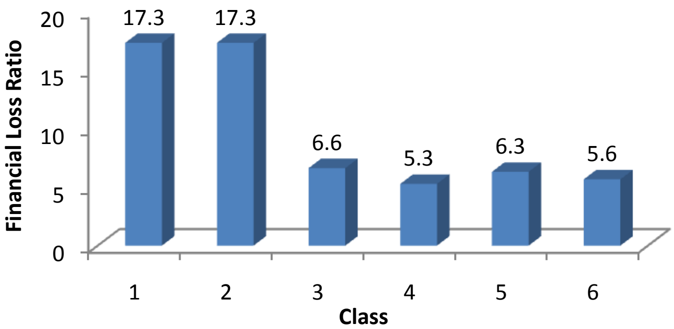


Figure 7-7 Ratio of financial loss of ASD-based processes and microprocessor-based processes

7.4.3 Process immunity

Table 7-11 groups processes into four classes for financial loss comparison based on process immunity. Results (Figure 7-8 and Figure 7-9) show that average financial loss suffered by low immunity processes is 18% higher than moderate immunity processes, and 459% higher than high immunity processes for microprocessor-based plants. For ASD-based plants, low immunity processes is 17% more costly than moderate immunity plants and 88% more costly than high immunity plants. Financial loss of microprocessor-based plants is more sensitive to process immunity than that of ASD-based process.

Table 7-11 Description of process characteristics for process immunity comparison

Class	Equipment Type	Interdependence Level
1	microprocessor	Low
2	microprocessor	High
3	drives and contactors	Low
4	drives and contactors	High

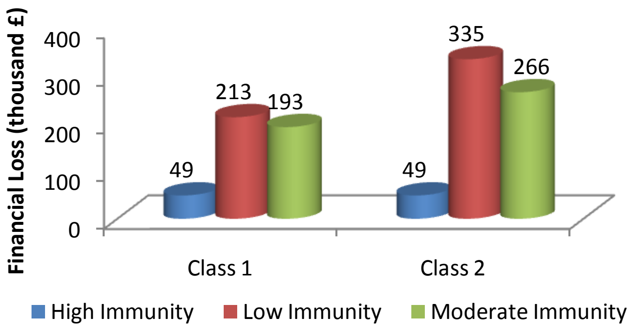


Figure 7-8 Financial loss comparison for microprocessor-based processes of different process immunity

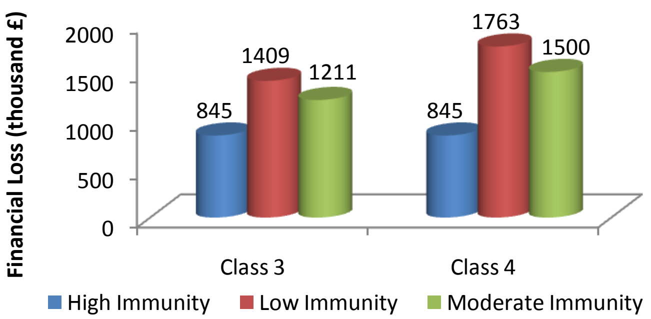


Figure 7-9 Financial loss comparison for drive-based processes of different process immunity

7.4.4 Interdependence

Table 7-12 groups processes into six classes for financial loss comparison based on the level of process interdependence. Results (Figure 7-10) show that average financial loss suffered by high interdependence processes is between 0% to 50% higher than that of low interdependence processes depending on process equipment type and process immunity.

Table 7-12 Description of process characteristics for level of interdependence comparison

Class	Equipment type	Process Immunity
1	microprocessor	Low
2	microprocessor	High
3	microprocessor	Moderate
4	drives and contactors	Low
5	drives and contactors	High
6	drives and contactors	Moderate

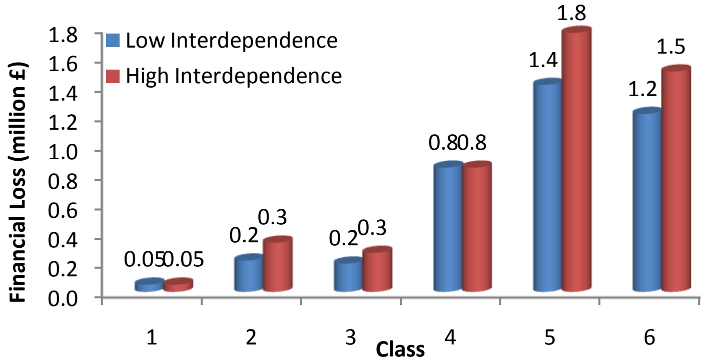


Figure 7-10 Financial loss comparison for processes of different interdependence levels

7.4.5 Location in The Network

Due to different system impedances at different network locations, voltage sag performance and financial loss differ at different busbars. Figure 7-11 shows that financial losses suffered by the same plant may differ by up to 25% (location 2 and 6) at different locations in the network.

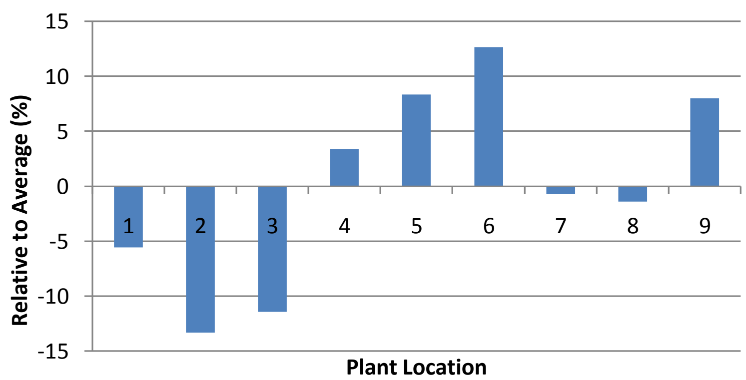


Figure 7-11 Base case financial loss at different locations

Figure 7-12 shows financial loss of processes with different equipment types at different network locations. The general trend of financial loss is similar for both equipment types with some difference in the magnitude of losses. These figures indicate that plants located close to bulk supply substations (location 1, 2, 3) suffer lower financial losses whilst plants at all other locations generally suffer from losses above the average value.

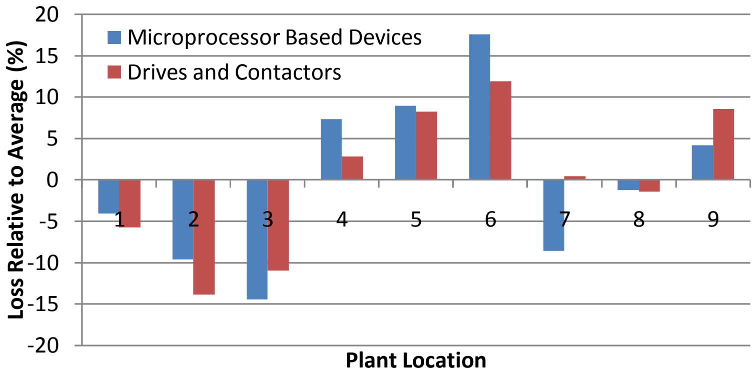


Figure 7-12 Base case financial loss of processes with different equipment type

7.5 Mitigation Schemes

All mitigating solutions modelled in Chapter 6.2 are implemented in the assessment. The aim is to determine the value of each mitigating solution for all 48 customer models at all nine network locations. The general procedure for determining the value of mitigation devices is shown in Figure 7-13, and can be described as follows:

1. Calculate base case financial losses using the flow chart in Figure 7-4.
2. Search for the best location in the network for implementation of network level mitigation devices using Genetic Algorithm (GA) search.
3. For plant level devices, obtain optimal size of mitigation (power injecting devices) using GA search.
4. For static transfer switch, obtain best busbar for connection of backup feeder through trial and error.
5. Implement mitigation scheme in the network.
6. Recalculate customer failure risk and ten year financial loss.
7. Compare the result with base case financial losses to obtain the value of mitigation.

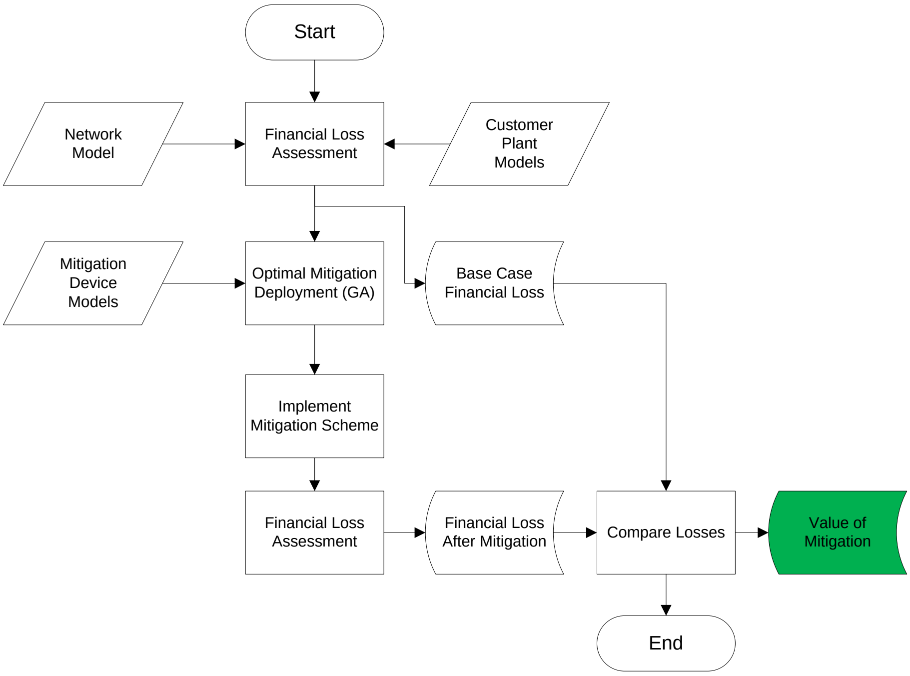


Figure 7-13 Value of sag mitigation assessment flow chart

7.5.1 Genetic Algorithm Search

Genetic Algorithm is a search technique that mimics the way living organisms evolve through inheritance, mutation, selection, and crossover [157]. With GA, a large pool of candidate solutions (individuals) with different characteristics are generated to form the initial population. These individuals are evaluated according to a pre-defined fitness function that acts as the objective function of the mathematical problem. Based on their fitness, a few individuals are selected and randomly modified to produce the next generation of population. The modification to individuals in the population explores the effect of adding new traits to the solution in the hope of improving their fitness. This process is repeated with the new population until a pre-defined stop criteria, normally a maximum number of generation is met. The solution to the problem comes in the form of the fittest individual from all generated populations.

In this research, GA is needed due to the non-linearity of the problem and the sheer number of possible solutions made it impossible to obtain any meaningful result using conventional optimization and trial and error methods. By using GA, it is thought that reasonably good results can be obtained for significantly shorter simulation time. Even so, the simulation time required is still long. Therefore, in all assessments conducted, a balance between accuracy and simulation effort have to be struck so that results can be obtained within limited timeframe.

In all simulations, the GA is set to search for the case with maximum value (minimum total cost) of mitigation. The objective function is set such that:

$$\min f = min\left[NPV_{10}\left(C_{mitigation} + C_{sag}\right)\right] \tag{7-5}$$

Where NPV_{10} = net present value for the ten year assessment period

$C_{mitigation}$ = total cost of mitigation including initial, operating and maintenance costs.

C_{sag} = remaining financial loss after mitigation

For power injecting devices, variables include mitigation type (DVR, flywheel), number of mitigated processes in the customer plant, and device ratings. For individual network fault reduction devices, the location of the mitigated feeders is varied. For optimal network fault reduction, different solution mix are attempted at different feeders to obtain the best value solution mix.

Simulations are conducted using the GA toolbox in Matlab. The parameters for GA (number of generations, number of individual per generations) are selected to obtain a balance between simulation time and accuracy of results. It should be noted that due to the huge number of possible outcome for some simulations, and the limited sample explored (due to time constraints), the results obtained might not be the true optimum. Therefore, it is deemed acceptable that the sample size (number of individuals and generations) is chosen such that a reasonable error margin can be satisfied.

Figure 7-14 shows the difference between simulation output with, Case 1 having a population size of 50 and generation number of 200, and Case 2 having a population size of 100 and generation number of 100. Total GA search space is less than $1*10^{-98}\%$ of possible solutions. It can be seen that the difference is reasonable (<3%) considering the size of the search space. This also confirms that the size of the search space (10,000 individuals) produces sufficiently good results for comparison purposes between cases. Parameters for cross-over and mutation [157] are selected arbitrarily and tuned from trial and error.

7.5.2 Power Injecting Devices

Figure 7-15 shows detailed simulation procedure for determining the optimal power injecting device for each customer plant. For each simulation, GA will search for the optimal solution in terms of device type (DVR, DVR with capacitor storage or flywheel) for the plant, and the number of mitigated process (all processes can be mitigated independently).

Once a device type is chosen, the optimal size of energy storage will be obtained through trial and error. For example, if DVR is selected, the simulation will run through all options in Table 7-13 such that the selected energy storage size results in maximum savings in plant financial loss. To achieve the same objective, if DVR with capacitor storage is selected, simulation will attempt all ratings from 1 to 7 MVAr. On the other hand, if flywheel is selected, the energy storage size is selected such that the flywheel can restore a complete loss of voltage for the entire customer plant for 5 seconds.

Table 7-14 summarizes the simulations conducted for the assessment. Due to the small number of possible solutions it is possible to verify the algorithm by comparing a selected number of GA search results with results obtained through conventional trial and error method. It is found that the algorithm is able to provide the optimal solution for all compared cases.

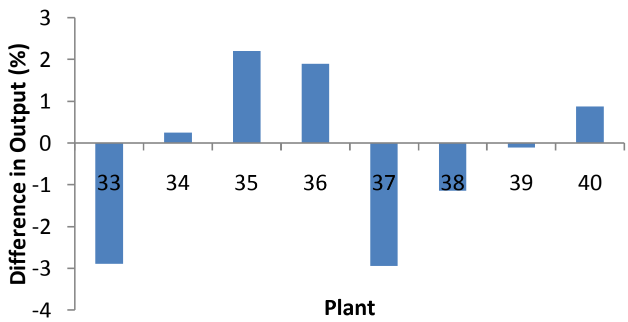


Figure 7-14 Difference in optimal solution for different GA search parameters

Table 7-13 DVR sizes considered in assessment

Option	P_rated	Q_rated
1	0.25	1.0
2	0.50	1.0
3	1.0	2.0
4	1.5	2.0
5	2.0	3.0
6	3.0	4.0
7	4.0	5.0
8	5.0	6.0
9	6.0	7.0

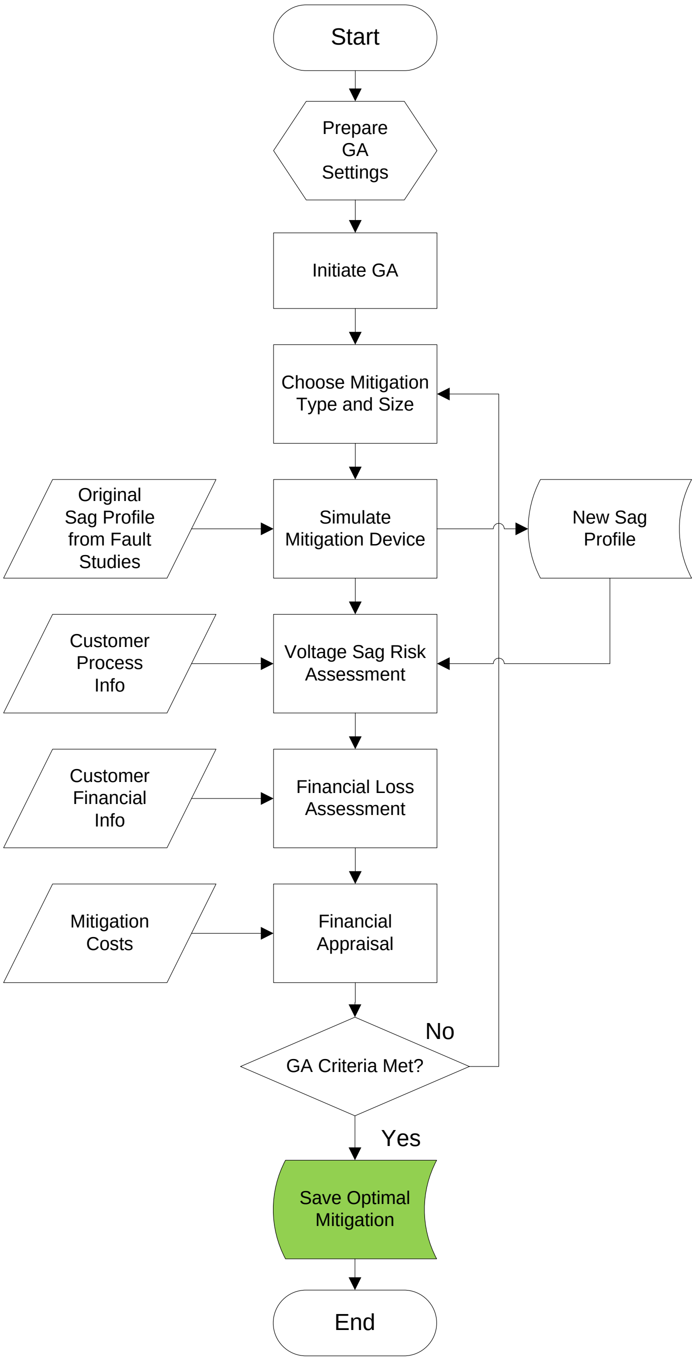


Figure 7-15 Optimal mitigation device assessment flow chart

Table 7-14 Summary of optimal power injecting device assessment

Assessment	Number of Customer Types Assessed	48
	Number of Locations Assessed	9
	Total Number of Assessments	432
GA Search for each Assessment	Number of Generations per Assessment	10
	Population Size	10
	Possible Solutions	64
	Searched Solutions	100
	Search Space (%)	156
	Simulation Time per Assessment (minute)	49.6
	Total Simulation Time (hour)	357

Figure 7-16 and Figure 7-17 show the NPV for microprocessor-based plants and drive-based plant with optimal deployment of power injecting devices. It can be seen that post-mitigation financial loss (remaining losses + mitigation cost) is capped at around 1M£ for microprocessor-based processes and around 2M£ for drive-based processes over ten years.

For microprocessor-based processes, post-mitigation financial losses consist of large proportion of losses due to remaining sags. There are also some processes where no mitigation is selected. For drive-based processes, post-mitigation losses are mainly investment costs of mitigation, with only a handful of plants (plants 34 and 38) still suffering from significant sag induced losses. It should be noted that all financial values given are NPVs calculated using (6-28).

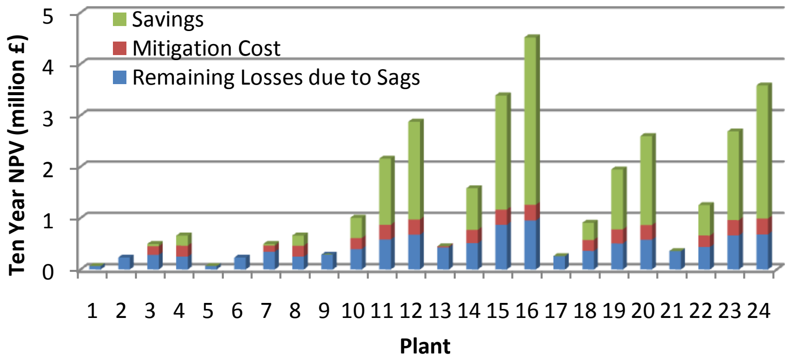


Figure 7-16 Ten year NPV for microprocessor-based processes with installation of power injecting device

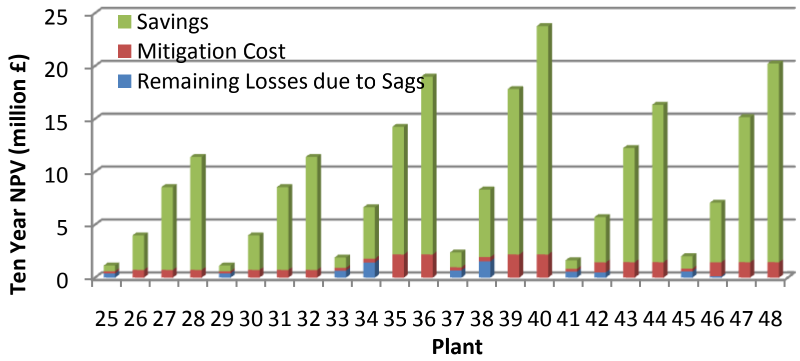


Figure 7-17 Ten year NPV for drive-based processes with installation of power injecting device

Figure 7-18 and Figure 7-19 show the optimal power injecting device for microprocessor-based and drive-based plants respectively. The pie chart in each cell represents the distribution of optimal device type at different plant locations. From the figures the following is evident:

1) Power injecting devices have no value for all microprocessor-based plants (Group 1 to 6) with low nominal loss value (30£), or moderate nominal loss per sag (105k) with high process immunity.

2) For microprocessor-based plants where savings are achievable, DVR with real and reactive power compensation is often the optimal device except in some locations for Group 4 (low immunity, high interdependence) plants where DVR with reactive power compensation is preferred.

3) For ASD-based plants (Group 7 to 12) with low nominal loss per sag (30k£), the best device is either DVR with full compensation or DVR with reactive power compensation depending on plant location.

4) For moderate nominal loss (105k£) plants, optimal device depends on process immunity and interdependence levels.

5) At higher nominal loss values (225k£ and above), flywheel is the most valuable mitigation device for voltage sag mitigation.

Table 7-15 Description of process groups

Group	Equipment Type	Process Immunity	Interdependence
1	microprocessor	High	Low
2	microprocessor	High	High
3	microprocessor	Low	Low
4	microprocessor	Low	High
5	microprocessor	Moderate	Low
6	microprocessor	Moderate	High
7	drives and contactors	High	Low
8	drives and contactors	High	High
9	drives and contactors	Low	Low
10	drives and contactors	Low	High
11	drives and contactors	Moderate	Low
12	drives and contactors	Moderate	High

Figure 7-20 shows the difference in the average value of power injecting devices for all 48 plants located at different network locations. The difference in value can be as high as 40% for microprocessor-based plant and 29% for drive-based plants. Difference in value for both plant types is consistent with the difference in value (relative to average) for initial plant losses.

The value of mitigation is calculated using (7-6).

$$Value\ of\ Mitigation = \frac{Savings}{Initial\ Loss} \times 100 = \left(1 - \frac{(Remaining\ Loss + Mitigation\ Cost)}{Initial\ Loss}\right) \times 100 \quad (7\text{-}6)$$

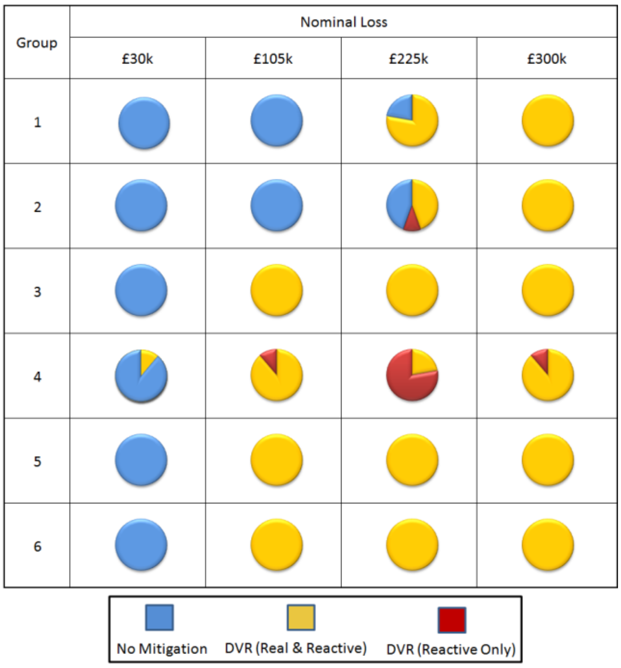


Figure 7-18 Optimal power injecting device for process Group 1 to 6

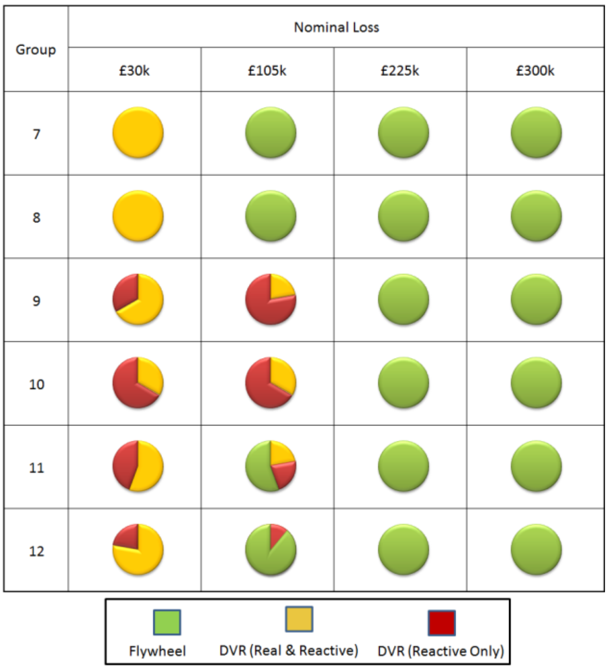


Figure 7-19 Optimal power injecting device for process Group 7 to 12

Figure 7-21 and Figure 7-22 show the value of power injecting devices to microprocessor-based and ASD-based plants respectively calculated using (7-6).

It can be seen that for both plant types, mitigation value increases with increase in plant nominal loss. The value of mitigation is significantly higher for drive-based plants compared to microprocessor-based plants. This is mainly due to the following two factors:

1) Higher base case losses of ASD-based plants open up a wider option for more effective but expensive devices.

2) Lower base case losses of microprocessor-based plants produces lower savings when the same cost of mitigation is applied in (7-6).

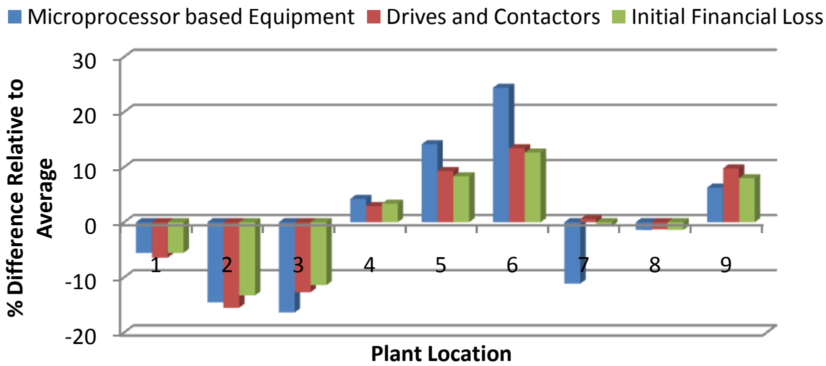


Figure 7-20 Influence of plant location on the value of power injecting device

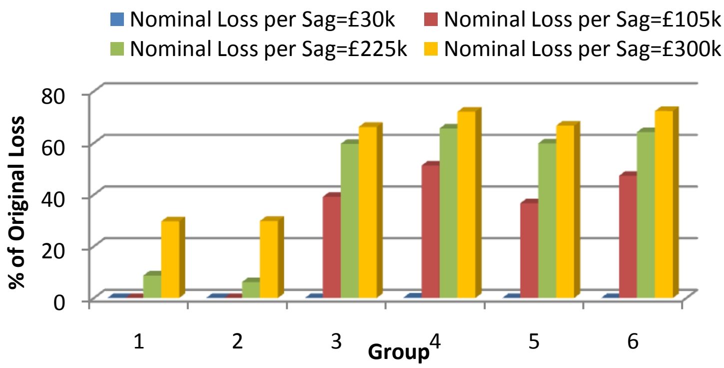


Figure 7-21 Financial value of power injecting device for process Group 1 to 6

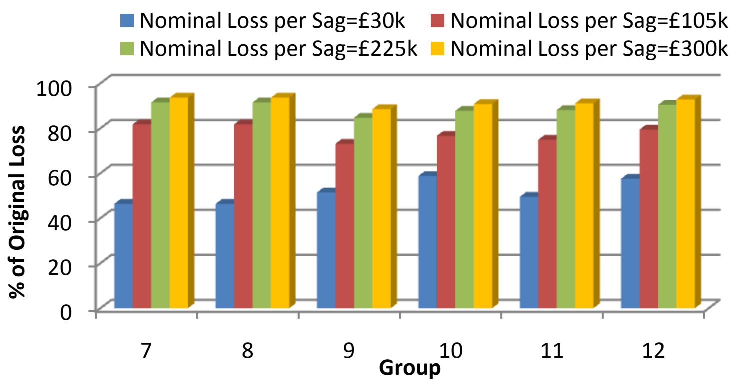


Figure 7-22 Financial value of power injecting device for process Group7 to 12

Figure 7-23 shows the sensitivity of the value of power injecting devices to process immunity. The values shown are average values of all 48 plants in all 9 locations. There is a 378% leap in average value from high immunity processes to moderate immunity processes for microprocessor-based plant. This is due to the leap in base case financial losses (see Figure 7-8) when process immunity changes. The difference between moderate immunity and low immunity processes is negligible.

The value of power injecting devices for ASD-based plants is not sensitive to the immunity level of their processes.

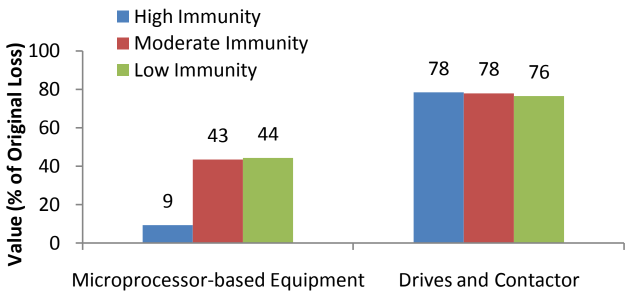


Figure 7-23 Value of power injecting device for different process immunity levels

Figure 7-24 shows the sensitivity of the value of power injecting device to the interdependence level of processes. Average increase in value of 10% and 4% are achievable for higher interdependence plants.

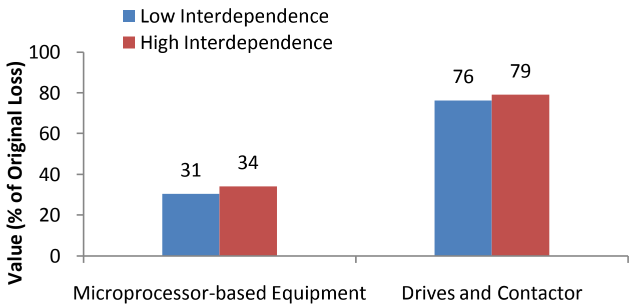


Figure 7-24 Value of power injecting device for different process interdependence levels

The frequency of network faults increases the number of process trips and consequently the customer financial loss. This affects the value of mitigation and thus requires sensitivity assessment. Figure 7-25 shows the change in mitigation value for Plant 40 at location 9 for different network fault rates. With base case losses of £26M over ten years, the optimal device for all fault rates remains to be flywheel. As there is no remaining loss after mitigation, all post-mitigation costs are due to investment in mitigation. For this plant, there is a linear relationship between the value of power injecting devices and network fault rate with 262k£ or 1.1% increase/decrease in value per 1% increase/decrease in fault rates.

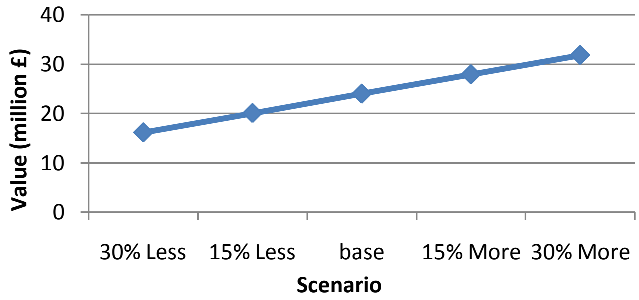


Figure 7-25 Sensitivity of the value of power injecting devices to network fault rates

A larger plant requires devices with higher ratings and more stored energy to restore lost energy during sag. Therefore, the cost of power injecting devices is also dependent on the size of the plant. Figure 7-26 shows the change in mitigation value for Plant 40 at location 9 for different plant size. The value of power injecting devices is found to be inversely proportional to the mitigated plant size. The relationship is linear with 3% decrease/increase in value per 1MW increase/decrease in plant size.

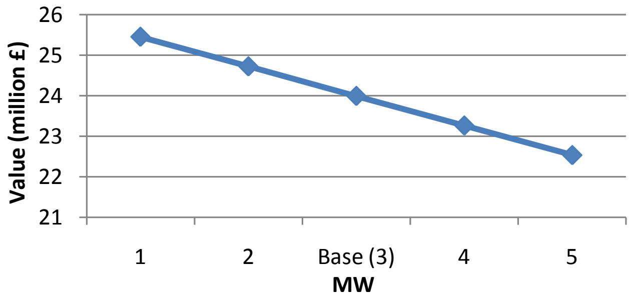


Figure 7-26 Sensitivity of the value of power injecting devices to customer plant size

Based on regression of the assessment results using the least square method in MS Excel, the correlation between the value of power injecting devices and initial plant losses is obtained. As shown in Figure 7-27, the relationship can be represented by a logarithmic function with a high goodness of fit (R^2 close to 1). It should be noted that the regression model should only be used for initial plant loss of up to 2.9M£ as higher plant losses produce values of mitigation of more than 100%, which is practically impossible.

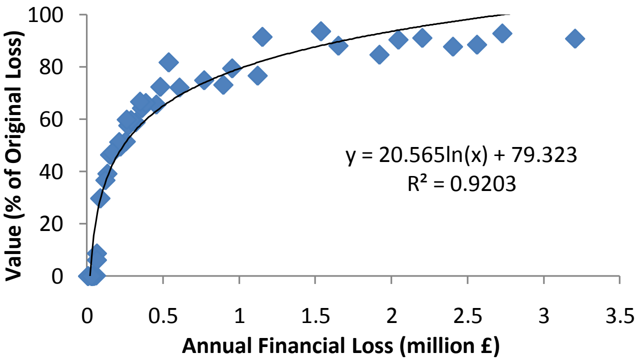


Figure 7-27 Correlation between initial plant loss and the value of power injecting device

7.5.3 Redundant Supply with Static Transfer Switch

Figure 7-28 shows detailed procedure for determining the optimal redundant supply for backup feeder connection. A trial and error approach is used where all potential backup supplies are tested one by one for cost effectiveness. Mitigation costs are calculated based on the method described in Section 6.2. Upgrade cost (refer to (6-26)) will only be incurred if power flows in lines and transformers exceed the original flows by 20% during switch operation when the full load is supplied by the backup feeder.

Optimal connection of backup supplies to customer plants results in ten year plant financial NPV as shown in Figure 7-29 and Figure 7-30. Results indicate that redundant feeders operated by static transfer switches have no value at all for microprocessor-based plants and have very little value for a handful of drive-based plants.

The low value of redundant supply is due to the following:

- High cost in building new lines to connect to backup supplies and upgrade costs (average line and upgrade cost /switch cost is 2.85 to 1). Upgrade costs are triggered when flow in lines increases to more than 20% of original flow.
- Limited difference in bus performance across the network (refer to Figure 7-11) results in limited savings.
- The possibility of connecting to an independent supply from other 132kV network was not explored.
- STS has no effect on sags originated from the transmission network.

For the plants where redundant supply produced savings, the value of mitigation differs at different plant locations. From Figure 7-31, the difference in value could reach 200% (compared to average). This difference is due to the difference in initial sag performance at the locations, and the availability of a better performing busbar in its vicinity. Section 7.4.5 has established that plants at locations 1, 2 and 3 have better performance (lowest financial loss). Mitigation values are also seen to follow the trend of initial financial loss as shown in Figure 7-31.

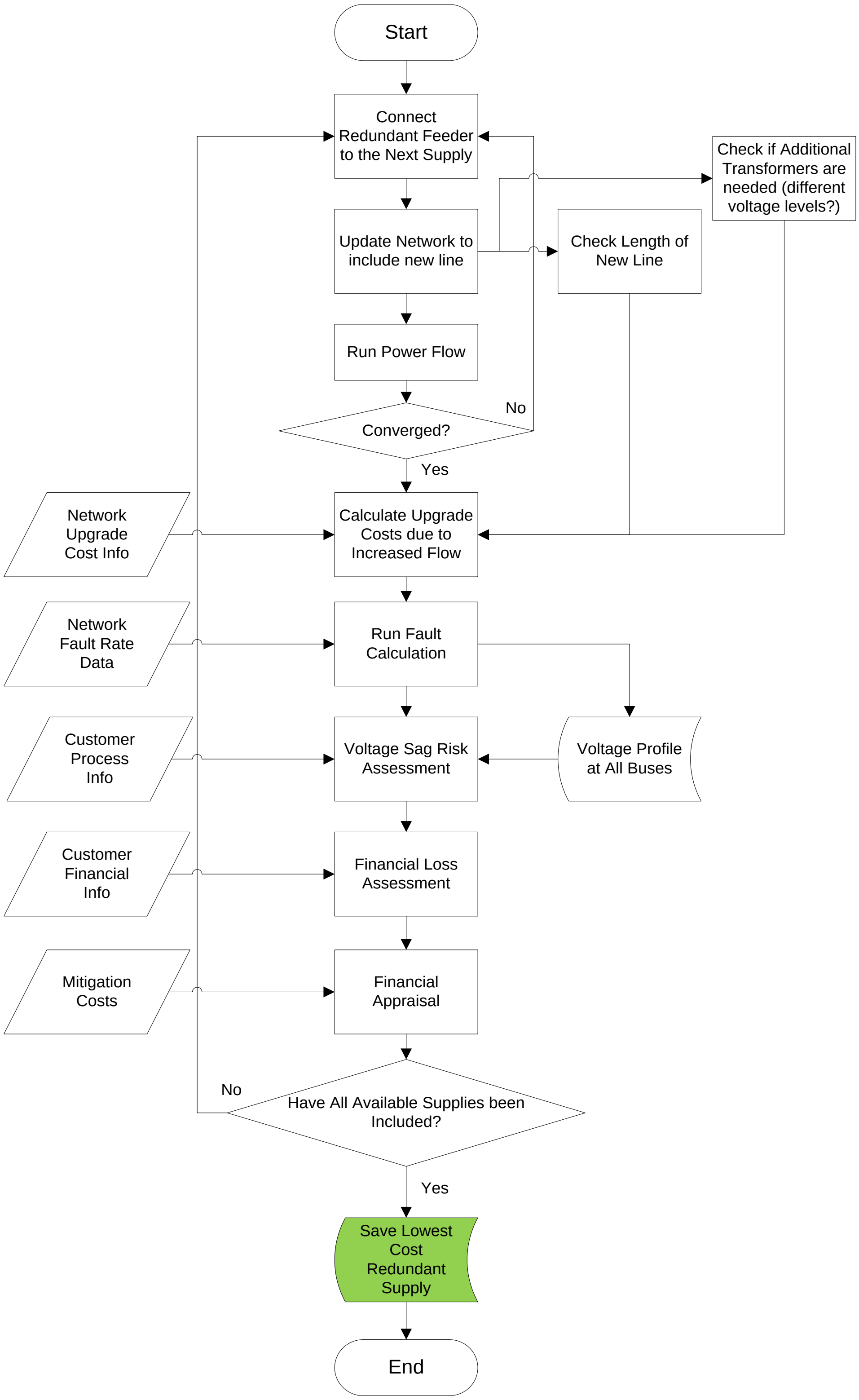


Figure 7-28 Optimal redundant supply assessment flow chart

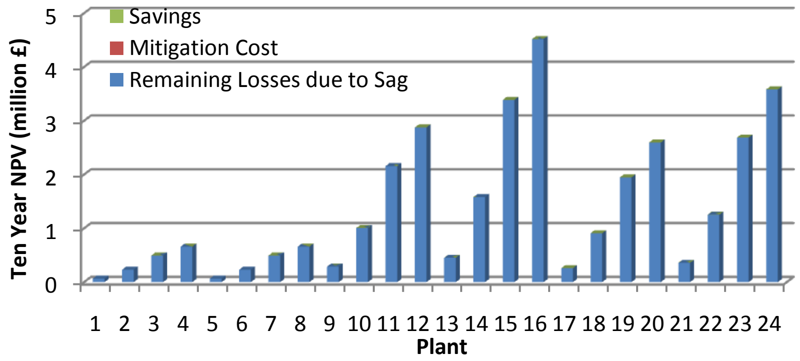


Figure 7-29 Ten year NPV for microprocessor-based processes with redundant supply

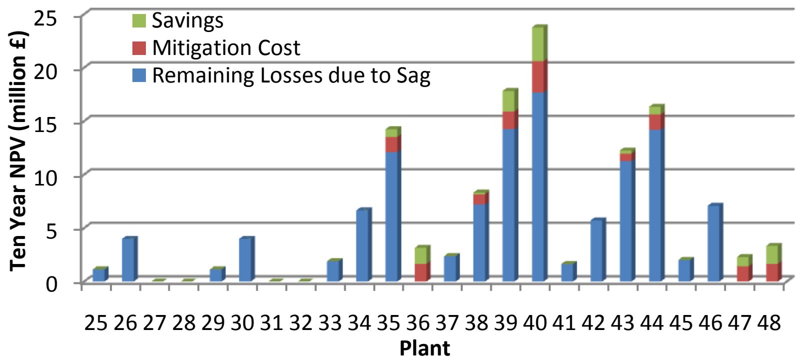


Figure 7-30 Ten year NPV for drive-based processes with redundant supply

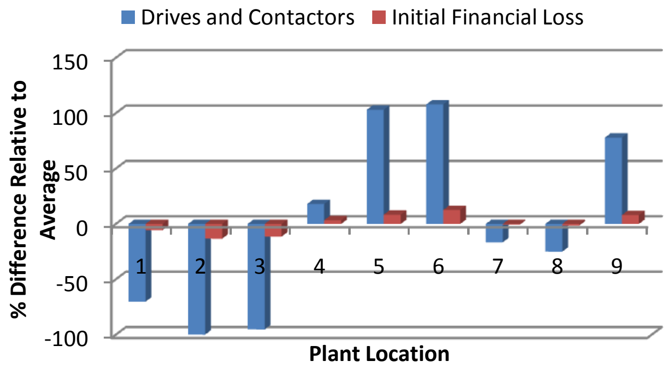


Figure 7-31 Influence of plant location to the value of redundant supply

The influence of plant nominal loss on the value of redundant supply is shown in Figure 7-32. A leap in value is seen for plants 9 to 12 when plant nominal loss increases from £105k to £225k.

Figure 7-33 and Figure 7-34 show respectively the influence of process immunity and interdependence level to the value of redundant supply. The values shown are average values of all 48 plants of all 9 locations. It is found that redundant supply has no value at all for plants with high immunity processes, and very low value for all other immunity or interdependence levels.

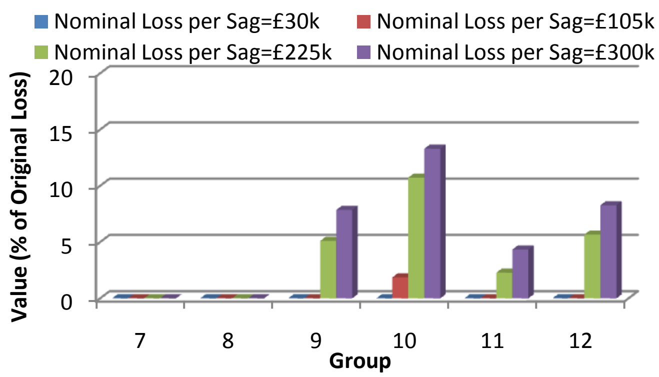


Figure 7-32 Financial value of redundant supply for process Group7 to 12

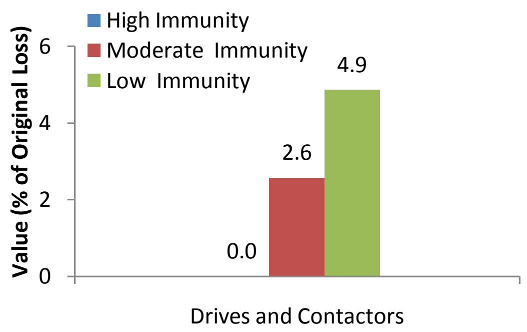


Figure 7-33 Value of redundant supply for different process immunity levels

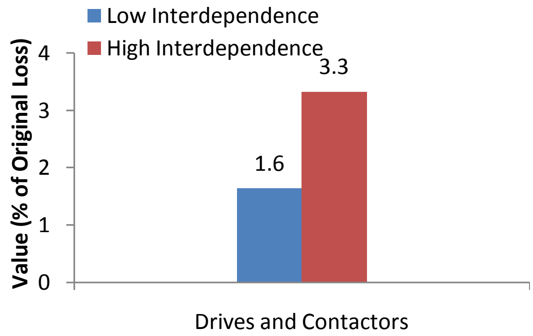


Figure 7-34 Value of redundant supply for different process independence levels

Figure 7-35 shows the change in mitigation value for Plant 40 at location 9 for different network fault rates. With base case losses of £26M over ten years, the value of redundant supply increases/decreases by 1.6% from the base scenario for every 1% increase/decrease in network fault rates.

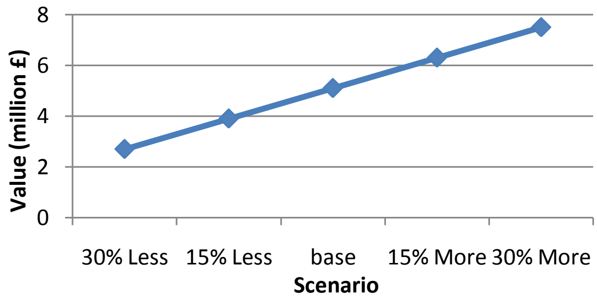


Figure 7-35 Sensitivity of the value of redundant supply to network fault rates

In terms of sensitivity to customer plant size, the value of redundant supply is found to be inversely proportionate to plant size, with around 8.2% decrease/increase in value per 1MW increase/decrease in plant size.

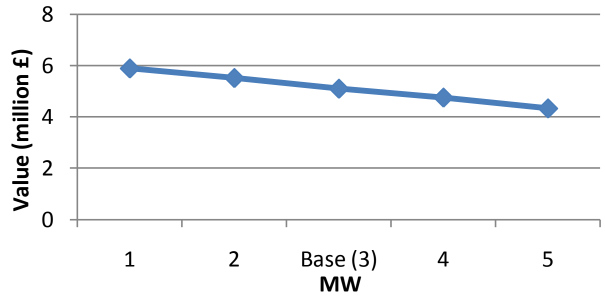


Figure 7-36 Sensitivity of the value of redundant supply to customer plant size

7.5.4 Reducing Frequency and Severity of Faults

As discussed in Chapter 6, the frequency of fault is reduced by reducing the fault rates in the network, while the severity of fault is reduced through reducing fault clearing time and through fault current limiting. Figure 7-37 shows the flow chart for determining the optimal feeders where mitigation devices are to be installed.

7.5.4.1 Mitigation Solutions

This section investigates the viability of individual solution in reducing financial loss. The main purposes for the assessments are to:

1. Determine the value of individual solution with limited investment (only 1, 3 and 5 feeders).
2. Determine the sensitivity of mitigation value to the cost and effectiveness of mitigation.
3. Determine the sensitivity of mitigation value to network fault rate.

4. Compare the value of different solutions.

A total of nine mitigation solutions are investigated to determine potential value to the customer plants. Assessments are conducted for four levels of investment; one mitigated feeder, three mitigated feeders, five mitigated feeders and the entire network. The first three levels considered all 48 customer plant types at all 9 network location. The fourth level of investment (entire network) considered one customer plant type (plant 40) at one network location (location 9) for sensitivity analysis purposes. Plant 40 is chosen due to its vulnerability to sags (low immunity, high interdependence processes) and high nominal loss, hence resulting in the highest value from most mitigation solutions. Table 7-16 summarizes the assessments considered in this section.

Table 7-16 Summary of assessment of optimal network mitigating solution

Assessment		Number of Customer Types Assessed	48
		Number of Locations Assessed	9
		Number of Mitigating Solutions Assessed	9
		Number of Scenarios Assessed	3
		Total Number of Assessments	11664
GA Search for each Assessment	Investment Level 1	Number of Generations per Assessment	20
		Population Size	15
		Possible Solutions	104
		Searched Solutions	300
		Search Space (%)	288
		Simulation Time per Assessment (minute)	4.7
		Total Simulation Time (hour)	302.4
	Investment Level 2	Number of Generations per Assessment	20
		Population Size	15
		Possible Solutions	$1.12*10^{6}$
		Searched Solutions	300
		Search Space (%)	0.03
		Simulation Time per Assessment (minute)	4.7
		Total Simulation Time (hour)	302.4
	Investment Level 3	Number of Generations per Assessment	25
		Population Size	100
		Possible Solutions	$1.22*10^{10}$
		Searched Solutions	2500
		Search Space (%)	$2.05*10^{-5}$
		Simulation Time per Assessment (minute)	40.6
		Total Simulation Time (hour)	2628
	Investment Level 4	Number of Generations per Assessment	100
		Population Size	75
		Possible Solutions	$2.03*10^{31}$
		Searched Solutions	7500
		Search Space (%)	$2.05*10^{-26}$
		Simulation Time per Assessment (minute)	120.9
		Total Simulation Time (hour)	815.9

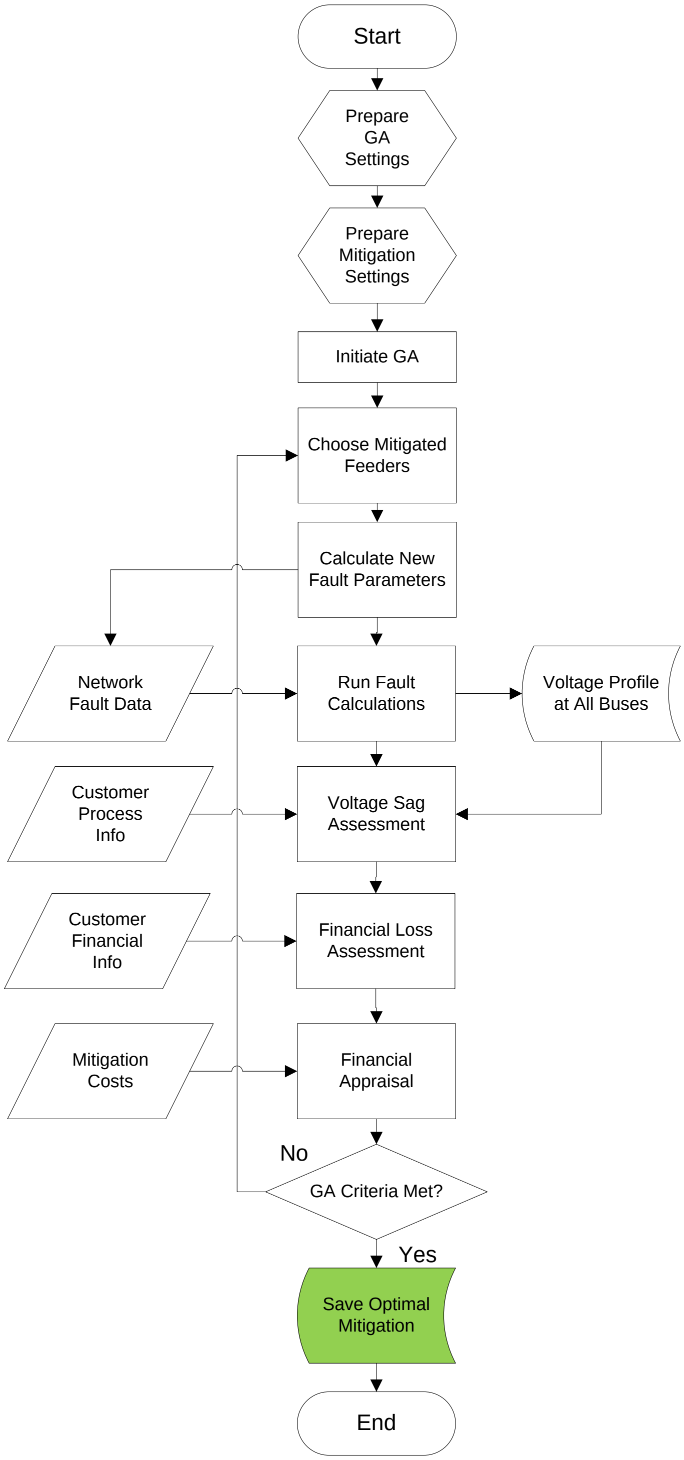


Figure 7-37 Flow chart for optimal reduction of fault frequency and severity

7.5.4.1.1 Insulating Lines

Figure 7-38 shows the value of insulating lines with different levels of investment. It is found that mitigation value increases with higher levels of investment. The mitigation value varies slightly across network locations with the highest values of 3%, 7% and 9% of original loss for 1, 3 and 5 mitigated plants achieved at Location 3.

Sensitivities of the value of insulating lines to mitigation cost and effectiveness are shown in Figure 7-39, while sensitivity to network fault rates are shown in Figure 7-40. It is found that the value of insulating lines is more sensitive to the mitigation cost compared to its effectiveness. The value increases/decreases with the increase/decrease in network fault rate. Value of insulating lines decreases to zero when network fault rate decreases by 30% or more.

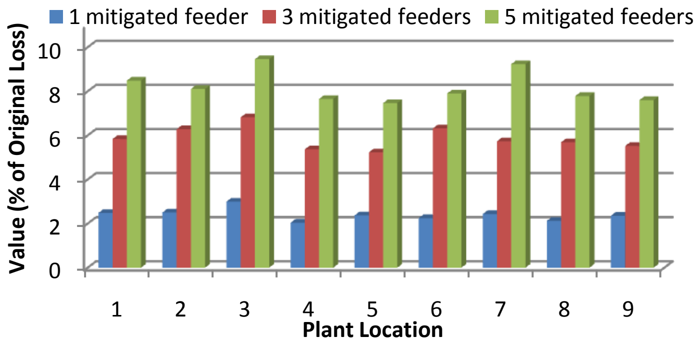


Figure 7-38 Value of insulating lines for various levels of investment

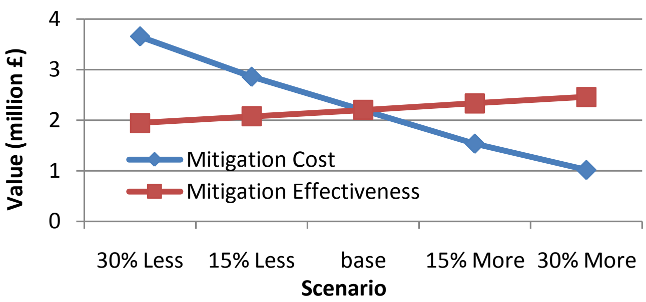


Figure 7-39 Sensitivity of the value of insulating lines to mitigation cost and effectiveness

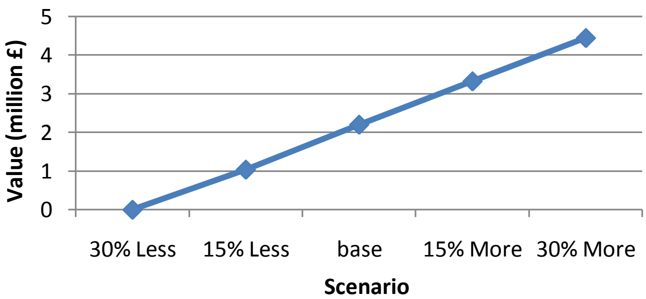


Figure 7-40 Sensitivity of the value of insulating lines to network fault rates

7.5.4.1.2 Tree Trimming

Figure 7-41 shows the value of tree trimming with different levels of investment. It is found that mitigation value increases with higher levels of investment. The mitigation value varies slightly across network locations with the highest values of 0.07%, 0.24% and 0.52% of original loss for 1, 3 and 5 mitigated plants achieved at different locations.

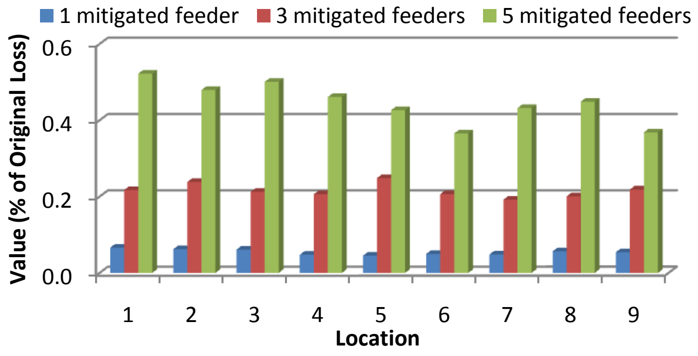


Figure 7-41 Value of tree trimming for various levels of investment

Sensitivities of the value of tree trimming to mitigation cost and effectiveness are shown in Figure 7-42, while sensitivity to network fault rates are shown in Figure 7-43. It is found that the value of insulating lines is more sensitive to the effectiveness of mitigation compared to its costs. The value increases/decreases with the increase/decrease in network fault rate. Value of tree trimming decreases to zero when its effectiveness decreases by 30% or network fault rates decrease by 15%.

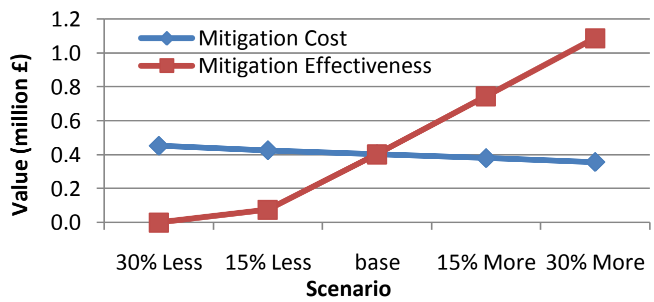


Figure 7-42 Sensitivity of the value of tree trimming to mitigation cost and effectiveness

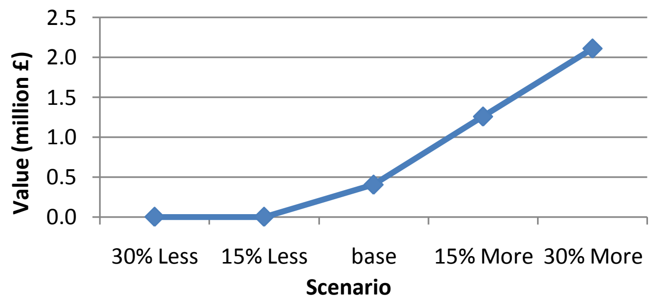


Figure 7-43 Sensitivity of the value of tree trimming to network fault rates

7.5.4.1.3 Undergrounding Lines

Undergrounding lines provides no saving at all for all the cases assessed. For Plant 40, no saving is achieved even though mitigation cost is reduced by 30%, or mitigation effectiveness improved by 30% (Figure 7-44). However, savings do pick up when network fault rates are increased, as shown in Figure 7-45.

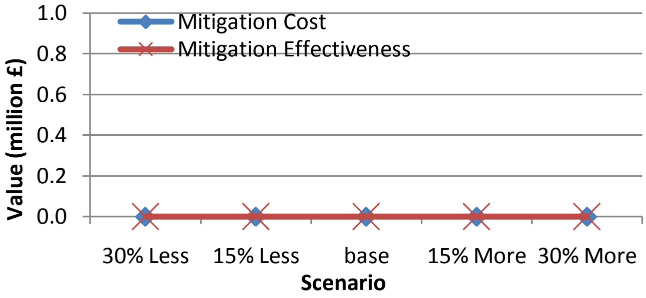


Figure 7-44 Sensitivity of the value of underground system to mitigation cost and effectiveness

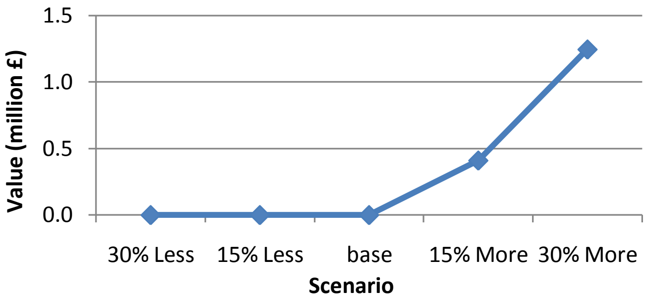


Figure 7-45 Sensitivity of the value of underground system to network fault rates

7.5.4.1.4 Surge Arresters

Figure 7-46 shows the value of surge arresters with different levels of investment. It is found that mitigation value increases with higher levels of investment. The mitigation value varies across network locations with the highest values of 0.5%, 1.4% and 2% of original loss for 1, 3 and 5 mitigated plants achieved at Location 3.

Sensitivities of the value of surge arrester to mitigation cost and effectiveness are shown in Figure 7-47, while sensitivity to network fault rates are shown in Figure 7-48. It is found that the value of surge arrester is more sensitive to the cost of mitigation compared to its effectiveness. The value increases/decreases with the increase/decrease in network fault rate. Value of surge arrester decreases to zero when its cost increases by 15% or when network fault rates decrease by 15%.

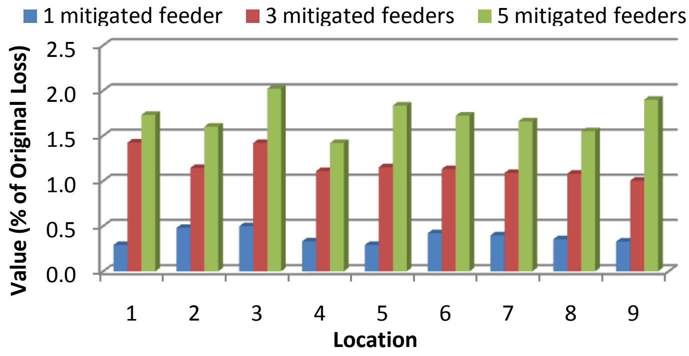


Figure 7-46 Value of surge arresters for various levels of investment

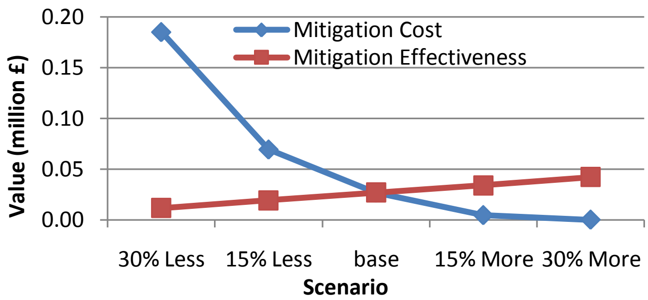


Figure 7-47 Sensitivity of the value of surge arresters to mitigation cost and effectiveness

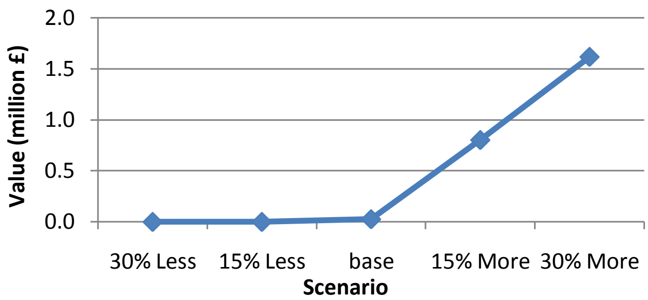


Figure 7-48 Sensitivity of the value of surge arresters to network fault rates

7.5.4.1.5 Animal Guards

For installation of animal guards, mitigation value also increases with higher levels of investment. As shown in Figure 7-49, the mitigation value varies across network locations with the highest values of 0.4%, 1.4% and 2.2% of original loss for 1, 3 and 5 mitigated plants achieved at Location 3 and Location 2.

Sensitivities of the value of animal guards to mitigation cost and effectiveness are shown in Figure 7-50, while sensitivity to network fault rates are shown in Figure 7-51. The value of animal guards is more sensitive to the effectiveness of mitigation compared to its costs. The value increases/decreases with the increase/decrease in network fault rate. Value of animal guards decreases to zero when network fault rates decrease by 30% or more.

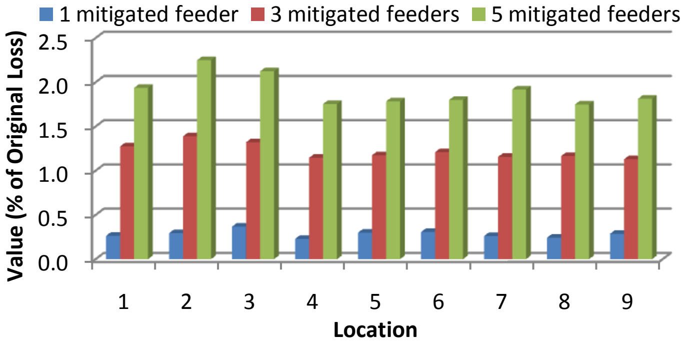


Figure 7-49 Value of animal guards for various levels of investment

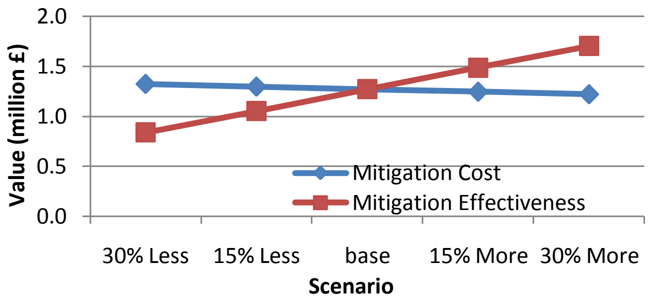


Figure 7-50 Sensitivity of the value of animal guards to mitigation cost and effectiveness

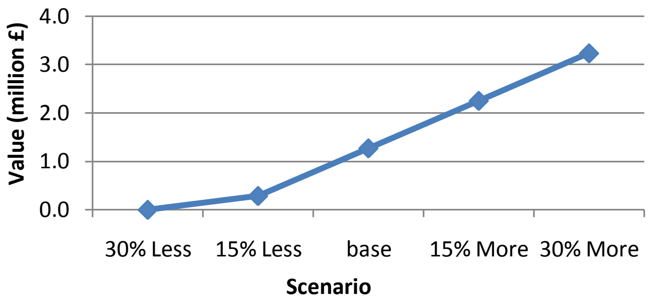


Figure 7-51 Sensitivity of the value of animal guards to network fault rates

7.5.4.1.6 Shield Wire

Installation of shield wires provides no savings at all when only one feeder is mitigated. It provides minimal savings for some plants when three and five feeders are mitigated. From Figure 7-52 The value of mitigation peaked at less than 0.04%.

For Plant 40, no saving is achieved even though mitigation cost is reduced by 30%, or mitigation effectiveness improved by 30% (Figure 7-53). However, savings do pick up when network fault rates are increased from the base rate, as shown in Figure 7-54.

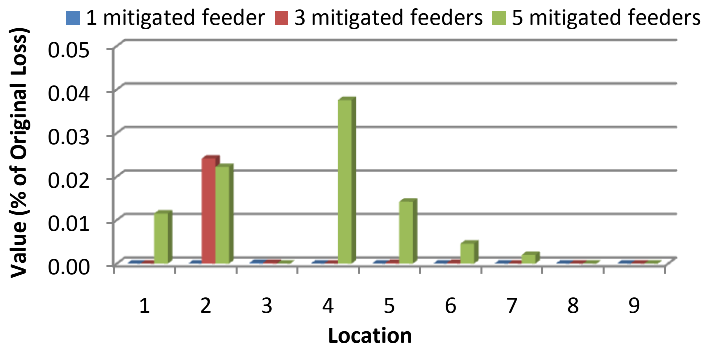


Figure 7-52 Value of shield wires for various levels of investment

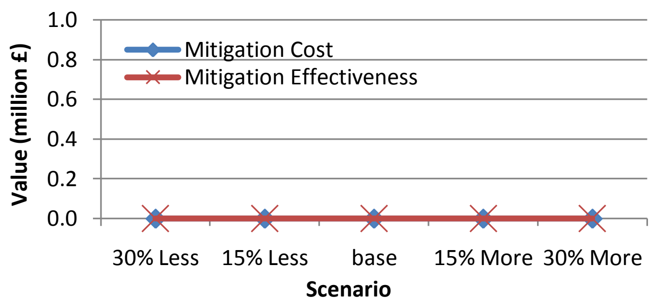


Figure 7-53 Sensitivity of the value of shield wires to mitigation cost and effectiveness

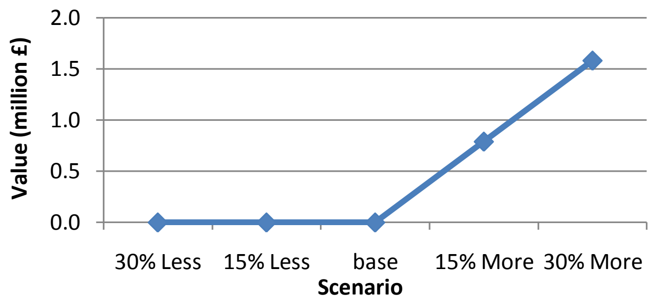


Figure 7-54 Sensitivity of the value shield wires to network fault rates

7.5.4.1.7 Communication System

Investment in communication system that reduces accidental dig-ins on cables produced results as shown in Figure 7-55. The value of such a system is found to increase with higher levels of investment. However, the value varies significantly across the network due to the non-uniform distribution of cables in the network. The value peaked at Location 5 with values of 0.04%, 0.15% and 0.2% of original loss for 1, 3 and 5 mitigated plants.

Sensitivities of the value of communication system to mitigation cost and effectiveness are shown in Figure 7-56, while sensitivity to network fault rates are shown in Figure 7-57. The value of mitigation is more sensitive to changes in effectiveness compared to changes in costs. The value increases/decreases with the increase/decrease in network fault rate. Value of mitigation decreases to zero when network fault rates decrease by 15% or more.

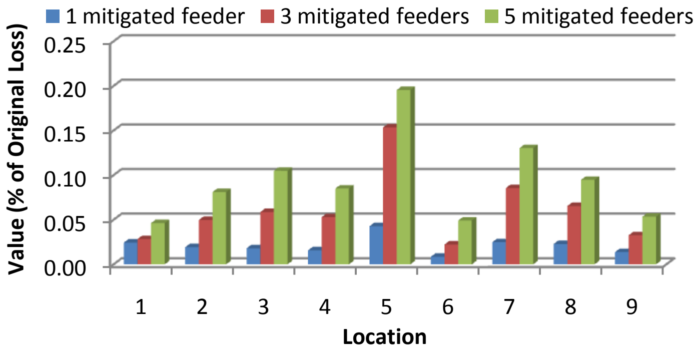


Figure 7-55 Value of communication system for various levels of investment

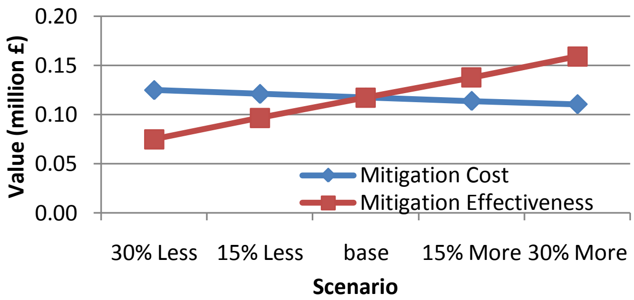


Figure 7-56 Sensitivity of the value of communication system to mitigation cost and effectiveness

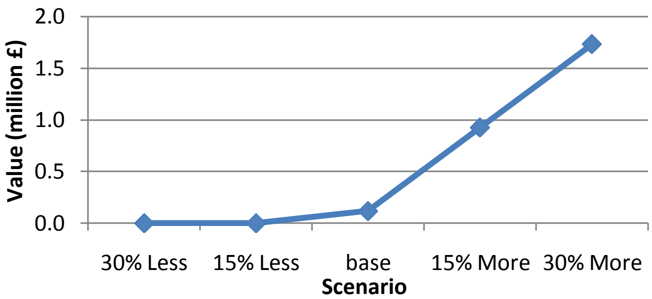


Figure 7-57 Sensitivity of the value of communication system to network fault rates

7.5.4.1.8 Fault Clearing Time

Reducing fault clearing times at selected breakers in the network reduces duration severity of sags at surrounding feeders. The savings produced with low levels of investment are shown in Figure 7-58. The value increases with higher levels of investment. Savings vary significantly across different locations in the network due to the dependency of such mitigation to the characteristics (length, number of connected feeders) of the local network. The value peaked at Location 2 with values of 0.21%, 1.13% and 2.15% of original loss for 1, 3 and 5 mitigated plants.

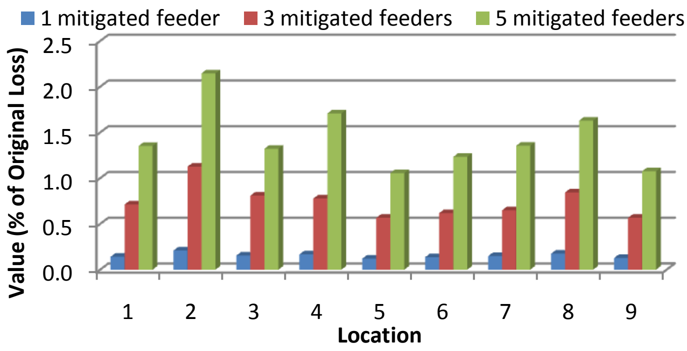


Figure 7-58 Value of reducing fault clearing time for various levels of investment

Sensitivities of the value of mitigation to mitigation cost and effectiveness for Plant 40 at Location 9 are shown in Figure 7-59, while sensitivity to network fault rates are shown in Figure 7-60. With zero value at base case cost and effectiveness, the value of mitigation picks up when effectiveness of mitigation is improved. The value of mitigation also increases with increase in network fault rates, from zero value to more than £1.5M over ten years when network fault rates increase by 30%.

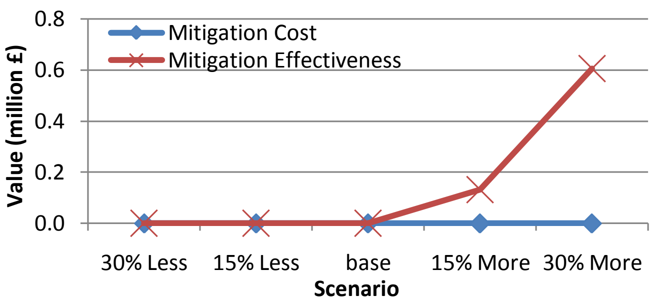


Figure 7-59 Sensitivity of the value of reducing fault clearing time to mitigation cost and effectiveness

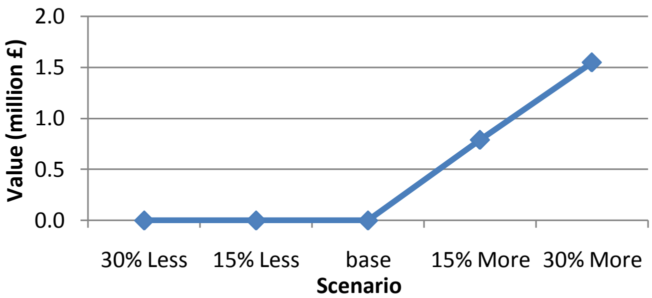


Figure 7-60 Sensitivity of the value of reducing fault clearing time to network fault rates

7.5.4.1.9 Fault Current Limiting

Installation of fault current limiters at selected feeders in the network reduces magnitude severity of sags at surrounding feeders. The savings produced with low levels of investment are shown in Figure 7-61. It is found that significant (up to 14%) savings are achieved with low levels of investment. The value increases with higher levels of investment. Savings vary across different locations in the network, also due to the dependency of such mitigation to the characteristics (length, number of connected feeders, system impedances) of the local network. The value peaked at different locations with values of 6.6%, 12% and 13.9% of original loss for 1, 3 and 5 mitigated plants.

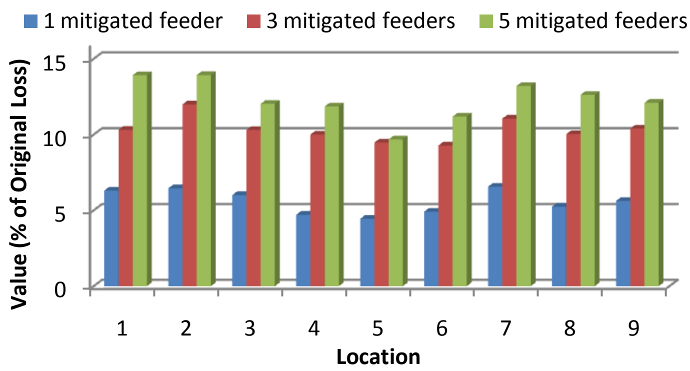


Figure 7-61 Value of fault current limiting for various levels of investment

Sensitivities of the value of mitigation to mitigation cost and effectiveness for Plant 40 at Location 9 are shown in Figure 7-62, while sensitivity to network fault rates are shown in Figure 7-63. The value of mitigation is very sensitive to the effectiveness of mitigation at effectiveness levels lower than the base case. The value of mitigation is also very sensitive to changes in network fault rates, with 1.7% increase/decrease in value for every 1% increase/decrease in network fault rates.

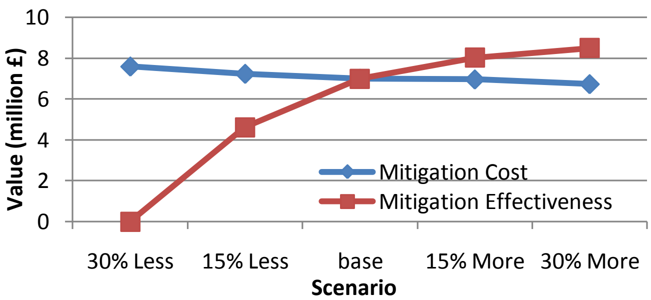


Figure 7-62 Sensitivity of the value of fault current limiting to mitigation cost and effectiveness

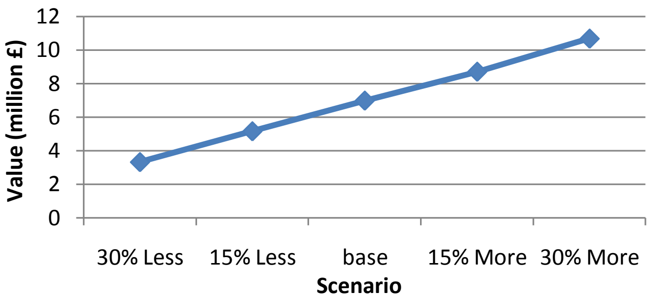


Figure 7-63 Sensitivity of the value of fault current limiting to network fault rates

7.5.4.1.10 Comparison Between Solutions

The average values of mitigating five feeders in the network are given in Figure 7-64. Considering assessment of all plant types at all locations, fault current limiting produces the highest savings in financial losses at an average value of 12%, followed by insulation of overhead lines, which produces average savings of 8%. All other solutions have values of less than 2% of original losses.

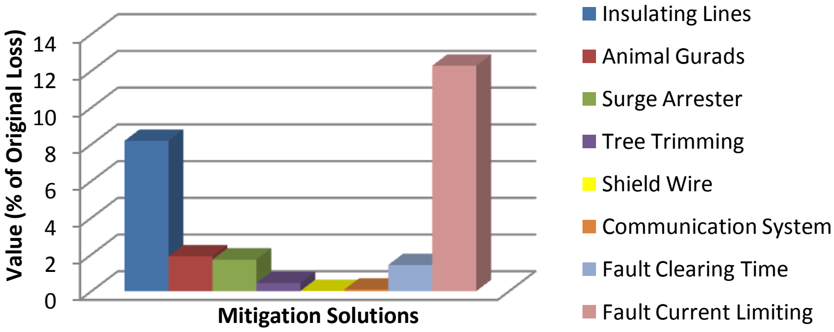


Figure 7-64 Comparison of mitigation value with five mitigation feeders

7.5.4.2 Optimal Solution Mix

This section investigates the potential value of network level sag mitigation with unlimited investment using all network level solutions discussed. It represents the maximum achievable savings with network level mitigation. The same procedure (see flow chart in Figure 7-37) is used for assessment as before. Mitigation solutions can be placed in all of the 104 branches in the network. However, in order to limit the already gigantic number of possible solutions, it is decided in this case study that only one solution can be assigned to each mitigated feeder. The assessed cases and simulation details are summarized in Table 7-17.

Table 7-17Summary of optimal network solution mix assessment

Assessment	Number of Customer Types Assessed	48
	Number of Locations Assessed	9
	Total Number of Assessments	432
GA Search for each Assessment	Number of Generations per Assessment	100
	Population Size	100
	Possible Solutions	$1*10^{104}$
	Searched Solutions	10000
	Search Space (%)	$1*10^{-98}$
	Simulation Time per Assessment (minute)	480
	Total Simulation Time (hour)	3456

Figure 7-65 and Figure 7-66 show the NPV for microprocessor-based plants and ASD-based plant with optimal network level mitigation. It can be seen that very low savings are achieved for microprocessor-based plant, while most drive-based plants returned modest savings. Significant savings are only seen at plants with high (>£3M) initial loss. For plants with lower initial loss, there is either no or negligible savings offered by network level solutions. It should be noted that network level mitigation solutions have no effect on sags originated in the transmission network.

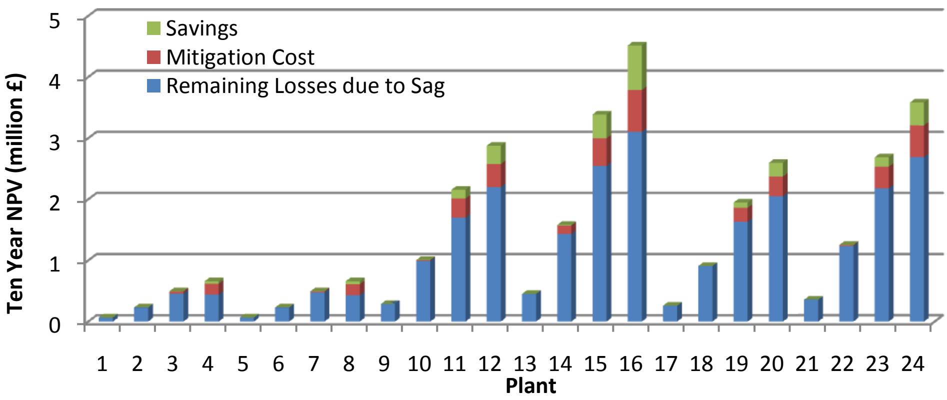


Figure 7-65 Ten year NPV for microprocessor-based processes with optimal network fault reduction

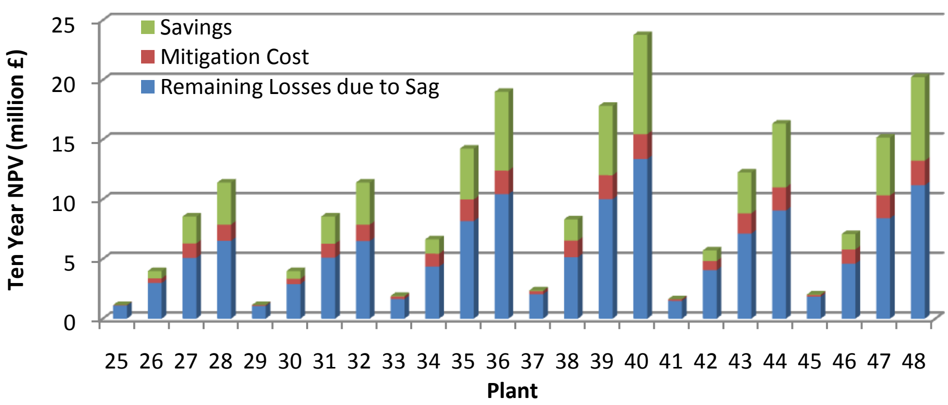


Figure 7-66 Ten year NPV for drive-based processes with optimal network fault reduction

Figure 7-67 and Figure 7-68 show the optimal mix of solutions for all plant types at Location 1 and Location 6. Results for these two locations are presented as they are located at very different parts of the network (see Figure 7-1). It can be seen from these figures that:

1. The most frequently used mitigating solutions are installation of animal guards, tree trimming, insulating overhead lines and communication system.
2. Higher costs solutions such as insulation of overhead lines are more suitable for protection of ASD-based processes (Plant 25 to 48) justified by the higher financial loss of such processes.
3. The optimal level of protection for the same plant at different location varies. The difference could be very significant for some plants (e.g. Plant 3, 10, 22, 41, 45).
4. For plants where mitigation is deployed, the level of protection is always very high (covers more than 30% of network) in order to obtain optimal savings.
5. The types of solutions used for the same plants at different location are generally the same but at different proportions.

Figure 7-69 and Figure 7-70 show the investment profile for optimal network level investment at Location 1 and Location 6. The investment profile shows the total money (% of original losses) invested into different mitigation solutions to obtain maximum savings (also shown in the figures). The following observations can be made:

1. The dominant solutions (most investment) for microprocessor-based plants (Plant 1 to 24) are fault current limiting and fault clearing time reduction.
2. The dominant solutions for ASD-based plants (Plant 25 to 48) are insulation of overhead lines and fault current limiting.
3. For microprocessor-based plants, mitigation costs are generally higher than the savings achieved (benefit/cost ratio less than 1).
4. For ASD-based plants, mitigation costs are generally lower than the savings achieved (benefit/cost ratio more than 1), with some exceptions (Plant 33, 37, 41).
5. Comparing Figure 7-67 and Figure 7-69, the investment profile is very different from the protection profile, as low cost solutions such as animal

guards are spread across the system, with high cost solutions (insulating lines) focused in small but critical parts of the network.

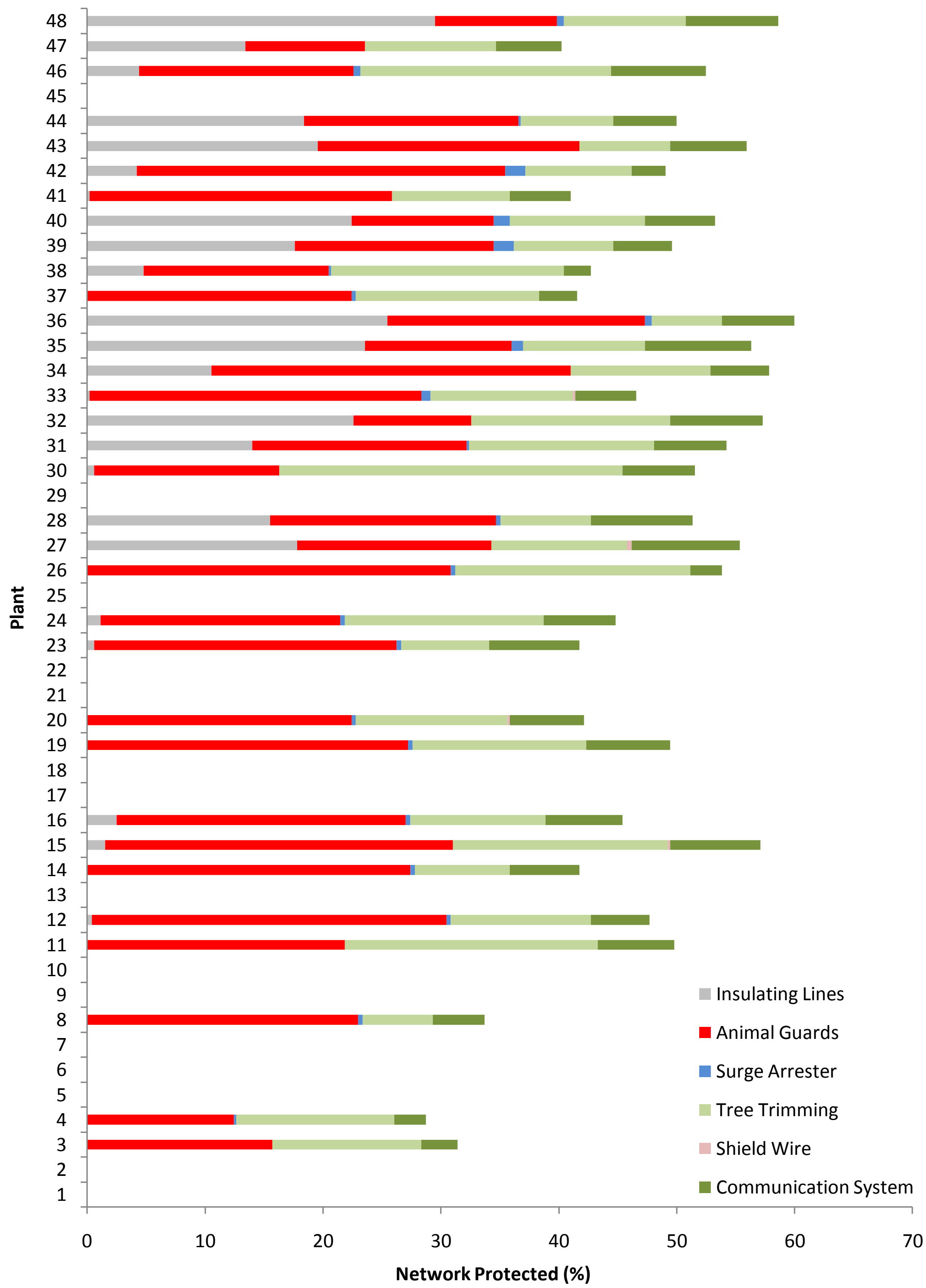


Figure 7-67 Solution mix for plants at Location 1 with optimal network fault reduction

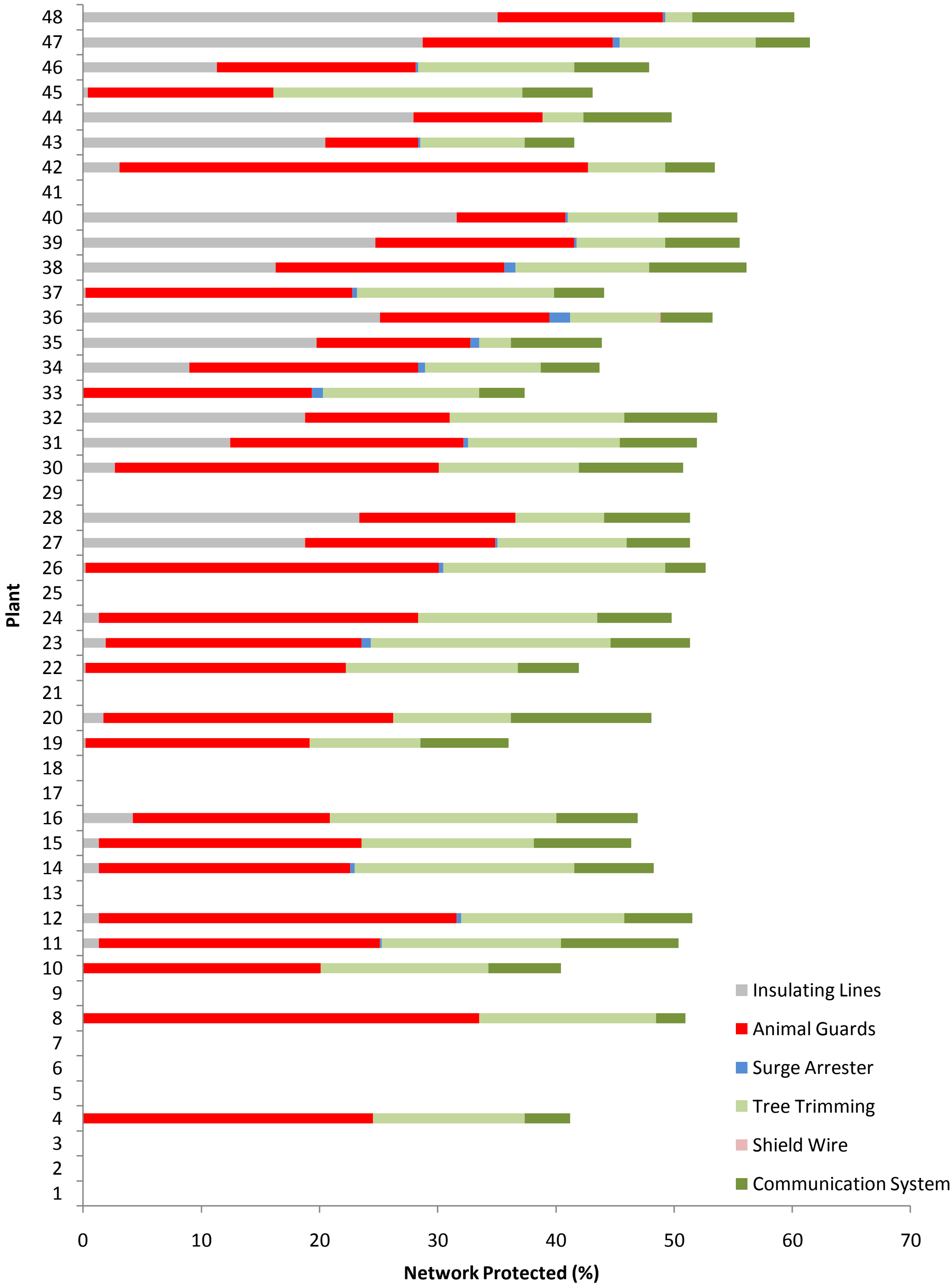


Figure 7-68 Solution mix for plants at Location 6 with optimal network fault reduction

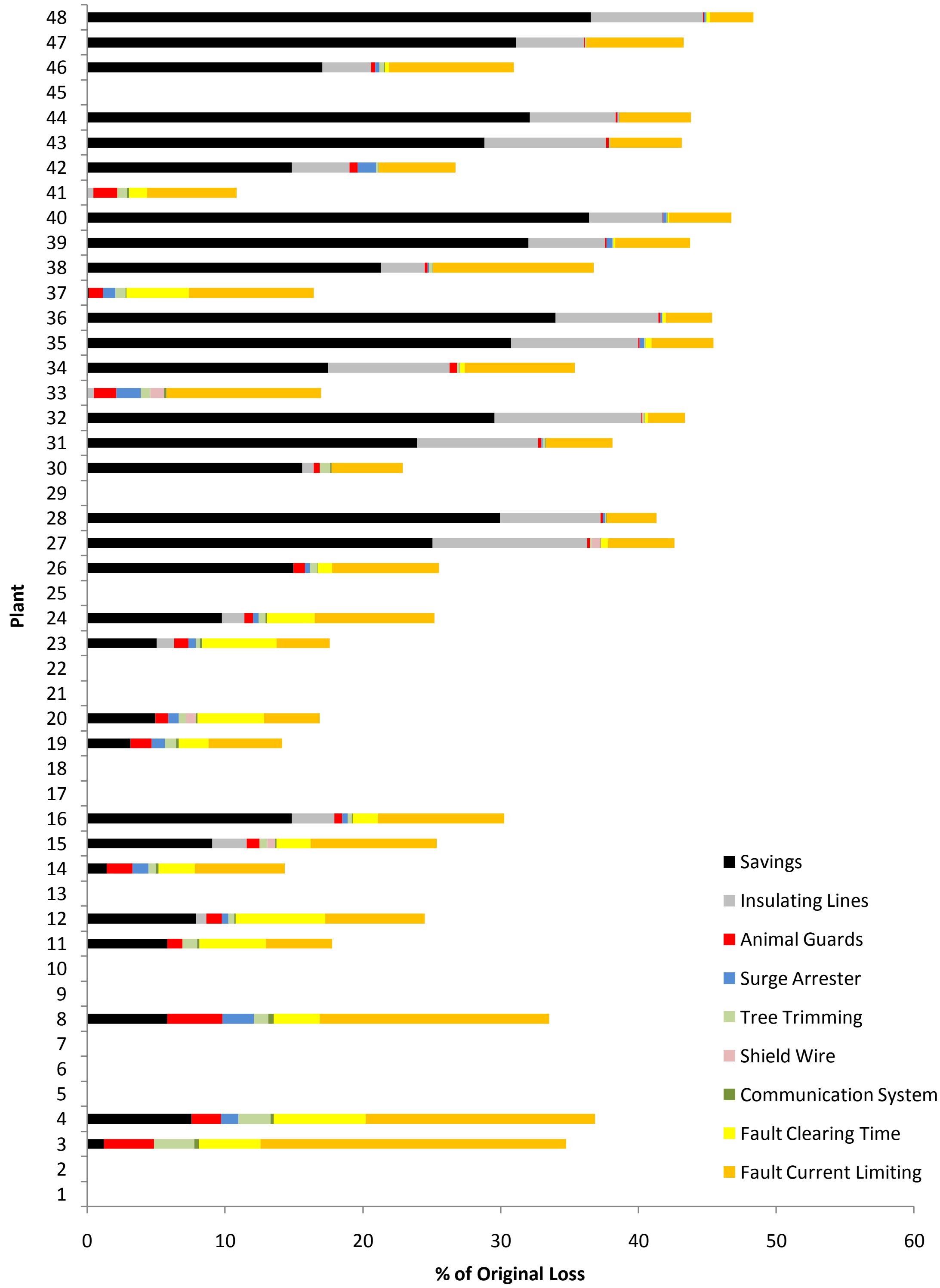


Figure 7-69 Investment profile for plants at Location 1 with optimal network fault reduction

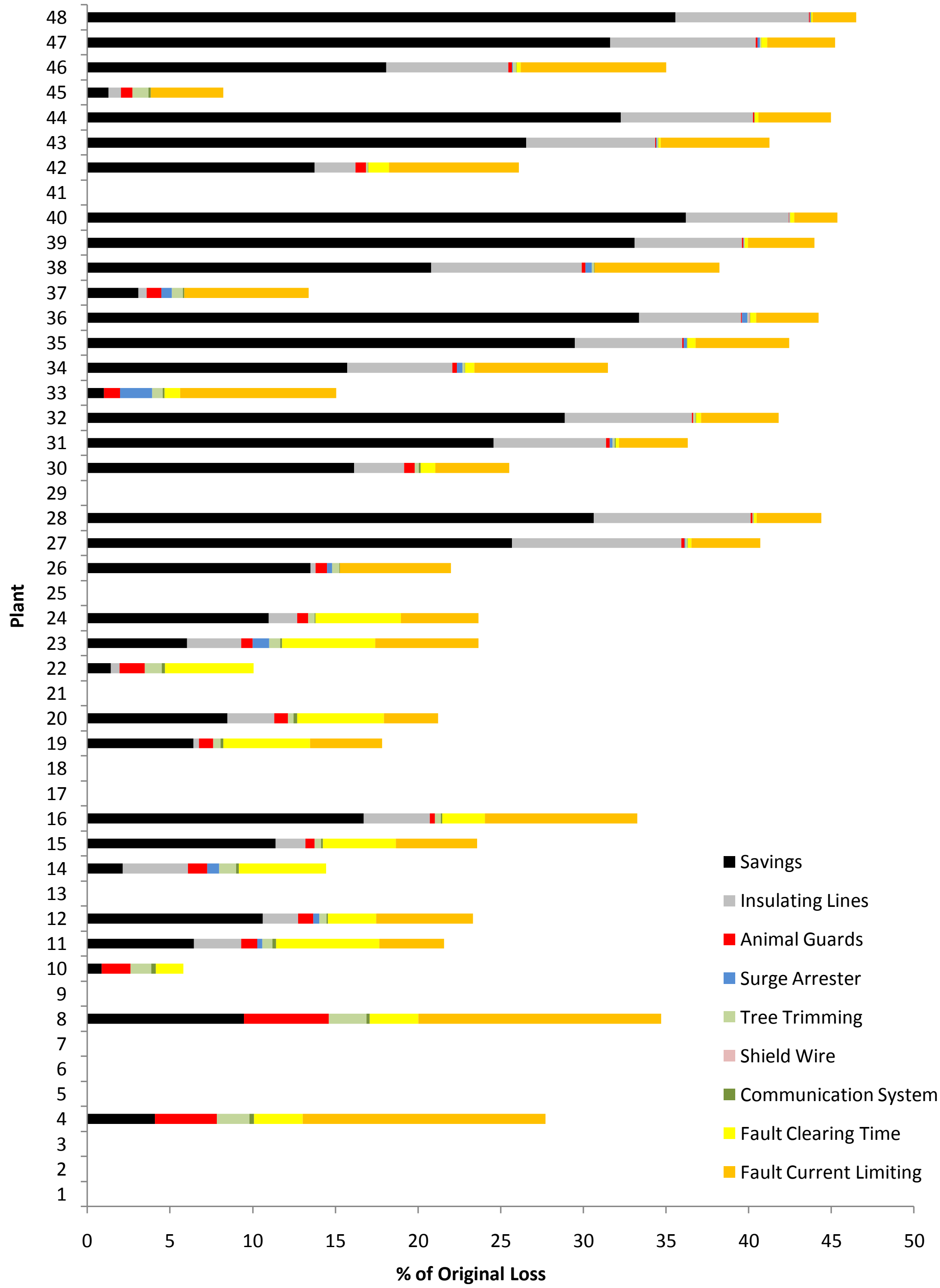


Figure 7-70 Investment profile for plants at Location 6 with optimal network fault reduction

Figure 7-71 shows the difference in the average value of optimal network mitigation for all 48 plants located at different network locations. The difference in value can be as high as 94% for microprocessor-based plant and 17% for ASD-based plants. The large difference in value is logical as the characteristics of the local network at different plant locations are very different.

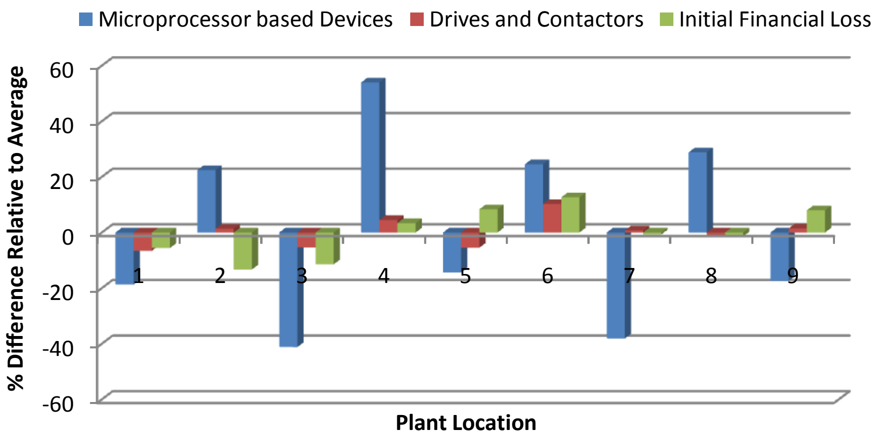


Figure 7-71 Influence of plant location to the value of optimal reduction of fault frequency and severity

Figure 7-72 and Figure 7-73 show the value of optimal network mitigation to microprocessor-based and ASD-based plants respectively. It can be seen that for both plant types, mitigation value generally increases with increase in plant nominal loss. The value of mitigation is significantly higher for ASD-based plants compared to microprocessor-based plants. This is because higher base case losses of ASD-based plants opened up a wider option for more effective but expensive solutions.

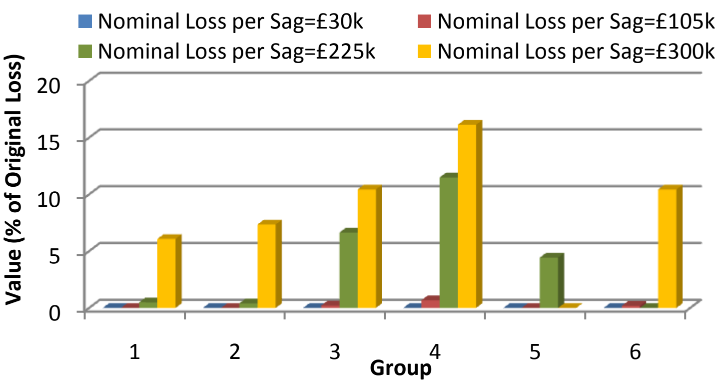


Figure 7-72 Financial value of optimal network fault reduction for process Group 1 to 6

Figure 7-74 shows the sensitivity of the value of optimal network mitigation to process immunity. The values shown are average values of all 48 plants in all 9 locations. There is a 200% leap in average value from moderate immunity processes to high immunity processes for microprocessor-based plant. The difference between moderate immunity and low immunity processes is negligible. The value of optimal network mitigation for ASD-based plants increases when immunity level decreases.

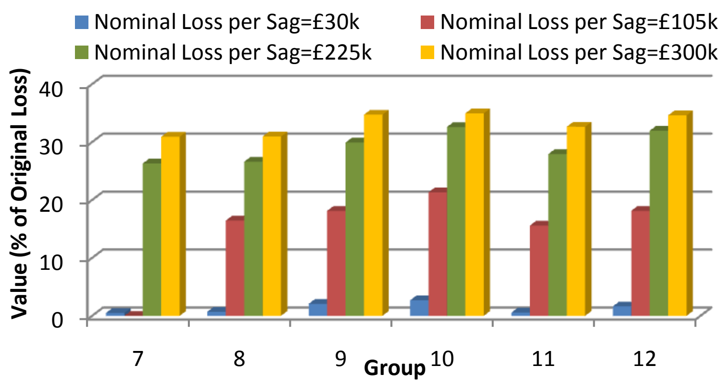


Figure 7-73 Financial value of optimal network fault reduction for process Group 7 to 12

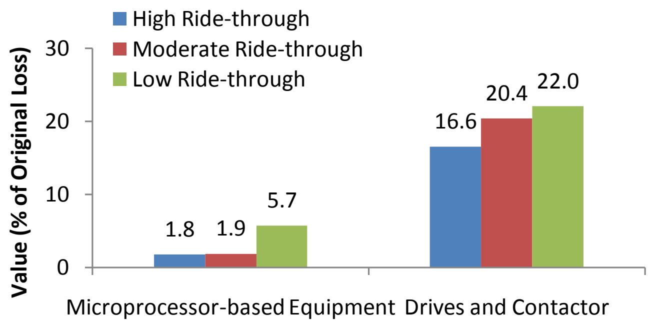


Figure 7-74 Value of optimal fault reduction for different process immunity levels

Figure 7-75 shows the sensitivity of the value of optimal network mitigation to the interdependence level of processes. Microprocessor-based plants are very sensitive to process interdependence levels with average increase in value of 63% from low to high interdependence level. Drive-based plants show a 15% increase for the higher interdependence level plants.

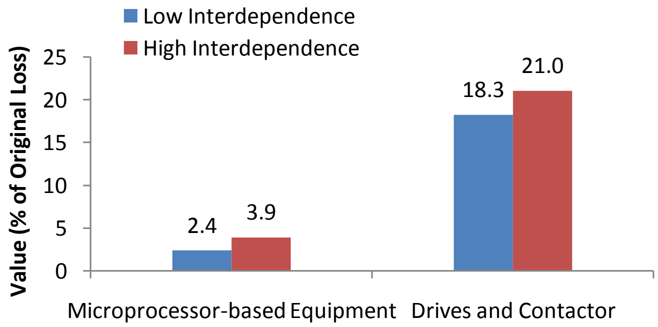


Figure 7-75 Value of optimal fault reduction for different process independence levels

Based on regression of the assessment results using the least square method in MS Excel, the correlation between the value of optimal network mitigation and initial plant losses is obtained. As shown in Figure 7-76, the relationship can be represented by a quadratic function with a very high goodness of fit (R^2 close to 1). The regression model is logical for annual plant loss of up to 2.7M£ before the quadratic function reaches its maximum value.

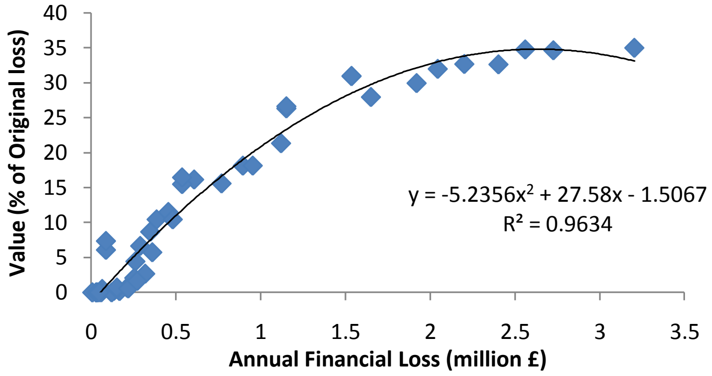


Figure 7-76 Correlation between initial plant loss and the value of optimal fault reduction

7.5.4.3 Multiple Participants

Although the value of optimal network mitigation is significant enough (up to 35% original loss) to be considered for investment. It is still very low compared to plant level mitigation (power injecting devices) where value of up to 90% of original loss is achievable. However, network level mitigation involves targeted reduction in network fault rates and severities that would also benefit plants at other locations. When there are multiple participants in a network mitigation scheme, additional savings can be achieved if optimal mitigation scheme for one plant also benefits plants in other locations. By sharing the cost of mitigation amongst multiple participants, the value of mitigation increases.

To investigate cost saving through multiple participants, the plant types in Table 7-18 are chosen for assessment. These plants are chosen for the following reasons:

- Plant 13 - Base case financial loss too low to justify installation of power injecting devices.
- Plant 16 - High remaining losses even with installation of power injecting devices.
- Plant 37 - Same reason as Plant 16 but different main equipment type.
- Plant 40 - Highest savings from installation of power injecting devices, thus serves as a reference for comparison.

Table 7-18 Plants selected for investigation of the effect of multiple participants in network mitigation

Plant Identifier	Main Sensitive Equipment	Process Immunity	Interdependence	Nominal Loss ('000 £)
13	Microprocessor-Based	Low	High	30
16		Low	High	300
37	Drive and Contactor Based	Low	High	30
40		Low	High	300

Table 7-19 summarizes the assessments involved in this section. The assessment investigates cases with different number of participants of the same plant type at different network locations. For example, when Plant 13 is assessed for the case with three participants, one Plant 13 each will be placed at Locations 1, 3 and 5, before the GA is initiated to search for the optimal mitigation mix for the plants, with GA objective function (refer to (7-5)) set to minimize total costs of all three plants. In this assessment, the mitigation costs are shared equally amongst all participants regardless of the benefit resulting from mitigation.

7.5.4.3.1 Plant 13

Assessment results for Plant 13 with three, five, seven and nine participants are shown in Figure 7-77, Figure 7-78, Figure 7-79 and Figure 7-80 respectively. It is found that optimal network mitigation with multiple participant is the best mitigation option for Plant 13. Significant savings can be achieved with five participating plants onwards. The value for the plant is seen to increase with the number of participants and could reach 27% of original loss (Figure 7-80) with nine participants. However, the value of mitigation for the same plant type at different locations vary significantly, and should be considered in the pricing structure of the mitigation scheme.

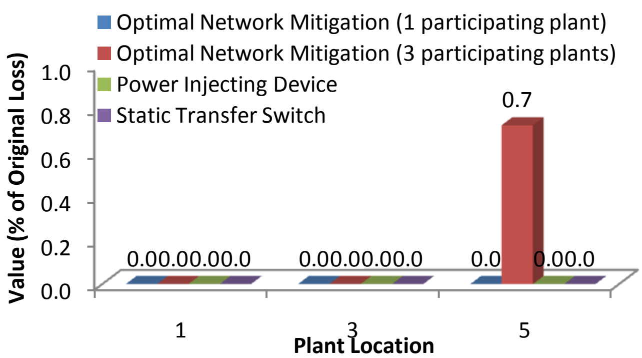


Figure 7-77 The value of optimal network fault reduction with three participating type-13 plants

Figure 7-81 shows the value of optimal network fault reduction at different plant locations. Plants at Locations 4 and 7 are the largest beneficiary of the scheme whilst plants at Location 1 and 2 have the lowest benefit/cost ratio. The figure also provides the range of values at different locations. For example, with nine participating plants, value of mitigation ranges from 11% to 27% of original losses.

Table 7-19 Summary of multiple participant assessment

Assessment		Number of Customer Types Assessed	4
		Number of Locations Assessed	various
		Number of Scenarios Assessed	4
		Total Number of Assessments	16
GA Search for each Assessment	3 Participating Plants	Number of Generations per Assessment	200
		Population Size	50
		Possible Solutions	$1*10^{104}$
		Searched Solutions	10000
		Search Space (%)	$1*10^{-98}$
		Simulation Time per Assessment (minute)	866
		Total Simulation Time (hour)	57.7
	5 Participating Plants	Number of Generations per Assessment	200
		Population Size	50
		Possible Solutions	$1*10^{104}$
		Searched Solutions	10000
		Search Space (%)	$1*10^{-98}$
		Simulation Time per Assessment (minute)	1156.6
		Total Simulation Time (hour)	77.1
	7 Participating Plants	Number of Generations per Assessment	200
		Population Size	50
		Possible Solutions	$1*10^{104}$
		Searched Solutions	10000
		Search Space (%)	$1*10^{-98}$
		Simulation Time per Assessment (minute)	1457.6
		Total Simulation Time (hour)	97.2
	9 Participating Plants	Number of Generations per Assessment	200
		Population Size	50
		Possible Solutions	$1*10^{104}$
		Searched Solutions	10000
		Search Space (%)	$1*10^{-98}$
		Simulation Time per Assessment (minute)	1709.2
		Total Simulation Time (hour)	113.9

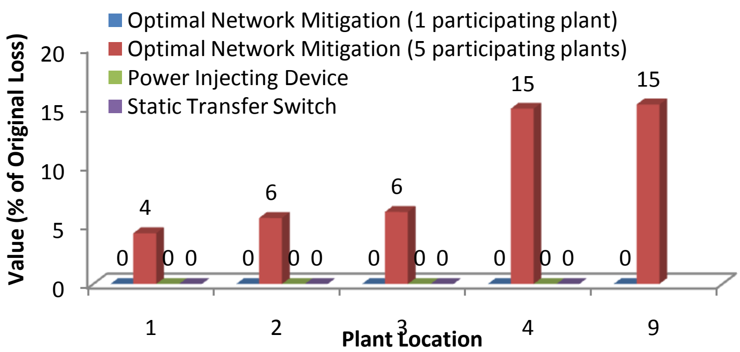


Figure 7-78 The value of optimal network fault reduction with five participating type-13 plants

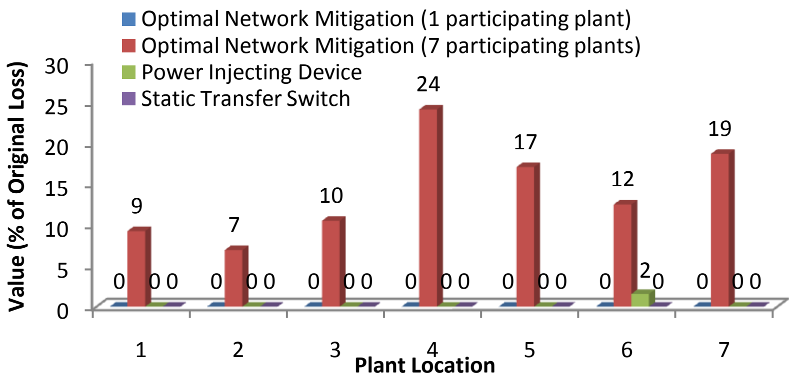


Figure 7-79 The value of optimal network fault reduction with seven participating type-13 plants

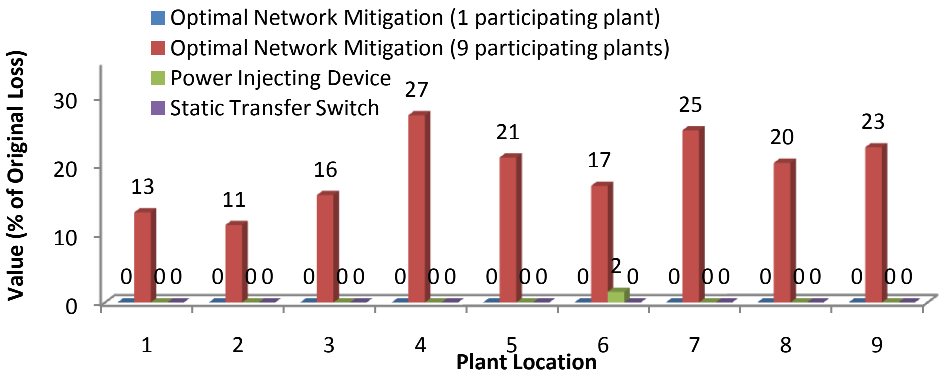


Figure 7-80 The value of optimal network fault reduction with nine participating type-13 plants

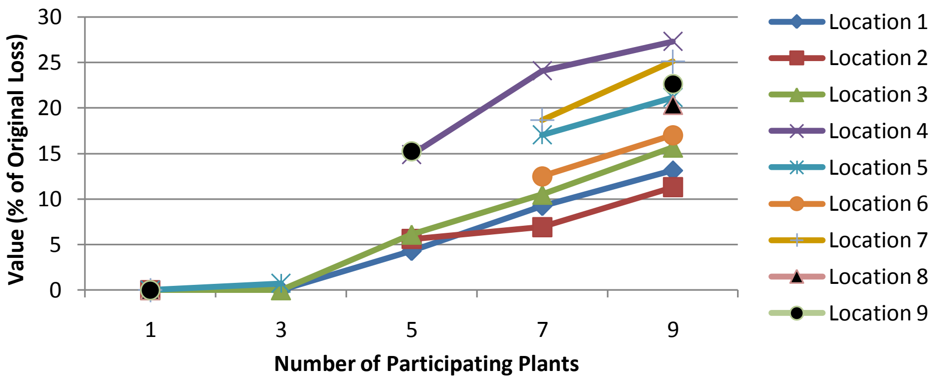


Figure 7-81 The value of optimal network fault reduction for type-13 plants at different plant locations

7.5.4.3.2 Plant 16

Assessment results for Plant 16 with three, five, seven and nine participants are shown in Figure 7-82, Figure 7-83, Figure 7-84 and Figure 7-85 respectively. It is found that significant savings is achieved compared to cases with single participant. However, power injecting devices are still the best mitigation solution for Plant 16 even with nine participating plants.

The value for the plant is seen to increase with the number of participants and could reach 53% of original loss (Figure 7-85) with nine participants, just 17% short of the savings with power injecting devices. The value of mitigation for the same plant type at different locations vary significantly.

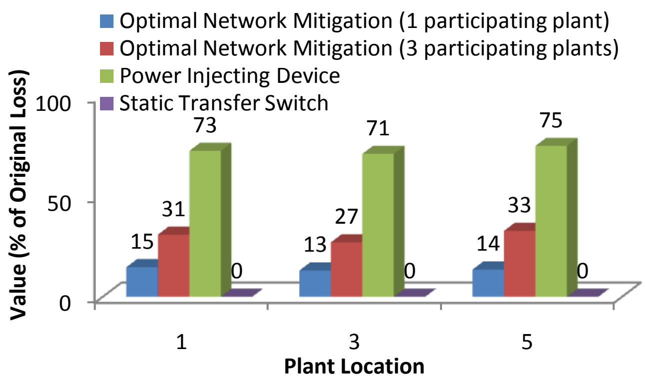


Figure 7-82 The value of optimal network fault reduction with three participating type-16 plants

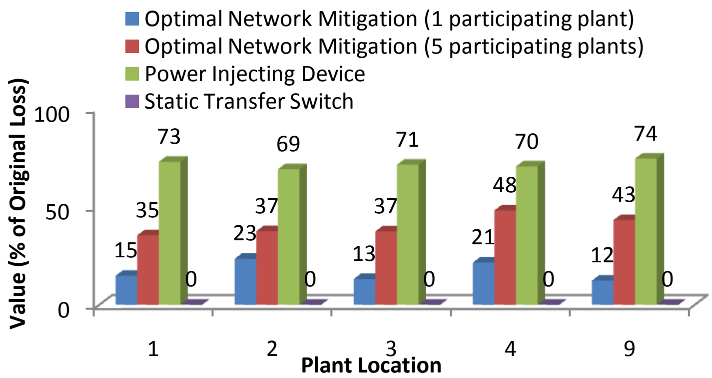


Figure 7-83 The value of optimal network fault reduction with five participating type-16 plants

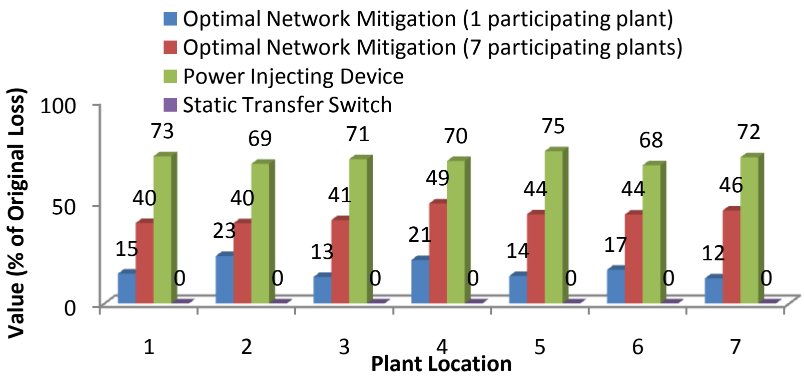


Figure 7-84 The value of optimal network fault reduction with seven participating type-16 plants

Figure 7-86 shows the value of optimal network fault reduction at different plant locations. Again, plants at Locations 4 and 7 are the largest beneficiary of the scheme whilst plants at Location 1, 2 and 3 have the lowest benefit/cost ratio.

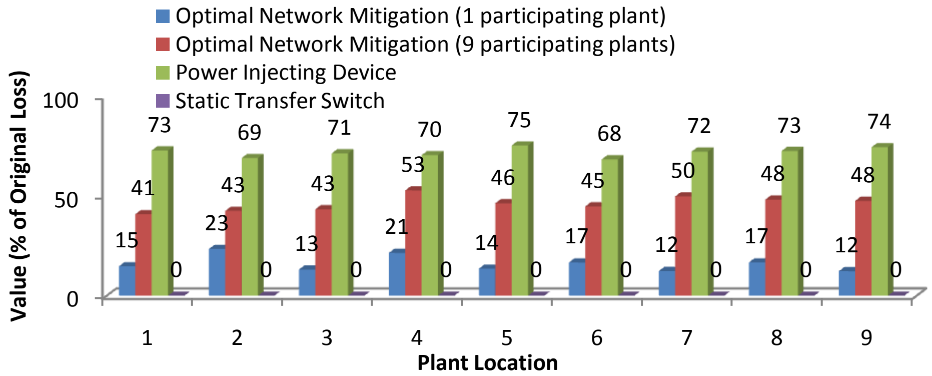


Figure 7-85 The value of optimal network fault reduction with nine participating type-16 plants

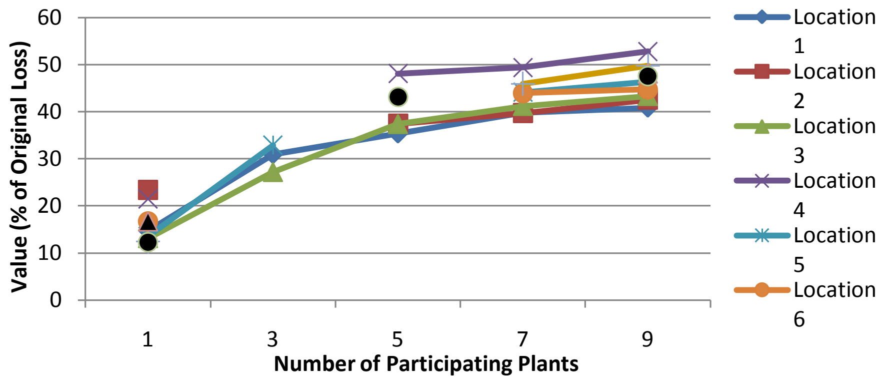


Figure 7-86 The value of optimal network fault reduction for type-16 plants at different plant locations

7.5.4.3.3 Plant 37

Assessment results for Plant 37 with three, five, seven and nine participants are shown in Figure 7-87, Figure 7-88, Figure 7-89 and Figure 7-90 respectively. It is found that huge savings is achieved compared to cases with single participant. However, power injecting devices are still the best mitigation solution for the plant type even with nine participating plants.

The value for the plant is seen to increase with the number of participants and could reach 51% of original loss (Figure 7-90) with nine participants, just 11% short of the savings with power injecting devices. Although unlikely, with a few more participating plants, the savings offered by this solution could rival that of power injecting devices, and becomes an alternative to installation plant level devices.

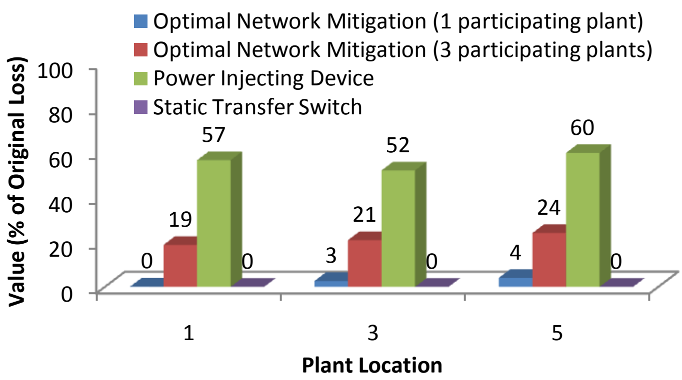


Figure 7-87 The value of optimal network fault reduction with three participating type-37 plants

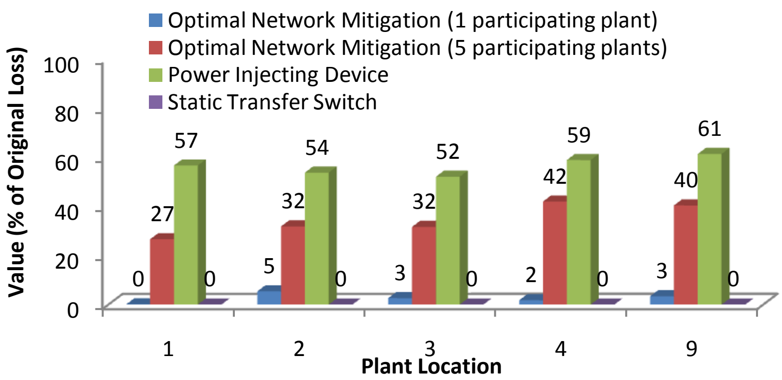


Figure 7-88 The value of optimal network fault reduction with five participating type-37 plants

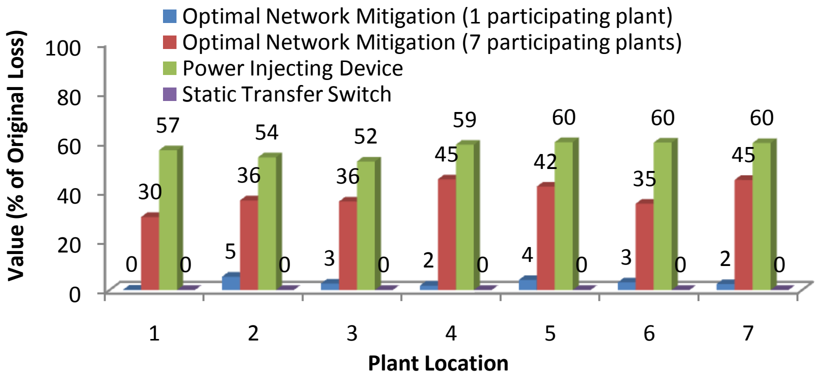


Figure 7-89 The value of optimal network fault reduction with seven participating type-37 plants

Figure 7-91 shows the value of optimal network fault reduction at different plant locations. Plants at Locations 4, 7, 8 and 9 are the larger beneficiary of the scheme whilst plant at Location 1 has the lowest benefit/cost ratio.

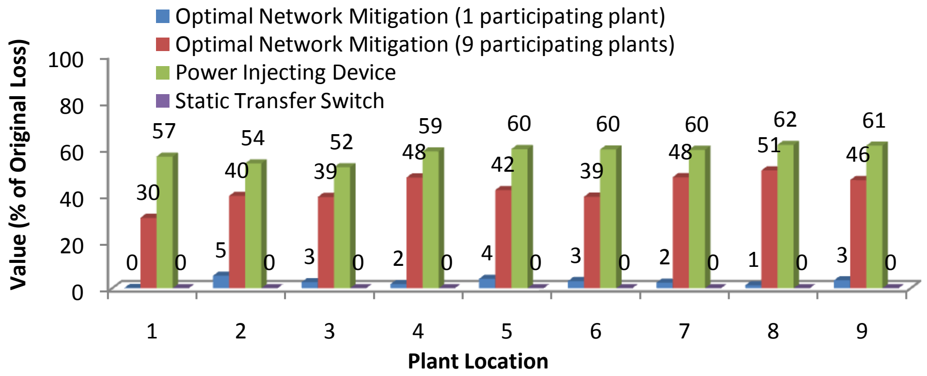


Figure 7-90 The value of optimal network fault reduction with nine participating type-37 plants

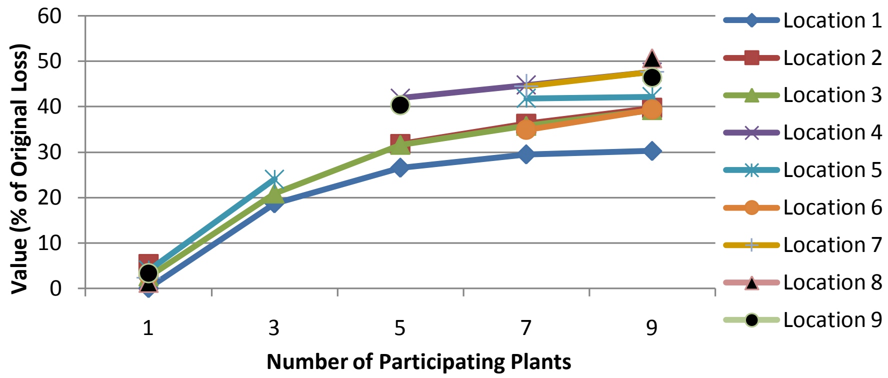


Figure 7-91 The value of optimal network fault reduction for type-37 plants at different plant locations

7.5.4.3.4 Plant 40

Assessment results for Plant 40 with three, five, seven and nine participants are shown in Figure 7-92, Figure 7-93, Figure 7-94 and Figure 7-95 respectively. It is found that savings is achieved compared to cases with single participant. However, the difference in value is not as large as that achieved in all other assessed plant types. Power injecting devices are the best mitigation solution by a distance for the plant type regardless of the number of participating plants.

The change in value with increase in the number of participants is not apparent. The highest value obtained is 59% of original loss with seven and nine participants at different locations.

Figure 7-96 shows the value of optimal network fault reduction at different plant locations. Plants at Locations 4, 7, 8 and 9 are the larger beneficiary of the scheme whilst plants at Location 1 and 3 have the lowest benefit/cost ratio.

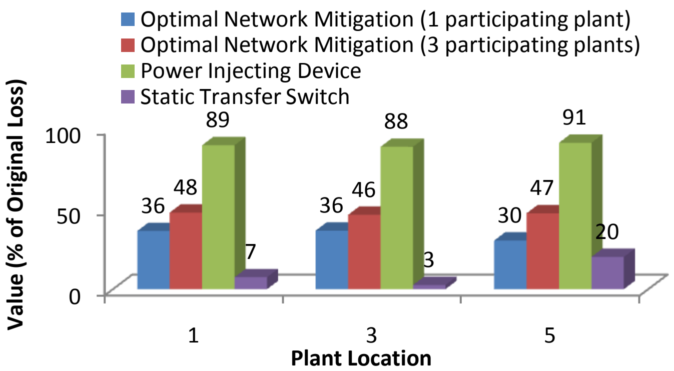


Figure 7-92 The value of optimal network fault reduction with three participating type-40 plants

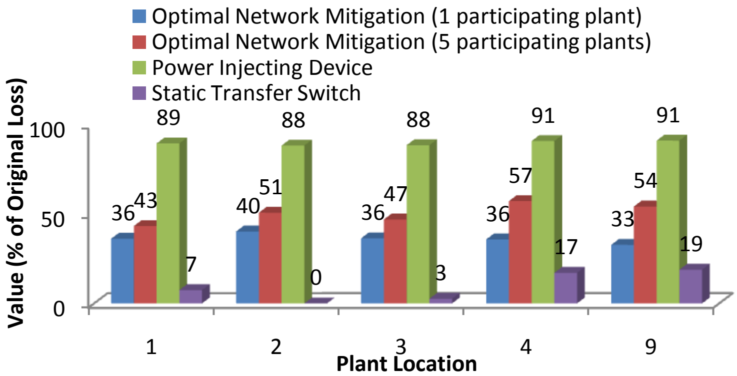


Figure 7-93 The value of optimal network fault reduction with five participating type-40 plants

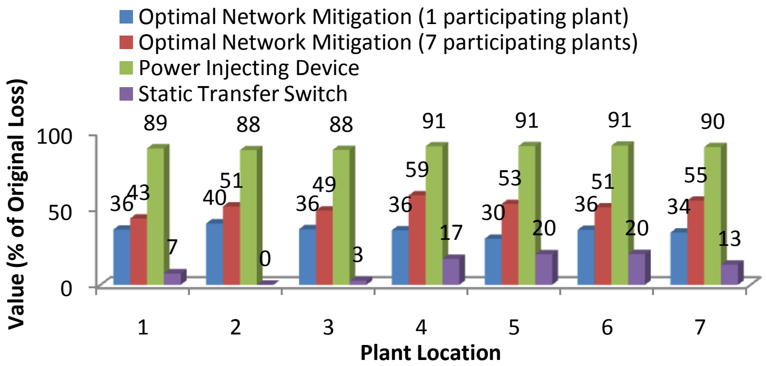


Figure 7-94 The value of optimal network fault reduction with seven participating type-40 plants

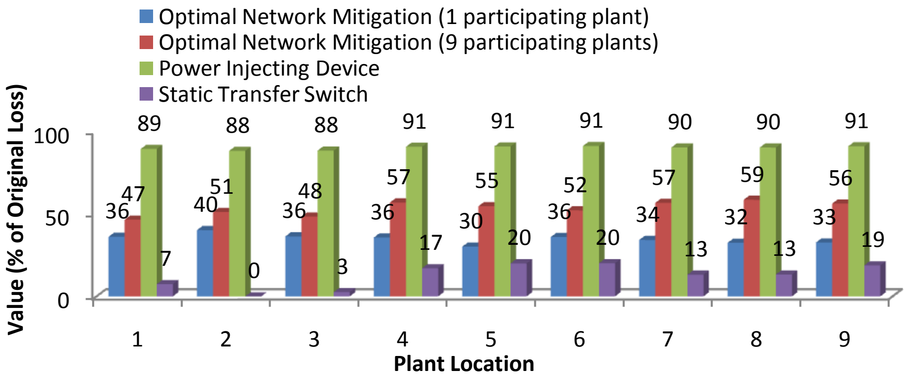


Figure 7-95 The value of optimal network fault reduction with nine participating type-40 plants

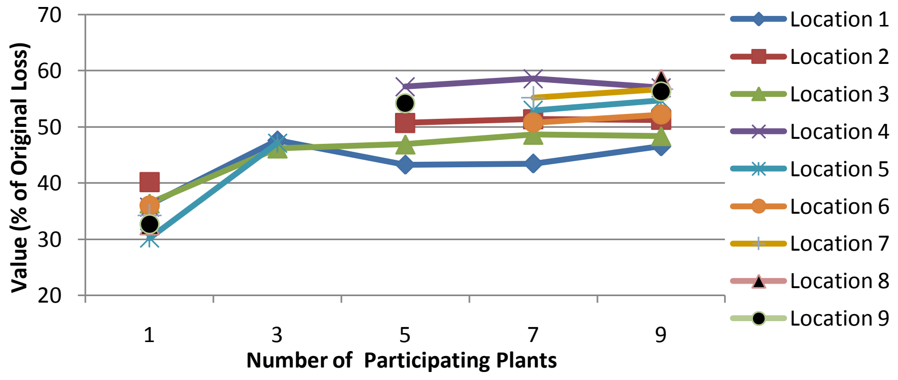


Figure 7-96 The value of optimal network fault reduction for type-40 plants at different plant locations

7.5.4.3.5 Summary

Figure 7-97 shows the sensitivity of the value of multiple participant scheme to the number of participants. For Plant 13, although initial value is low, the value increases at considerable pace when the number of participants increase. Plant 16 shows steady increment in value with increasing number of participant. For Plant 37, huge savings is achieved with multiple participants compared to the single participant case. The plant also have highest sensitivity to the number of participants. Finally, multiple participant scheme has the lowest impact on Plant 40, with very little sensitivity to the increase in the number of participants.

One important feature of this scheme is that money is pooled from the participants to install network level mitigation solutions. If sufficient funds can be secured to finance the expensive but effective solutions (undergrounding lines), a leap in savings is foreseeable.

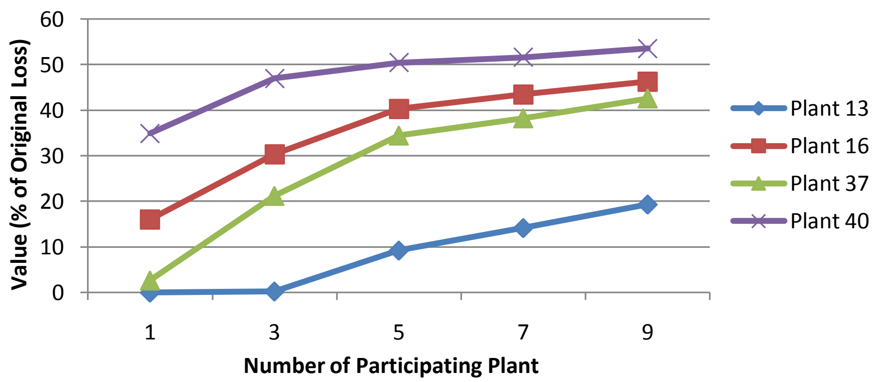


Figure 7-97 The average value of optimal network fault reduction with multiple participants

7.6 Conclusions

From the analysis and case studies presented in this chapter, the following general conclusions can be drawn:

- The value of mitigation varies according to customer plant characteristics; equipment type, process immunity, process interdependence and nominal loss.
- The value of mitigation is sensitive to changes in customer plant size (power injecting device and redundant supply), network fault rates, the costs and effectiveness of mitigating solutions/options.

The following specific conclusions can be drawn with respect to mitigating option considered:

➢ For power injecting devices:

- Power injecting devices are the best solution when the financial loss is sufficient (high) to justify installation.
- Power injecting devices mitigate sags originated in both transmission and distribution network.
- Power injecting devices have no value for microprocessor-based plants with low nominal loss value (30£), or moderate nominal loss per sag (105k) with high process immunity.
- For microprocessor-based plants where savings are achievable, DVR with real and reactive power compensation is often the optimal device except in low immunity, high interdependence plants where DVR with reactive power compensation is preferred.
- For ASD-based plants with low nominal loss per sag (30k£), the best device is either DVR with full compensation or DVR with reactive power compensation depending on plant location.
- For moderate nominal loss (105k£) plants, the type of optimal device depends on process immunity and process interdependence levels.
- At higher nominal loss values (225k£ and above), flywheel is the most valuable mitigation device for voltage sag mitigation.
- The value of power injection device and customer initial plant loss can be correlated with a logarithmic function.

- For redundant supply with static transfer switch
  - The value of redundant supply with STS is low (or none) for all investigated plant types.
  - High cost in building new lines to connect to backup supplies, high upgrade costs, and limited difference in bus performance across the network are the main factors for the low value (average line and upgrade cost /switch cost is 2.85 to 1) of this solution.
  - The possibility of connecting to an independent supply from other 132kV network was not explored.

- For network level mitigation
  - Fault current limiting is the most valuable solution for low level investments (less than 5 mitigated feeders), followed by insulating overhead lines.
  - For optimal investment, the dominant solutions for microprocessor-based plants are fault current limiting and fault clearing time reduction.
  - The dominant solutions for ASD-based plants are insulation of overhead lines and fault current limiting.
  - For microprocessor-based plants, mitigation costs are generally higher than the savings achieved (benefit/cost ratio less than 1).
  - For ASD-based plants, mitigation costs are generally lower than the savings achieved (benefit/cost ratio more than 1).
  - The value of optimal network mitigation and customer initial plant loss can be correlated with a quadratic function.
  - Multiple participant schemes increase the value of network level mitigation.
  - If power injecting devices could not be justified, optimal network mitigation with multiple participant is the best option.
  - Network level mitigation solutions have no effect on sags originated in the transmission network.

Chapter 8 High Quality Power Zone

8.1 Introduction

This chapter investigates the potential value of a High Quality Power Zone (HPQZ) where a group of customer plants are placed into a single electrical zone with a common and shared mitigating scheme. The main reasons for grouping customers together are as follows:

- To achieve savings by sharing the cost of mitigation (similar to multiple participant schemes in Chapter 7).
- To enable mitigation for low financial loss plants that cannot afford their own mitigation device.
- To finance more expensive but effective mitigation schemes, i.e. combination of two or more mitigating solutions.
- To achieve further savings in mitigation costs via optimal loading management, where customer loading schedules are optimally shifted such that the peak demand of the entire zone is minimized.

The assessment focuses on determining the value of HPQZ to industrial plants of various sizes, process characteristics and initial financial loss values. The potential value of optimal loading management is also explored. Genetic Algorithm (GA) based optimization technique described in Chapter 7 is used to obtain the best solution for all relevant cases. The results obtained represent the seventh original contribution of this thesis.

8.2 Assessment Procedure

A case study where a group of nine customers connecting to the network at the same time is assessed. Base case scenario considers the plants connecting to different network locations, employing different mitigation schemes. The best mitigation scheme for each plant is obtained with the objective function given in (7-5), reiterated as (8-1). The total financial loss for all plants in the base case, S_{base_case}, is obtained using (8-2).

$$\mathrm{S_i} = \min f = min\left[NPV_{10}\left(C_{mitigation} + C_{sag}\right)\right] \tag{8-1}$$

$$S_{base\ case} = \sum_{i=1}^{N} S_i \tag{8-2}$$

Where S_i = optimum solution for the assessed plant *i*

NPV_{10} = net present value for the ten year assessment period

$C_{mitigation}$= total cost of mitigation including initial, operating and maintenance costs.

C_{sag} = remaining financial loss after mitigation

N = total number of plants

The next case considers all customer plants connecting to one optimally selected HQPZ with a zone-based mitigation scheme. The total losses for all plants in the HQPZ, S_{HQPZ} , is obtained using (8-3), with $C_{mitigation}$ as the zone-based mitigation cost and C_{sag} as the remaining financial loss after mitigation for all assessed plants.

$$\mathrm{S_{HQPZ}} = \min f = min\left[NPV_{10}\left(C_{mitigation} + C_{sag}\right)\right] \tag{8-3}$$

Finally, the case where an optimal loading management scheme is employed in a HQPZ is investigated. The management scheme involves shifting the load profile of individual plants in the HQPZ such that the peak demand of the HQPZ is minimized. The load profiles are shifted by bringing forward/delaying the entire operation schedule of customer plants by up to 8 hours. Reducing the peak demand enables mitigation devices of lower power ratings to be installed, hence reducing the cost of mitigation.

By comparing the post-mitigation financial loss in the optimal solutions of the cases, the values of the HPQZ and optimal loading management are obtained. Assessments assume that all customer plants involved are new plants connecting at same time, therefore, relocation costs are not incurred.

The mitigation schemes considered in all assessed cases are as follows:

- Power injecting devices
- Redundant supply from independent busbar (i.e. from a different 132kV supply)
- Redundant supply from independent busbar and power injecting device

The network and fault rates presented in Chapter 7 are reused in this chapter. On top of the voltage sags generated in the distribution network using fault positioning method, sags originated from the transmission network are also included in the assessments. The transmission level sags used are given in Table D-6 in Appendix D. Two cases with different levels of transmission level sags are assessed. The first case has an average of 10% of the total sag scores originated from the transmission level, while the second case considers 30% transmission sags in the sag scores of all buses. Higher percentages of transmission sags are achieved by increasing the occurrence rate of the transmission sags. Calculation of sag scores is described in Section 7.2 in Chapter 7.

In addition, a new set of customer plants of various sizes, process characteristics and initial financial loss values is modelled to enhance the practicality of the assessment.

8.3 Customer Plants

The customer plant characteristics used in the assessment are shown Table 8-1. The plants have the following characteristics:

- Financial loss specific to business type.
- A range of plant sizes (from 0.69MW to 7.3MW).
- Different numbers of sensitive processes in each plant (from 1 to 8).
- Different types of sensitive equipment type.
- Process with different interdependence levels, sizes, and cost factors (detailed plant models given in Appendix D).

Financial loss values are obtained from Table 3-3 in Chapter 3 with direct currency conversion (1 GBP = 1.64 US). The number of sensitive processes, plant sizes, equipment types and power factors are arbitrarily selected.

Plants with different nominal loss values are chosen for assessment to demonstrate the effect of HQPZ on different customers. In this case, customer nominal loss values ranges from less than £4.4k to more than £3M.

8.4 Plant Locations

The locations of customer plants in the base case, and the procedure of selecting the location of the HQPZ are described in the following sub-sections.

Table 8-1 Customer plant models used for assessment

Customer	Business	Financial Loss/Event (£)	Number of Sensitive Processes	Sensitive Equipment	Peak Power Demand (MW)	Power Factor
1	Pulp and paper integrated	18,300	5	AC Contactors, ASD	0.69	0.75
2	Metal works	152,500	4	ASD, PLC	2.2	0.7
3	Food Processing	4366	3	ASD, PLC, AC Contactors	0.74	0.75
4	Textile	15250	4	ASD, PLC, AC Contactors	2.14	0.75
5	Semiconductor fabrication	3344000	8	ASD, PLC	4	0.7
6	Automotive assembly	45750	5	ASD, PLC, AC Contactors, PC	3.5	0.75
7	Chemical	30500	2	ASD, PLC	3.15	0.75
8	Equipment manufacturing	61000	4	ASD, AC Contactors	3.75	0.7
9	Plastic extrusion	18300	1	ASD	7.3	0.7

8.4.1 Base Case Plant Locations

Base case represents the current practice in most parts of the world, where individual customer plants are scattered across the network, each employing their own sag mitigation scheme. A set of network locations is arbitrarily chosen for connecting the assessed plants. Figure 8-1 shows the selected plant locations. The buses that are not part of the network are shown in the figure as unconnected dots. These buses are connected to neighbouring networks of separate 132kV substations (not shown in the figure). These "independent" buses will be used for connecting redundant supplies to the customer plants, as one of the mitigation schemes considered in this investigation.

8.4.2 Location of HQPZ

The location of the HQPZ is optimally selected using the flow chart as shown in Figure 8-2. Power flow convergence and voltage limits at all network buses must be satisfied for any locations to be considered for connection of the HQPZ. Upgrade costs are triggered when the thermal limits of any transformers, lines and busbars are exceeded. Voltage support capacitors are added, at a cost, at busbars where voltage levels are lower than 0.94 p.u.. The bus that produces the lowest costs, including network upgrade costs and sag incurred financial loss for all assessed plants is chosen as the HQPZ. The general procedures in the assessment are:

1. Select an 11kV busbar and connect all customer plants to the selected busbar.

2. Run power flow to ensure convergence.
3. If voltage limit in any bus is exceeded, adjust transformer taps to boost voltage.
4. If transformer tap limits are exceeded, add shunt capacitor to the relevant bus to boost voltage.
5. Calculate upgrade costs due to increased line flows and costs of voltage support.
6. Run fault positioning calculations to obtain voltage sag profile at selected location.
7. Determine process failure risk and financial loss of all plants.
8. Choose location with lowest financial costs (financial loss + upgrade costs).

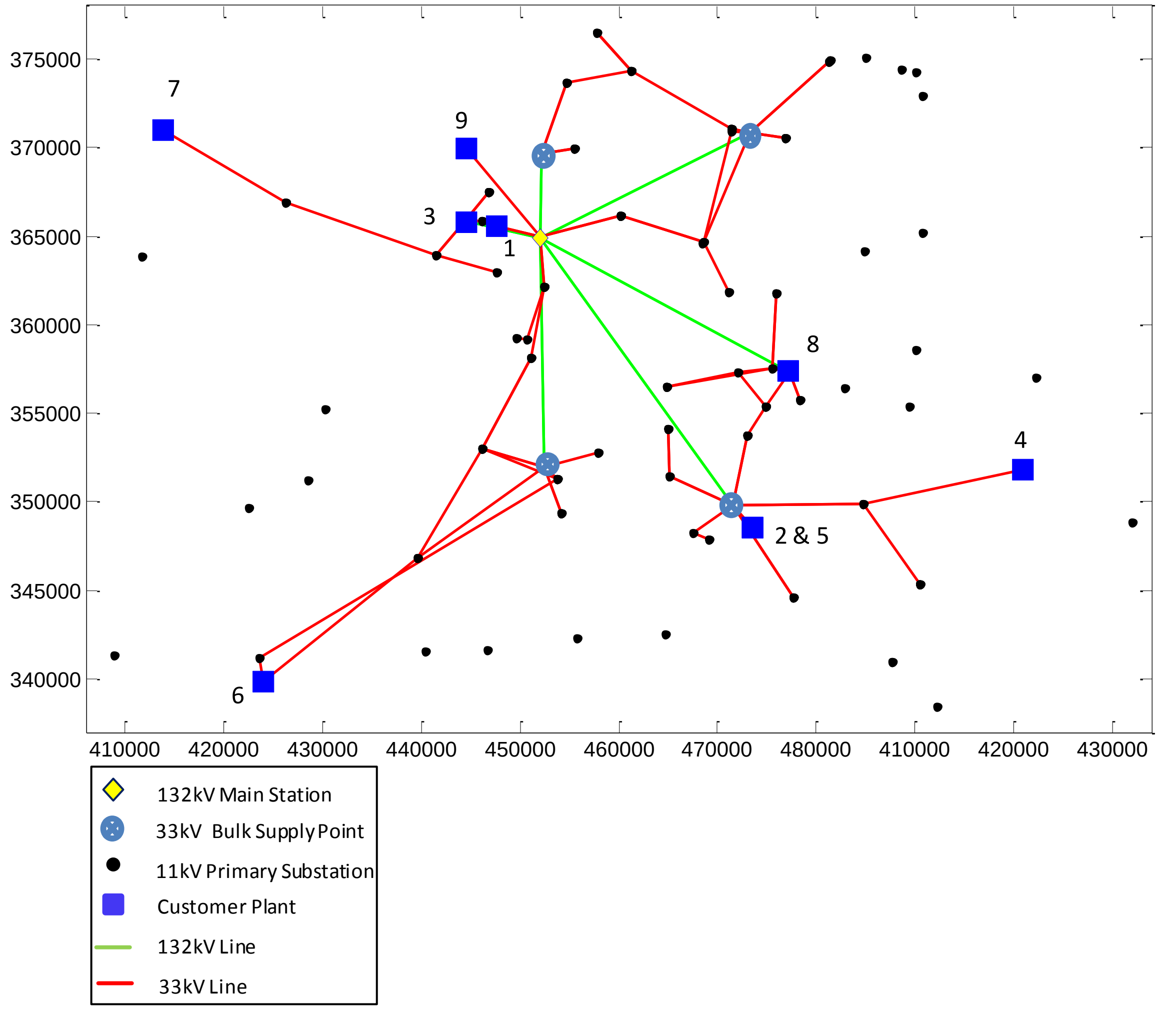


Figure 8-1 Plant Locations

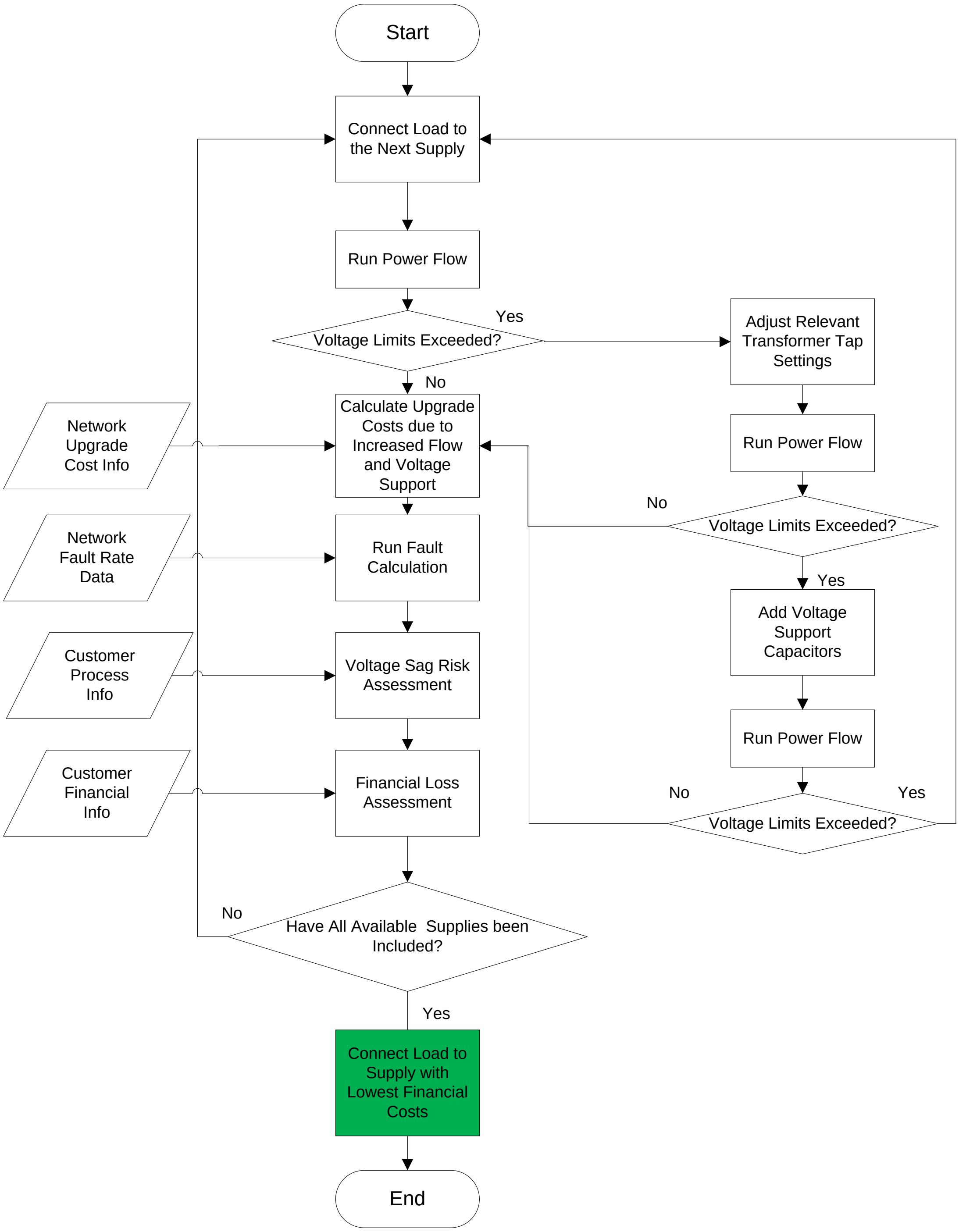


Figure 8-2 Flow chart for determining optimal location of HQPZ

Upgrade costs are calculated using the (8-4). The upgrade cost model given in Table 6-4 in Chapter 6 is used. For voltage support capacitors, a ten-year owning cost (NPV) of £5,000 per MVAr is assumed using figures given in [158] (based on 10MVAr capacitor, £1=$2 in 2006).

$$Upgrade\ Cost = Transformer\ Cost + Line\ Cost + Busbar\ Cost + Voltage\ Support\ Cost \quad (8\text{-}4)$$

The total cost of the segregating customers into the HQPZ is given by (8-5), where *n* is the customer plant and *N* is the total number of customer in the zone.

$$Total\ Cost\ of\ Segregation = Upgrade\ Cost + \sum_{n=1}^{N}(Sag\ Cost)_n \tag{8-5}$$

Figure 8-3 shows the location of the HQPZ selected using the procedure in Figure 8-2. The chosen location is a 11kV substation located close to the 132kV main substation. A total network upgrade cost of £3.21M is incurred.

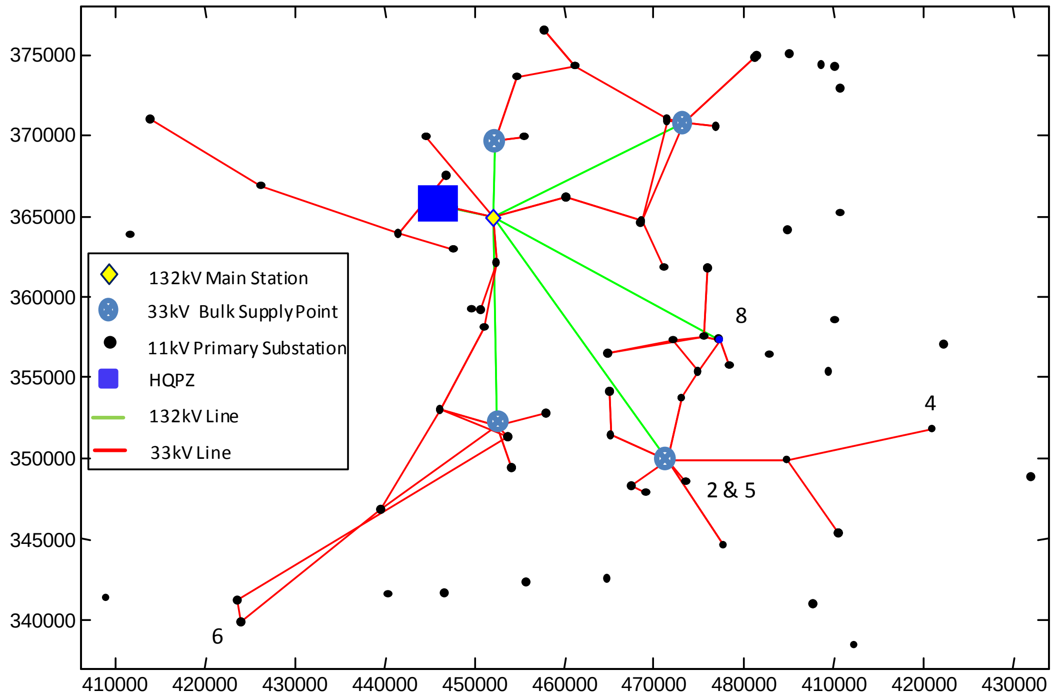


Figure 8-3 Location of the high quality power zone

8.5 Optimal Loading Management

Genetic Algorithm is used to search for the optimum operating schedule of plants in the HQPZ such that the peak demand of the entire zone is minimized. The scheme involves participation from all plants in the zone, where operation schedules of the plants are brought forward/delayed by up to 8 hours. Figure 8-4 shows the initial load profile of the plants and the HQPZ. The load profile takes the "office hour" type plant described in Section 5.3.1 in Chapter 5. The peak demand of the HQPZ is 38.3 MVA assuming constant power factor of all plants. All plants have the same loading schedule at any given time of the day.

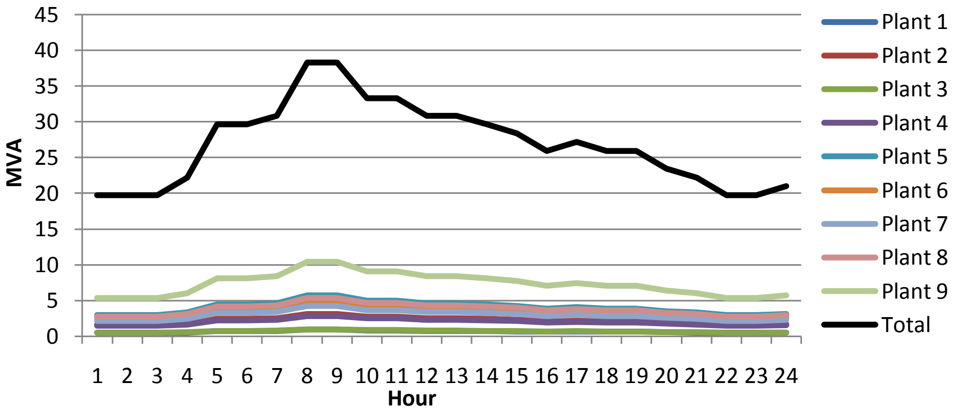


Figure 8-4 Load profile of plants in the HQPZ

Figure 8-5 shows the load profile of the plants and the zone with optimal loading management. It can be seen that the optimal load profile is more uniform in shape with minimum peaks in demand. The loading management has reduced the peak demand of the HQPZ by 27%, to 27.9MVA. Reducing the peak demand enables mitigation devices of lower power ratings to be installed, hence reducing the cost of mitigating solutions.

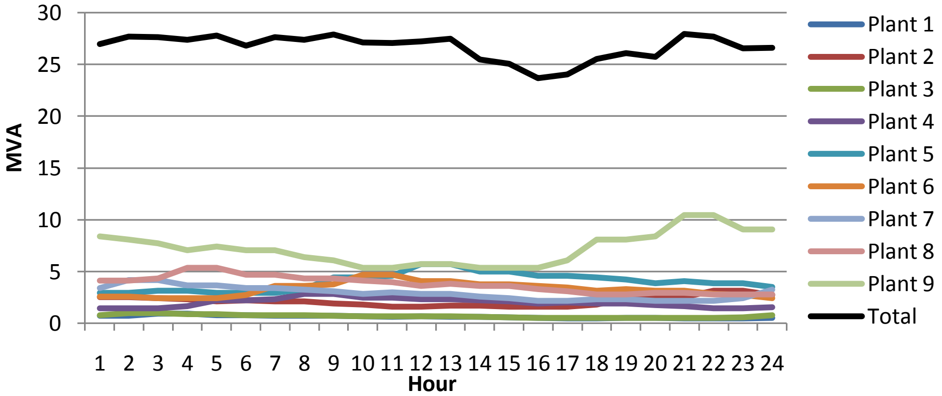


Figure 8-5 Load profile of plants in the HQPZ with optimal loading management

8.6 Initial Customer Financial Loss

The initial financial loss of customer plants due to voltage sags is obtained using the simulation procedure described in Section 7.4 of Chapter 7. The initial financial losses are described in the following sub-sections.

8.6.1 10% Transmission Sags

Table 8-2 and Figure 8-6 show the financial loss for each customer plant in all assessed cases. It can be seen that most plants suffer higher initial financial loss when placed in the HQPZ. Although the chosen location has the lowest overall segregation cost (refer to Equation (8-5)) amongst all feeders, its voltage sag performance is not the best in the network, as better performing buses might be unsuitable due to the high upgrade costs required to accommodate the zone.

Table 8-2 Initial financial losses due to voltage sags (10% transmission sags)

Customer	Business	10-Year NPV (M£)		
		Base Case	HQPZ	HQPZ Optimal Loading
1	Pulp and paper integrated	2.3	2.8	2.8
2	Metal works	17.0	20.8	20.8
3	Food processing	0.2	0.3	0.3
4	Textile	0.1	0.1	0.1
5	Semiconductor fab.	68.5	87.8	87.8
6	Automotive assembly	3.2	3.2	3.2
7	Chemical	2.2	2.7	2.7
8	Equipment manufacturing	1.9	2.3	2.3
9	Plastic extrusion	2.6	3.1	3.1
Total		98	123	123

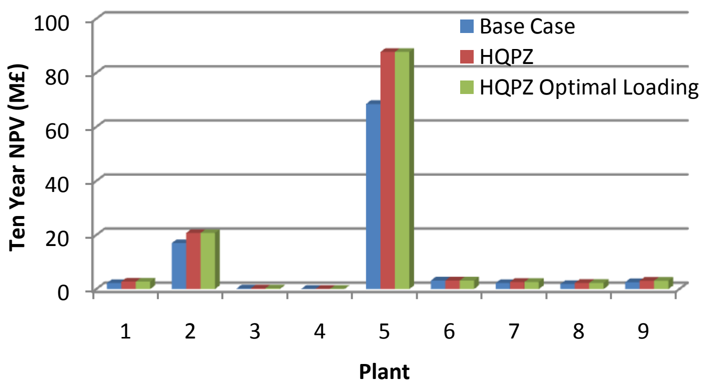


Figure 8-6 Initial financial loss for the assessed plants (10% transmission sags)

Figure 8-7 shows the total losses for all assessed cases. It can be seen that the initial financial loss in the HQPZ is 25.5% higher than the base case. This increases to 28.6% higher losses when network upgrade costs are included in the calculations.

8.6.2 30% Transmission Sags

Table 8-3 and Figure 8-8 show the financial loss for each customer plant with 30% transmission level sags in the voltage sag profiles of all buses. It can be seen that the initial losses for all plants in all cases are higher than the case with only 10% transmission level sags.

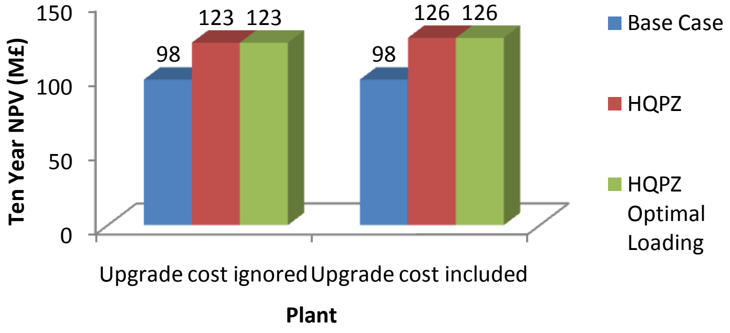


Figure 8-7 Total initial financial loss for all assessed plants (10% transmission sags)

Table 8-3 Initial financial losses due to voltage sags (30% transmission sags)

Customer	Business	10-Year NPV (M£)		
		Base Case	HQPZ	HQPZ Optimal Loading
1	Pulp and paper integrated	2.6	3.1	3.1
2	Metal works	19.9	23.7	23.7
3	Food processing	0.2	0.3	0.3
4	Textile	0.1	0.1	0.1
5	Semiconductor fab.	77.7	98.8	98.8
6	Automotive assembly	3.6	3.6	3.6
7	Chemical	2.6	3.0	3.0
8	Equipment manufacturing	2.0	2.4	2.4
9	Plastic extrusion	3.0	3.5	3.5
Total		111.8	138.6	138.6

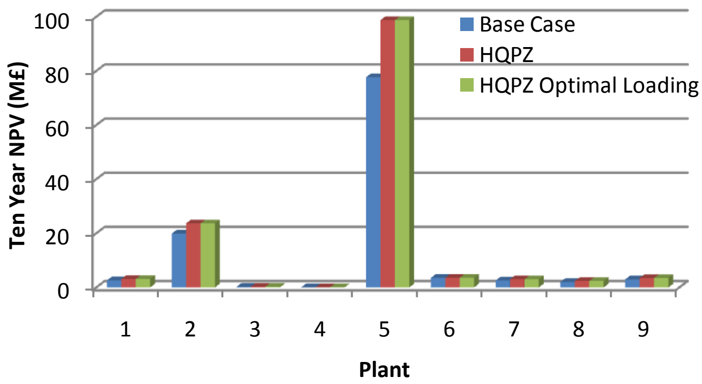


Figure 8-8 Initial financial loss for the assessed plants (10% transmission sags)

Figure 8-9 shows the total losses for all assessed cases. It can be seen that the initial financial loss in the HQPZ is 24.1% higher than the base case. This increases to 26.8% higher losses when network upgrade costs are included in the calculations.

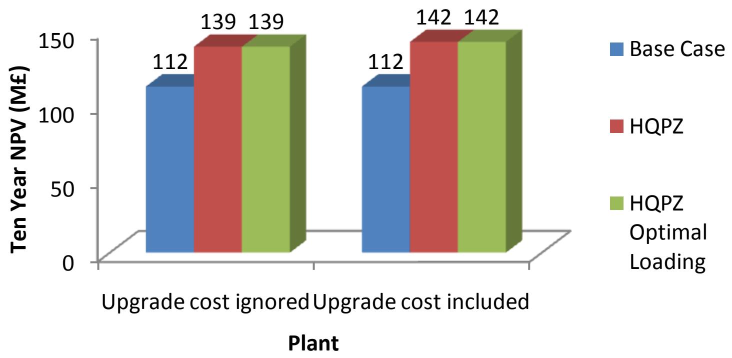


Figure 8-9 Total initial financial loss for all assessed plants (10% transmission sags)

8.7 Value of Mitigation

The assessment considers three different mitigation schemes; power injecting devices, redundant supply with static transfer switch, and combination of power injecting devices with redundant supply. The device models described in Chapter 6 are used to simulate the effect of the mitigating solutions.

8.7.1 Power Injecting Devices

The procedure described in Section 7.5.2 in Chapter 7 is used to select the best power injecting device for each plant in the base case, and the optimal device for the HQPZ. Only one device type is allowed to be installed in the HQPZ to ensure the same level of protection for all plants in the zone. The DVR sizes considered in assessment of HQPZ is given in Table D-5, Appendix D.

8.7.1.1 10% Transmission Sags

Table 8-4 shows the level of protection offered by power injecting devices and the optimal device type for all assessed cases. Plants in the base case have the flexibility to install their own devices, thus enabling the best device to be chosen for their plants. On the other hand, only one device type can be installed in the HQPZ, resulting in sub-optimal mitigation for some plants.

Table 8-4 Optimal power injecting device for the plants (10% transmission sags)

Customer	Sensitive Process Size (MVA)	Base Case		HQPZ		HQPZ Optimal Loading	
		Protected Process (%)	Best Device	Protected Process (%)	Best Device	Protected Process (%)	Best Device
1	0.7	81	Flywheel	81	Flywheel	81	Flywheel
2	2.8	78	Flywheel	78	Flywheel	78	Flywheel
3	1.0	0	none	0	none	20	Flywheel
4	2.6	0	none	0	none	0	none
5	5.7	45	Flywheel	45	Flywheel	45	Flywheel
6	4.4	16	Flywheel	16	Flywheel	16	Flywheel
7	3.8	83	DVR (reactive only)	0	none	83	Flywheel
8	3.8	50	DVR	14	Flywheel	50	Flywheel
9	7.8	100	DVR (reactive only)	0	none	0	none
Total/average	32.6	58		20		35	

Figure 8-10 shows the post-mitigation losses (remaining sag cost + mitigation cost) of the plants after installing power injecting devices, while Figure 8-11 shows the post-mitigation losses as a total of all plants. It can be seen that post-mitigation losses of HQPZ is higher than the base case for Plants 7, 8 and 9, indicating a negative value of the zone for these plants. HQPZ with optimal loading management performs better than the conventional HQPZ but still has a negative value compared to the base case. Post mitigation losses for HQPZ and HQPZ with optimal loading are 30% and 12% higher than that of the base case, respectively. These values increase to 65% and 47% when network upgrade costs are taken into account.

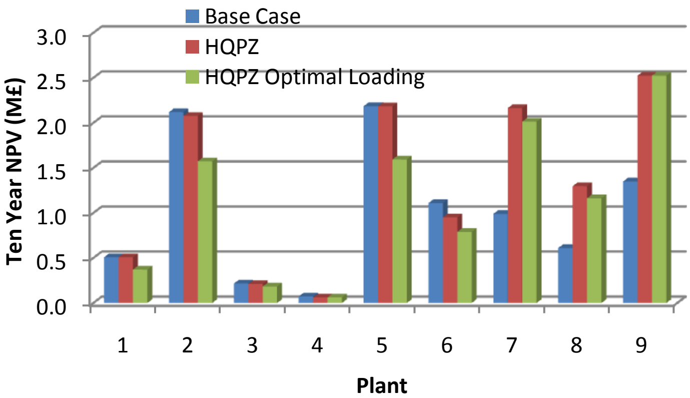


Figure 8-10 Post mitigation losses after installation of power injecting device (10% transmission sags)

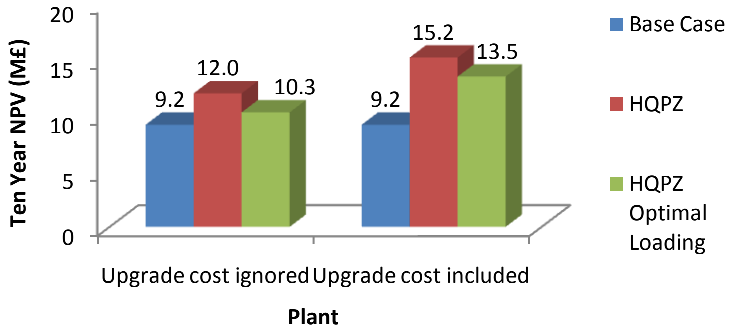


Figure 8-11 Total post mitigation losses after installation of power injecting device (10% transmission sags)

8.7.1.2 30% Transmission Sags

Table 8-5 shows the level of protection offered by power injecting devices and the optimal device type for all assessed cases with 30% transmission sags. DVR is found to be the best device for the HQPZ without optimal loading management, whilst flywheel is the best device for the HQPZ with optimal loading management.

Table 8-5 Optimal power injecting device for the plants (30% transmission sags)

Customer	Sensitive Process Size (MVA)	Base Case		HQPZ		HQPZ Optimal Loading	
		Protected Process (%)	Best Device	Protected Process (%)	Best Device	Protected Process (%)	Best Device
1	0.7	81	Flywheel	81	DVR	81	Flywheel
2	2.8	78	Flywheel	100	DVR	78	Flywheel
3	1.0	20	Flywheel	0	none	20	Flywheel
4	2.6	0	none	0	none	0	none
5	5.7	45	Flywheel	45	DVR	45	Flywheel
6	4.4	37	DVR	37	DVR	16	Flywheel
7	3.8	83	Dvr (reactive only)	83	DVR	83	Flywheel
8	3.8	64	DVR	50	DVR	50	Flywheel
9	7.8	100	Dvr (reactive only)	100	DVR	0	none
Total	32.6	63		63		35	

Figure 8-12 shows the post-mitigation losses (remaining sag cost + mitigation cost) of the plants after installing power injecting devices, while Figure 8-13 shows the post-mitigation losses as a total of all plants. It can be seen that post-mitigation losses of HQPZ is higher than the base case for most plants, indicating a negative value of the zone for these plants. HQPZ with optimal loading management performs better than the conventional HQPZ but still has a negative value compared to the base case. It is also interesting to see that there are plants benefiting from the HQPZ (e.g. Plant 1, 2 and 6) where positive values are obtained compared to the base case.

Overall post mitigation losses for HQPZ and HQPZ with optimal loading are 35% and 10% higher than that of the base case, respectively. These values increase to 67% and 43% when network upgrade costs are taken into account.

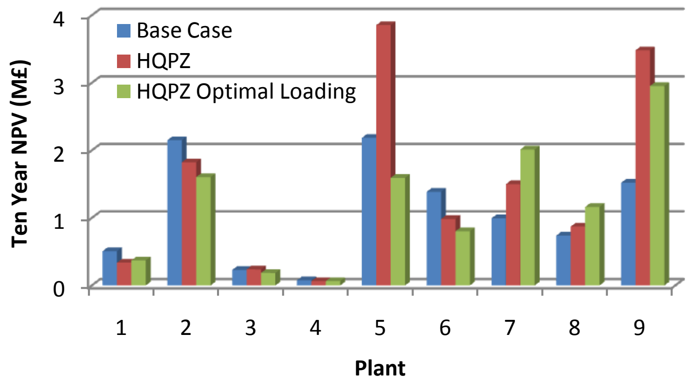


Figure 8-12 Post mitigation losses after installation of power injecting device (30% transmission sags)

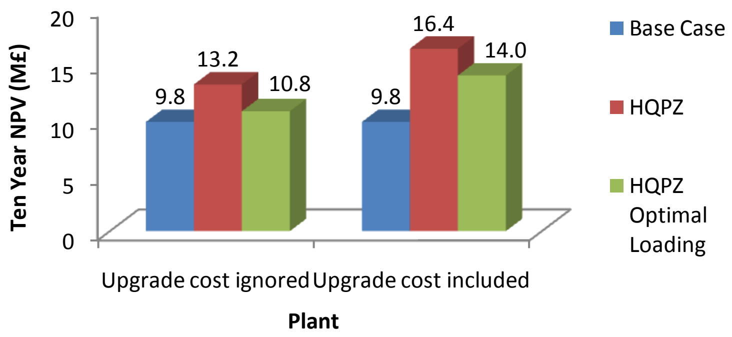


Figure 8-13 Total post mitigation losses after installation of power injecting device (30% transmission sags)

8.7.2 Redundant Supply from Independent Source

Unlike in Chapter 7, plants are able to connect to redundant supplies from independent busbars (i.e. from different 132kV supply point). Assuming that distribution sags do not propagate to the transmission network, switching to an independent busbar essentially eliminates all sags caused by faults within the distribution network. However, transmission level sags remain as all "independent" busbars are assumed to originate from the same 132kV network.

The procedure described in Section 7.5.3 in Chapter 7 is used to determine the best redundant supply. No upgrade costs are incurred as the independent network is assumed to be capable of accommodating the new loads without upgrades. Twenty independent busbars close to the network are included in the assessment. Details of these supply points are given in Table D-4, Appendix D.

8.7.2.1 10% Transmission Sags

Figure 8-14 shows the post-mitigation losses of the plants after installing the redundant supply, while Figure 8-13 shows the post-mitigation losses as a total of all plants. Post-mitigation losses of HQPZ are found to be lower than that of the base case for most plants, indicating positive value of the zone. HQPZ with optimal loading management performs marginally better than conventional HQPZ.

Overall post mitigation losses for HQPZ and HQPZ with optimal loading are 24% and 28% lower than that of the base case, respectively. However, when network upgrade cost (referring to the cost in Equation (8-4)) is included, negative values of 5% and 1% are obtained for HQPZ and HQPZ with optimal loading, respectively, compared to the base case.

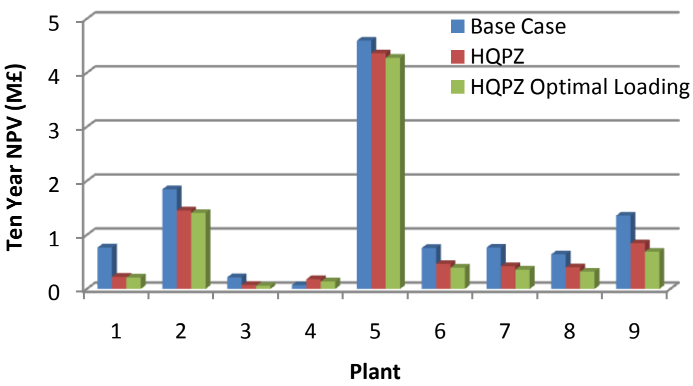


Figure 8-14 Post mitigation losses with redundant supply (10% transmission sags)

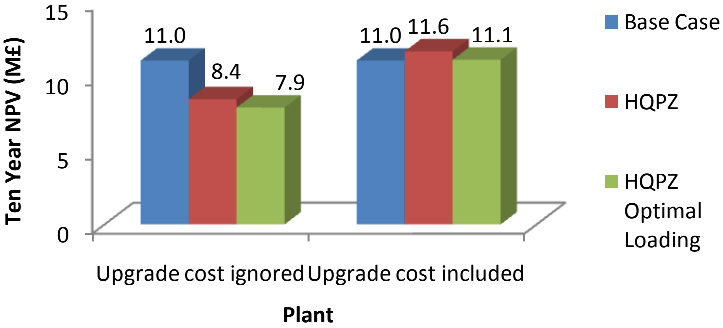


Figure 8-15 Total post mitigation losses with redundant supply (10% transmission sags)

8.7.2.2 30% Transmission Sags

Post-mitigation losses for redundant supply with 30% transmission sags are shown in Figure 8-16. Savings are observed in most plants compared to the base case. Overall post mitigation losses are shown in Figure 8-17. Installing redundant supplies produced 10% and 12.5% savings in total financial losses for HQPZ and HQPZ with optimal loading, respectively, compared to the base case. However, the losses become 2.8% and 0.4% higher for HQPZ and HQPZ with optimal loading, respectively, when network upgrade costs are included.

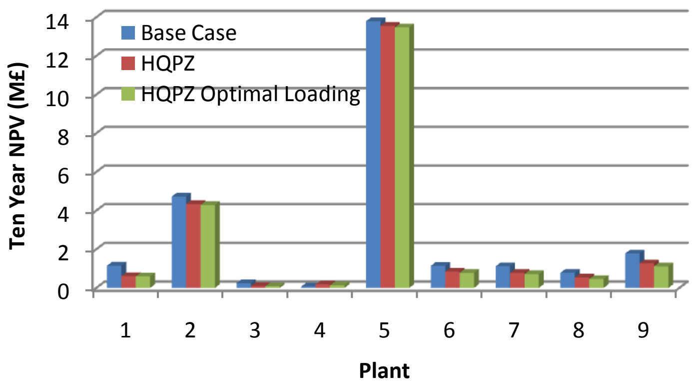


Figure 8-16 Post mitigation losses with redundant supply (30% transmission sags)

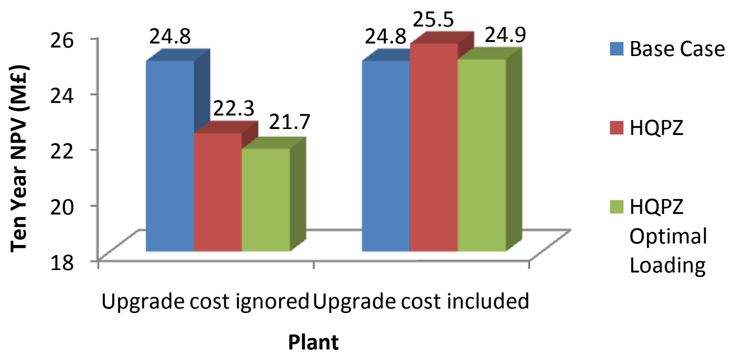


Figure 8-17 Total post mitigation losses with redundant supply (30% transmission sags)

8.7.3 Redundant Supply and Power Injecting Device

Cases where a combined use of redundant supply and power injecting device are investigated in this section. For high loss plants that can afford two device types on their own, HQPZ allows sharing of these costs with other plants. On the other hand, plants that can only afford one type of mitigation device (on their own) can benefit from the effect of ultra high power quality, achieved by combining the effects of two mitigation devices.

In all assessed cases, redundant supply is installed first before power injecting devices. For the base case scenario, if a plant can only afford one device type, redundant supply would be installed. No device is installed for low loss plants that cannot even afford one mitigation device.

8.7.3.1 10% Transmission Sags

Post-mitigation losses for the combined use of redundant supply and power injecting device are shown in Figure 8-18. Savings are observed in all except Plant 4, compared to the base case. Overall post mitigation losses are shown in Figure 8-19. It can be seen that HQPZ and HQPZ with optimal loading produced 56.7% and 65.7% of savings in total financial losses, respectively, compared to the base case.

The savings reduce to 9% and 16.4% for HQPZ and HQPZ with optimal loading, respectively, when network upgrade costs are included.

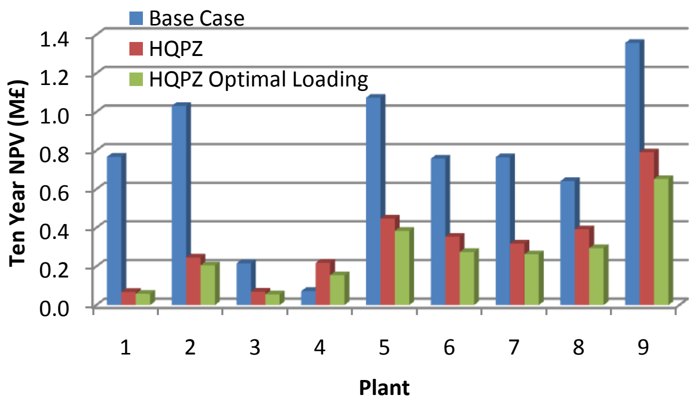


Figure 8-18 Post mitigation losses with redundant supply and power injecting device (10% transmission sags)

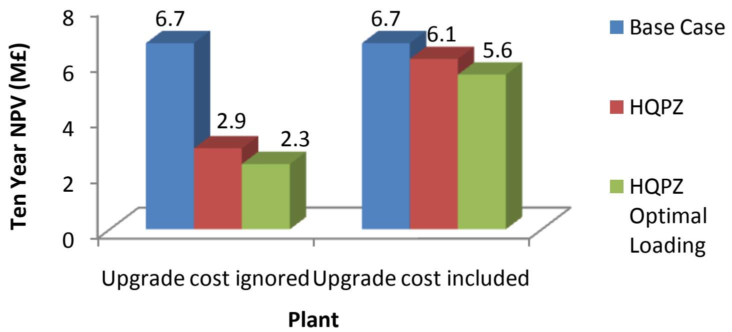


Figure 8-19 Total post mitigation losses with redundant supply and power injecting device (10% transmission sags)

8.7.3.2 30% Transmission Sags

Figure 8-20 shows post-mitigation losses for the scheme with 30% transmission sags. Higher savings are observed compared to the case with 10% transmission sags. All plants, except Plant 4, achieved savings in cases of HQPZ and HQPZ with optimal loading compared to the base case. Overall post mitigation losses are shown in Figure 8-21. It can be seen that HQPZ and HQPZ with optimal loading produced 65.1% and 71.1% of savings in total financial losses, respectively, compared to the base case.

Even with upgrade costs included, savings of 26.5% and 32.5% is achieved for HQPZ and HQPZ with optimal loading, respectively, compared to the base case.

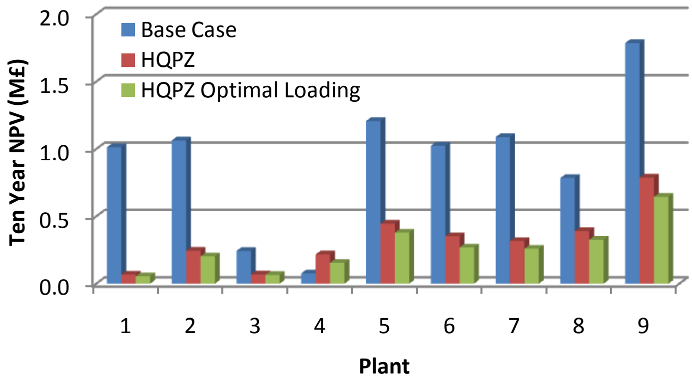


Figure 8-20 Post mitigation losses with redundant supply and power injecting device (30% transmission sags)

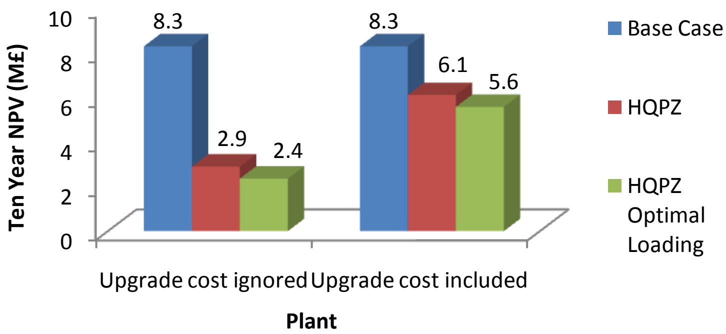


Figure 8-21 Total post mitigation losses with redundant supply and power injecting device (30% transmission sags)

8.7.4 Optimum Mitigation Scheme

This section summarizes the findings of the chapter by comparing the best values of mitigation achieved in the base case, the HQPZ and HQPZ with optimal loading management.

8.7.4.1 10% Transmission Sags

In base case, plants are free to choose the scheme that is best for them. The best mitigation scheme for the plants in base case is shown in Table 8-6. On the other hand, the combined use of redundant supply and DVR is found to be the best scheme for both HQPZ and HQPZ with optimal loading management.

Table 8-6 Best mitigation scheme for plants in the base case (10% transmission sag)

Plant	Best Mitigation Scheme
1	Flywheel
2	Redundant Supply and DVR
3	No Mitigation
4	No Mitigation
5	Redundant Supply and DVR
6	Redundant Supply
7	Redundant Supply
8	DVR
9	DVR (Reactive only)

Post mitigation losses with the best mitigation scheme for all cases are compared in Figure 8-22. It can be seen that all plants, except Plant 4, have lower post mitigation losses in HQPZ compared to the base case. In HQPZ, Plant 4 suffered more losses as it is forced to pay for mitigation devices that it cannot afford.

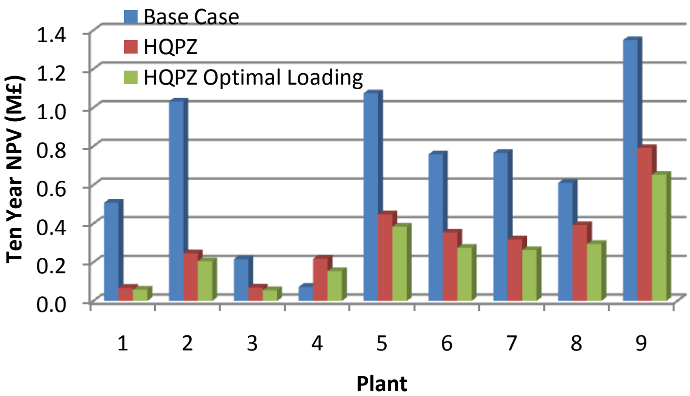


Figure 8-22 Post mitigation losses with best mitigation scheme (10% transmission sags)

Figure 8-23 compares the total post-mitigation losses between all assessed cases. It is found that HQPZ and HQPZ with optimal loading produced 54.7% and 64.1% savings, respectively, compared to the base case. When network upgrade costs are included, the savings reduce to 4.7% and 12.5% for HQPZ and HQPZ with optimal loading, respectively.

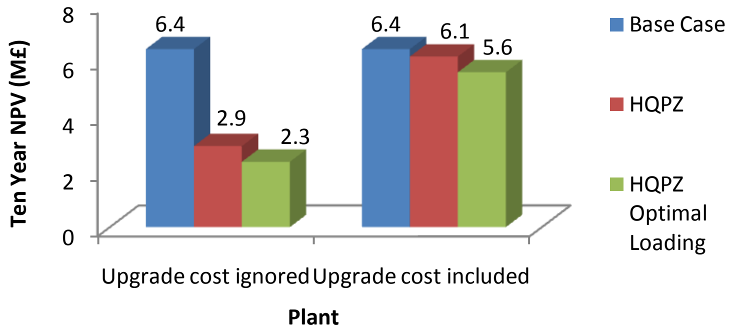


Figure 8-23 Total post mitigation losses with best mitigation scheme (10% transmission sags)

8.7.4.2 30% Transmission Sags

With 30% transmission sags, the best mitigation scheme for the plants in base case is found to be that of Table 8-7. On the other hand, the combined use of redundant supply and DVR is again found to be the best scheme for both HQPZ and HQPZ with optimal loading management.

Table 8-7 Best mitigation scheme for plants in the base case (10% transmission sag)

Plant	Best Mitigation Scheme
1	Flywheel
2	Redundant Supply and DVR
3	Flywheel
4	No Mitigation
5	Redundant Supply and DVR
6	Redundant Supply and DVR
7	DVR (reactive only)
8	DVR
9	DVR (reactive only)

Post mitigation losses with the best mitigation scheme for all cases are compared in Figure 8-24. Again, all plants, except Plant 4, have lower post mitigation losses in HQPZ and HQPZ with optimal loading compared to the base case.

The total post-mitigation losses between all assessed cases are compared in Figure 8-25. It can be seen that HQPZ and HQPZ with optimal loading produced 60.8% and 67.6% savings, respectively, compared to the base case. Even when network upgrade costs are included, significant savings of 17.6% and 24.3% are achieved for HQPZ and HQPZ with optimal loading, respectively.

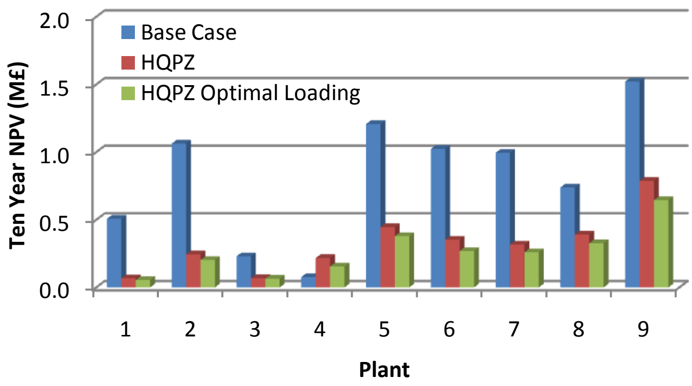


Figure 8-24 Post mitigation losses with best mitigation scheme (10% transmission sags)

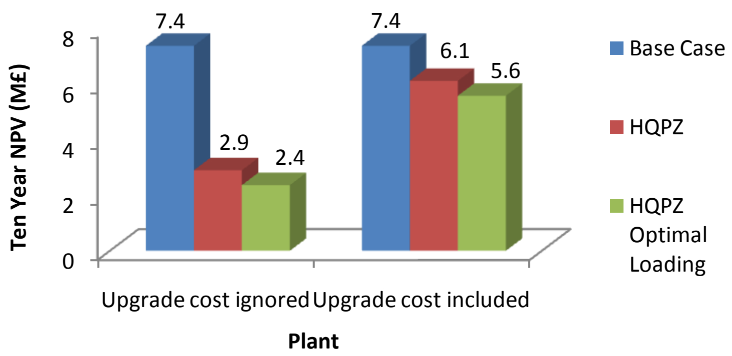


Figure 8-25 Total post mitigation losses with best mitigation scheme (30% transmission sags)

8.8 Conclusions

The values of High Quality Power Zone and High Quality Power Zone with optimal loading management were investigated. Results confirmed the economic feasibility of HQPZ, but also stressed the fact that not all plants would benefit from such a scheme. The following conclusions are drawn based on assessment results:

- HPQZ could produce moderate savings in financial loss to participating plants.
- Optimal loading management scheme improves significantly the value of the HQPZ.
- Higher value of zones is achievable in networks with higher level of transmission level sag.

- The value of HQPZ can be significantly impacted by network upgrade costs required for proper function of the zone.
- Plants with very low initial financial loss do not benefit from the zone.

It should be noted that all conclusions are based on assessment on a single set of plants in a single network, therefore, care must be taken when applying these conclusions in real life situations.

Chapter 9 Conclusions and Future Work

9.1 Conclusions

The thesis developed a general framework for technical and financial assessments of the impact of voltage sags on industrial and commercial customers, and the financial value of voltage sag mitigation solutions.

Review of past literature concluded that almost all major industries face power quality problems, with voltage sag, interruption, harmonics and transients being the most important problems. The most common sensitive equipment are AC and DC drives, contactors, programmable logic controllers (PLC), microprocessor based equipment, and lighting.

A thorough review of past surveys conducted around the world enabled the compilation of typical loss tables for various industries. It is found that voltage sags affect certain types of industrial customers, but the magnitude of the losses is very inconsistent, with huge disparities reported by different studies. These differences prevent the surveys from being compared effectively and meaningfully.

With increasing need for accurate financial loss estimation, a new methodology capable of grouping and analyzing the surveys is developed, the developed methodology is the first original contribution of this thesis. It is designed to derive customized customer damage function for individual industrial plant based on available data from surveys conducted at similar plants around the world. The existing customer damage functions (CDF), developed based on past surveys, are suitably scaled and transformed into comparable platform using financial conversions. The methodology then considers all known factors that influence costs, including customer process type, size and location, and implements the well known Hooke’s Law of elasticity to derive the appropriate customized CDF. The methodology can be used by distribution companies as an alternative to conducting customer survey on their network, as well as industrial and commercial plant owners to benchmark the performance of their plant with other plants.

Next, methodologies for modeling and assessment of equipment and industrial processes sensitivity to voltage sags and short interruptions are developed. Simple Magnitude Duration Severity Indices (MDSI) and probabilistic models are developed to provide realistic equipment representation in terms of voltage sag assessment and to incorporate the capability to assess financial loss due to unbalanced sags. This is the second original contribution of this thesis. Extensive simulations showed that the proposed models yield good consistency in assessments compared to existing fuzzy method, with the added advantage of shorter simulation time.

The factors that influence the outcome of financial loss analysis in voltage sag studies are also investigated. Parameters of the financial loss assessment, namely, limited availability of sag monitoring data, sag characteristics, process operation cycle and process load profile, that typically were not at all, or at least not simultaneously, considered in the past in this type of studies, were taken into account. This represents the third original contribution of this research. Several different approaches were used for modelling each of the influential parameters and their merits were discussed and compared. Analysis of the individual factors revealed that each of the parameters considered greatly affects the magnitude of financial loss estimation and that probabilistic modelling and risk based assessment are essential for meaningful conclusions regarding potential investments in costly mitigating solutions. Through the use of Stochastic Net Present Value (SNPV) method, the entire range of potential financial loss due to multiple varying risk factors was found.

Practical industrial grade software is developed for implementation of the models developed to assess customized customer damage function, customer equipment and process failure risks, and customer financial loss due to voltage sags and short interruptions. The developed software is the fourth original contribution of this thesis. Using Microsoft Excel as platform, the software is developed for the industrial sponsor (UK distribution network operator) to assist in decision making regarding network investments in reliability improvement and sag mitigation.

Issues, related to application of Stochastic Net Present Value method in assessment of economic merits of mitigating solutions are also discussed. The influence of nominal loss value and mitigation costs in financial analysis has been investigated, and resulted in the development of generalized formulae for mitigation option comparison. It is demonstrated that the problem can be decoupled into two separate lines of inquiry; technical and economic. In this way technical experts could focus on dealing with technical problems, and financial experts on dealing with financial problems while preserving generality of conclusions, i.e. full assessment of techno-economic merits of the solution. This framework presents another, the fifth, original contribution of this thesis.

Next, the technical effectiveness and associated costs of representative voltage sag mitigation solutions at different levels, from process/plant level to utility network level, are modelled, and applied on case study of actual UK distribution network. For network level sag mitigation, this thesis is one of the first (if not the first) to explore targeted network fault reduction in the context of voltage sag financial loss reduction. Optimal deployment of devices and solutions using developed Genetic Algorithm based optimisation provided much insight into the value of mitigating solutions and the influence of important assessment parameters. Detailed analysis showed that the value of mitigation depends on customer plant characteristics (equipment type, process immunity, process interdependence and nominal loss), customer plant size (in particular in case of power injecting devices and redundant supply), network fault rates, and the assumed parameters (cost and effectiveness) of mitigation solutions used. The results obtained represent the sixth original contribution of this thesis.

Finally, The financial benefit of grouping customer plants into a single location with high quality of electricity supply is explored. The research investigated potential savings in mitigation costs achieved through cost sharing amongst plants within the zone, and the potential savings achieved through optimal loading management. Results confirmed the economic feasibility of High Quality Power Zones. HPQZ is found to produce moderate savings in financial loss to participating plants. On the other hand, deploying a HQPZ with optimal loading management scheme improves significantly the value of the zone. The results obtained represent the seventh original contribution of this thesis.

9.2 Future Work

This research is bound by contractual requirements to achieve specific research aims agreed with the industrial sponsor. Therefore, throughout the duration of the research, many assumptions had to be made in assessments to ensure that research goals are met within agreed time frame, with technically sound and defendable results and conclusions.

The effort and time spent in assessing the impact of voltage sags have resulted in sufficiently good equipment (Chapter 5), process (Chapter 5) and financial loss (Chapter 4 and 5) models for future assessments. The equipment and financial loss models are “open ended” so that further improvement in accuracy can be achieved by updating the database used by the models.

The models used and assessment procedures for network level sag mitigation are newly developed for this research and thus provide room for improvement. Three areas are identified for future work; improvement of current models, incorporation of more assessment parameters, application of methodology in different networks.

The effectiveness of some of the mitigating solutions used for reducing the severity and frequency of faults was based on assumed values when their typical effectiveness was not available. The uncertainties resulting from this assumption were addressed in relevant sensitivity analyses. Though the approach taken is acceptable in this research where demonstration of the methodology is the main goal, assessments that require more accurate results would need better representation of relevant parameter. Further research is therefore required to obtain more realistic assessment of effectiveness of some of the mitigation solutions. This can be achieved both via literature survey on tests results with specific mitigating solutions, and through actual field measurements.

There are several factors known to influence the outcome of fault positioning method for simulating sags in the network, such as the number of fault positions on the lines [159], pre-fault voltage profiles [159], fault distribution in feeders [160] and load models [161], etc. To improve the accuracy of network level assessments in future studies, the influence of these factors have to be either modelled, accounted for through sensitivity analyses, or actual sag measurements should be performed at relevant sites/parts of the network.

All results and analysis presented in the thesis are obtained using a single network. It would be therefore useful to run simulations on different network topologies to verify/benchmark the conclusions obtained. Through further research along these lines, it would be also possible to come up with more general conclusions regarding network topologies, e.g., “The cost of network level mitigation is higher in radial networks compared to meshed networks”.

The time required to run simulations has to be reduced. The speed of simulations depends on three factors; the efficiency of the developed code, the simulation tool, and the optimisation tool. To improve the efficiency of the code, the inefficient parts of the code have to be identified and modified accordingly. On the other hand, switching from Matlab to other simulation tools would require recoding of all assessment procedures.

Simulation time can also be reduced by adopting a more efficient optimisation tool. The optimisation tool (Genetic Algorithm) developed and used in this research is chosen for its ease of application and compatibility with Matlab environment. However, though widely used in these types of studies, GA may not be optimal tool for problems with large search space and multiple local minima [67]. Therefore, more cases with different GA optimisation parameters (population size and generation) have to be simulated to ensure that the results are robust and within acceptable error margins. This translates to prolonged simulation times, and limitation in the size of the search space. Adopting a more suitable optimisation tool might involve extensive programming effort but would improve assessment time and accuracy.

Reducing the simulation time would unlock features in the existing program where assessment was possible but had not been attempted due to the simulation time required. For example, current simulations for optimum network mitigation (Section 7.5.4.2) allow only one solution at one feeder due to the number of the possible solution ($1*10^{104}$). Adding n solutions to the equation increases the search space by a factor of 2^n. To obtain the same percentage size of GA search area, the number of searched solutions and therefore simulation time will also increase by the same factor. Given that it takes 8 hours to solve the case for a single plant, considering nine solutions (modelled network level solutions) at a time would have taken about 85 days of simulation.

Most of the parameters (customer failure risks, financial losses, network fault rates, etc.) used in network level assessments in this research were based on expected values (i.e. probability of occurrence of discrete states). The other option is to use risk-based assessments where a range of solutions is obtained with varying input parameters through e.g., Monte Carlo simulations. This would result in possibly more acceptable format of solution for investment decision making in risk oriented business world. However, this assessment is only possible if current simulation time is drastically reduced.

This thesis also provides the inspiration and foundation for future research in different areas. One of the main findings of Chapter 7 is that network level mitigation with multiple participant is more profitable, and sometimes the only option for some customer types. However, to implement such a scheme, determining proper arrangement for cost sharing amongst participants and service pricing becomes an issue, as participants of different process types located at different places benefit differently from the same scheme. Moreover, the problem becomes even more complicated with plants participating at different times (i.e., having differentiated benefits in time).

It should also be noted that network level mitigation in this thesis accounted for only 55% to 60% of all power system faults (refer to Table 7-4). The remaining 40% of faults, mainly due to equipment failure in the network were not considered, as this would require thorough research into asset management. Future research therefore should incorporate some aspects of asset management and its integration into current models. It would be very interesting to obtain optimal network maintenance schedule to deal with faults due to equipment failure, and subsequently, global network level (or at least area-level) solutions for voltage sags. In addition, future research should consider incorporating network level mitigation, power injecting devices, and redundant supplies together in a "global" voltage sag mitigation scheme.

Research conducted in the area of high quality power zone can be extended to include more improvement possibilities. For example, it is possible to define zones with multiple level of power quality so that plants with different quality requirements could be optimally segregated into different sections of a zone, or into multiple zones located across the network. This would theoretically result in additional savings in financial loss as not all plants require the same level of power quality and placing them in a zone with a fixed level of power quality would result in wastage due to over/under mitigation. In this way plants within the zones would have improved level of flexibility for selecting the optimum mitigating scheme for each zone, whilst sharing the cost of mitigation amongst plants in each zone.

Chapter 10 References

[1] R. Targosz and J. Manson, "Pan European LPQI power quality survey," presented at *CIRED 19th International Conference on Electricity Distribution*, Vienna, 2007.

[2] *IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment*, IEEE Std 1346, 1998.

[3] "Voltage dip immunity of equipment and installation," CIGRE/CIRED/UIE Joint Working Group C4.110, ISBN 978-2-85873-099-5, April 2010.

[4] S. Z. Djokic and J. V. Milanovic, "Advanced voltage sag characterisation. Part I: Phase shift," *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 153, pp. 423, 2006.

[5] S. Z. Djokic, J. V. Milanovic, and S. M. Rowland, "Advanced voltage sag characterisation ii: point on wave," *Generation, Transmission & Distribution, IET*, vol. 1, pp. 146, 2007.

[6] M. H. J. Bollen, *Understanding power quality problems*. ed. New York: IEEE Press, 2000.

[7] *IEEE Recommended Practice for Monitoring Electric Power Quality*, IEEE Std 1159, 1995.

[8] *Voltage Characteristics of Electricity Supplied by Public Distribution Networks*, EN50160, 2007.

[9] "4th benchmarking report on quality of electricity supply 2008," Council of European Energy Regulators, December 2008.

[10] W. T. J. Hulshorst, E. L. M. Smeets, and J. A. Wolse, "Premium power quality contracts and labeling," KEMA Nederland B.V., 2007.

[11] *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems*, IEEE Std. 493, 2007.

[12] M. Bollen, I. McMichael, M.Stephens, K. Stockman, S. Djokic, F. Zavoda, B. Brumsickle, A. McEachern, J. R. Gordon, G. Ethier, and R. Neumann, "CIGRE/CIRED/UIE JWG C4.110 - Voltage dip immunity of equipment in installations - status April 2008," presented at *ICHQP*, 2008.

[13] R. R. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*. second ed.: McGraw-Hill, 2002.

[14] A. Baggini and F. Bua, "Costs: Investment analysis for PQ solutions," Leonardo Power Quality Initiative, July 2004.

[15] P. Heine, P. Pohjanheimo, M. Lehtonen, and E. Lakervi, "A method for estimating the frequency and cost of voltage sags," *IEEE Transactions on Power Systems*, vol. 17, pp. 290, 2002.

[16] P. Heine, P. Pohjanheimo, M. Lehtonen, and E. Lakervi, "Estimating the annual frequency and cost of voltage sags for customers of five Finnish distribution companies," in *Electricity Distribution, 2001. CIRED. 16th International Conference and Exhibition on*, 2001, pp. 5.

[17] J. V. Milanovic and C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sags - Part I: The methodology," *IEEE Transactions on Power Delivery*, vol. 21, pp. 918-924, 2006.

[18] J. V. Milanovic and C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sags - Part II: Practical implementation," *IEEE Transactions on Power Delivery*, vol. 21, pp. 925-932, 2006.

[19] M. F. Alves and V. R. C. Fonseca, "Voltage sag stochastic estimate," presented at *Conference Record of the 2001 IEEE Industry Application Conference.*, 2001.

[20] J. Wang, S. Chen, and T. T. Lie, "System voltage sag performance estimation," *IEEE Transactions on Power Delivery*, vol. 20, pp. 1738-1747, Apr 2005.

[21] D. L. Sikes, "Comparison between power quality monitoring results and predicted stochastic assessment of voltage sags-"real" reliability for the customer," *IEEE Transactions on Industry Applications*, vol. 36, pp. 677-682, March 2000.

[22] M. R. Qader, M. H. J. Bollen, and R. N. Allan, "Stochastic prediction of voltage sags in a large transmission system," *Industry Applications, IEEE Transactions on*, vol. 35, pp. 152-162, 1999.

[23] S. Quaia and F. Tosato, "Interruption costs caused by supply voltage dips and outages in small industrial plants: a case study and survey results," in *The IEEE Region 8 EUROCON. Computer as a Tool*, 2003, pp. 258.

[24] M. M. A. Aziz, G. A. A. Salam, and S. M. Kozman, "Cost and mitigation of voltage sag for industrial plants," in *Electrical, Electronic and Computer Engineering, 2004. ICEEC '04. 2004 International Conference on*, 2004, pp. 869-871.

[25] H. Arango, E. G. Domingues, J. P. G. Abreu, and D. M. Camposilvan, "Applying real options methodology to value electrical power quality projects," in *Harmonics and Quality of Power, 2002. 10th International Conference on*, 2002, pp. 385-389 vol.1.

[26] S. Quaia and F. Tosato, "A method for the computation of the interruption costs caused by supply voltage dips and outages in small industrial plants," in *EUROCON 2003. Computer as a Tool. The IEEE Region 8*, 2003, pp. 249.

[27] R. Lamedica, A. Patrizio, A. Prudenzi, E. Tironi, and D. Zaninelli, "Power quality costs and upgrading solutions: the energy centre," in *Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on*, 2000, pp. 691-696.

[28] *ITI (CBEMA) Curve and Application Note*, Information Technology Industry Council, 1998.

[29] *Specification for Semiconductor Processing Equipment Voltage Sag Immunity*, SEMI F47-0606, 2006.

[30] S. Ž. Djokic´, K. Stockman, J. V. Milanovic´, J. J. M. Desmet, and R. Belmans, "Sensitivity of AC adjustable speed drives to voltage sags and short interruptions," *IEEE Transactions on Power Delivery*, vol. 20, pp. 494-505, January 2005.

[31] S. Z. Djokic´, D. S. Kirschen, and J. V. Milanovic´, "Sensitivity of AC coil contactors to voltage sags, short interruptions, and undervoltage transients," *IEEE Transactions on Power Delivery*, vol. 19, pp. 1299-1307, July 2004.

[32] S. Ž. Djokic´, J. Desmet, G. Vanalme, J. V. Milanovic´, and K. Stockman, "Sensitivity of personal computers to voltage sags and short interruptions," *IEEE Transactions on Power Delivery*, vol. 20, pp. 375-383, January 2005.

[33] J. Y. Chan, "Methodology for assessment of financial losses due to voltage sags and short interruptions," MSc thesis, School of Electrical and Electronic Engineering, University of Manchester, Manchester, 2006.

[34] P. Pohjanheimo and M. Lehtonen, "Introducing prob-a-sag - a probabilistic method for voltage sag management," presented at *11th International Conference on Harmonics and Quality of Power*, 2004.

[35] C. P. Gupta and J. V. Milanovic, "Probabilistic assessment of equipment trips due to voltage sags," *IEEE Transactions on Power Delivery*, vol. 21, pp. 711-718, April 2006.

[36] C. P. Gupta and J. V. Milanovic, "Costs of voltage sags: Comprehensive assessment procedure," in *Power Tech, 2005 IEEE Russia*, 2005, pp. 1.

[37] J. Wang, S. Chen, and T. T. Lie, "Estimating economic impact of voltage sags," in *International Conference on Power System Technology*, Singapore, 2004, pp. 350-355.

[38] S. Y. Yun and J. C. Kim, "An evaluation method of voltage sag using a risk assessment model in power distribution systems," *International Journal of Electrical Power and Energy Systems*, vol. 25, pp. 829-839, Dec 2003.

[39] R. C. Leborgne, J. M. C. Filho, J. P. G. d. Abreu, T. C. Oliveira, A. A. Postal, and L. H. Zaparoli, "Alternative methodology for characterization of industrial process sensitivity to voltage sags," presented at *IEEE Bologna PowerTech Conference Proceedings*, Bologna, Italy, 2003.

[40] T. Andersson and D. Nilsson, "Test and evaluation of voltage dip immunity," STRI AB and Vatenfall AB, 27 Novenber 2002.

[41] C. P. Gupta, J. V. Milanovic, and M. T. Aung, "The influence of process equipment composition on financial losses due to voltage sags," in *Harmonics and Quality of Power, 2004. 11th International Conference on*, 2004, pp. 28.

[42] S. C. Vegunta and J. V. Milaniovic, "Financial impact of power quality on Indian Pharmaceutical Industry - Survey results," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1.

[43] S. C. Vegunta, "Impact of voltage sags on continuous industrial processes," PhD. thesis, School of Electrical and Electronic Engineering, University of Manchester, 2008.

[44] S. C. Vegunta and J. V. Milanovic, "Estimation of cost of downtime of industrial process due to voltage sags," *Power Delivery, IEEE Transactions on*, vol. PP, pp. 1, 2009.

[45] K. K. Kariuki and R. N. Allan, "Evaluation of reliability worth and value of lost load," *IEE Proceedings: Generation, Transmission and Distribution*, vol. 143, pp. 171-180, 1996.

[46] Y. Zhang, "Techno-economic assessment of voltage sag performance and mitigation," PhD thesis, School of Electrical & Electronic Engineering, University of Manchester, 2008.

[47] J. V. Milanovic and Y. Zhang, "Global minimization of financial losses due to voltage sags with FACTS based devices," *IEEE Transactions on Power Delivery*, vol. 25, pp. 298-306, Jan 2010.

[48] G.-J. Lee, M. M. Albu, and G. T. Heydt, "A power quality index based on equipment sensitivity, cost, and network vulnerability," *IEEE Transactions on Power Delivery*, vol. 19, pp. 1504-1510, July 2004.

[49] J. T. Crozier and W. N. Wisdom, "A power quality and reliability index based on customer interruption costs," *Power Engineering Review, IEEE*, vol. 19, pp. 59-61, 1999.

[50] M. McGranaghan and B. Roettger, "Economic evaluation of power quality," *IEEE Power Engineering Review*, vol. 22, pp. 8-12, Feb. 2002.

[51] R. Ghandehari and A. Jalilian, "Economical impacts of power quality in power systems," in *Universities Power Engineering Conference, 2004. UPEC 2004. 39th International*, 2004, pp. 893.

[52] Y. Shih-An, S. Chun-Lien, and C. Rung-Fang, "Assessment of power quality cost for high-tech industry," in *IEEE Power India Conference*, 2006, pp. 6.

[53] M. F. McGranaghan and W. C. Roettger, "The economics of custom power," in *Transmission and Distribution Conference and Exposition, 2003 IEEE PES*, 2003, pp. 944.

[54] M. Lehtonen and B. Lemstrom, "Comparison of the methods for assessing the customers outage costs," presented at *International Comference on Energy Management and Power Delivery*, 1995.

[55] F. Carlsson and P. Martinsson, "Does it matter when a power outage occurs? - A choice experiment study on the willingness to pay to avoid power outages," Department of Economics, Gothengurg University, 2004.

[56] F. Carlsson and P. Martinsson, "Willingness to pay among Swedish households to avoid power outages - A random parameter tobit model approach," Department of Economics, Gothenburg University, 2004.

[57] A. Sannino, M. G. Miller, and M. H. J. Bollen, "Overview of voltage sag mitigation," in *Power Engineering Society Winter Meeting, 2000. IEEE*, 2000, pp. 2872.

[58] J. V. Milanovic and Y. Zhang, "Modelling of FACTS devices for voltage sag mitigation studies in large power systems," *IEEE Transactions on Power Delivery*, vol. 25, pp. 3044-3052, Oct. 2010.

[59] C. da Costa Teixeira, "Power quality solutions for low and medium voltage critical loads," in *Transmission and Distribution Conference and Exposition: Latin America, 2004 IEEE/PES*, 2004, pp. 326.

[60] A. Elnady and M. M. A. Salama, "Unified approach for mitigating voltage sag and voltage flicker using the DSTATCOM," *Power Delivery, IEEE Transactions on*, vol. 20, pp. 992, 2005.

[61] B. Rogers, M.Stephens, and P. E. M. McGranaghan, "Power quality issues and solutions in the automotive industry," presented at *International Conference on Power System Technology - POWERCON 2004*, Singapore, 2004.

[62] A. Ruddell, "Investigation on storage technologies for intermittent renewable energies: evaluation and recommended R&D strategy," Investire-Network, June 2003.

[63] C. J. Melhorn, A. Braz, P. Hofmann, and R. J. Mauro, "An evaluation of energy storage techniques for improving ride-through capability for sensitive customers on underground networks," *Industry Applications, IEEE Transactions on*, vol. 33, pp. 1083, 1997.

[64] H. J. Kim, K. C. Seong, J. W. Cho, J. H. Bae, K. D. Sim, S. Kim, E. Y. Lee, K. Ryu, and S. H. Kim, "3 MJ/750 kVA SMES System for Improving Power Quality," *Applied Superconductivity, IEEE Transactions on*, vol. 16, pp. 574, 2006.

[65] D. V. Hertem, M. Didden, J.Driesen, and R. Belmans, "Choosing the correct mitigation method againsts voltage dips and interruptions:a customer based approach," *IEEE Transactions on Power Delivery*, vol. 22, pp. 331-339, January 2007.

[66] R. C. Degeneff, R. Barss, D. Carnovale, and S. Raedy, "Reducing the effect of sags and momentary interruptions: a total owning cost prospective," in *Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on*, 2000, pp. 397.

[67] Z. Yan and J. V. Milanovic, "Application of Niching Genetic Algorithms in System-wide Voltage Sag Mitigation Studies," in *Power Tech, 2007 IEEE Lausanne*, 2007, pp. 1515.

[68] Z. Yan and J. V. Milanovic, "Voltage sag cost reduction with optimally placed FACTS devices," in *Electrical Power Quality and Utilisation, 9th International Conference on*, 2007, pp. 1.

[69] Z. Yan and J. V. Milanovic, "Techno-economic improvement of voltage sag performance with FACTS devices," in *Electrical Power Quality and Utilisation, 9th International Conference on*, 2007, pp. 1.

[70] J. A. Oliver, R. Lawrence, and B. B. Banerjee, "How to specify power quality tolerant process equipment," *Industry Applications Magazine, IEEE*, vol. 8, pp. 21, 2002.

[71] J. E. Jipping and W. E. Carter, "Application and experience with a 15 kV static transfer switch," *Power Delivery, IEEE Transactions on*, vol. 14, pp. 1477, 1999.

[72] S. L. Chen, G. B. Chen, S. C. Hsu, A. Y. T. Chen, T. Y. Guo, F. F. Huang, and Y. C. Huang, "Mitigation of voltage sags by network reconfiguration of a utility power system," in *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES*, 2002, pp. 2067.

[73] S. Bahadoorsingh, J. V. Milanovic, Z. Yan, C. P. Gupta, and J. Dragovic, "Minimization of Voltage Sag Costs by Optimal Reconfiguration of Distribution Network Using Genetic Algorithms," *Power Delivery, IEEE Transactions on*, vol. 22, pp. 2271, 2007.

[74] J. C. Cebrian and N. Kagan, "Evolutionary algorithms for the reconfiguration of radial distribution networks considering long interruption and voltage sag disruption costs," in *Harmonics and Quality of Power, 13th International Conference on*, 2008, pp. 1.

[75] C. S. Chang and P. C. Loh, "Investigation of voltage quality improvement with coordinated applications of fault current limiter," in *IEEE Power Engineering Society Winter Meeting*, 2000, pp. 2562.

[76] M. A. Hannan and A. Mohamed, "Performance evaluation of solid state fault current limiters in electric distribution system," in *Research and Development, Proceedings. Student Conference on*, 2003, pp. 245.

[77] F. Tosato and S. Quaia, "Reducing voltage sags through fault current limitation," *Power Delivery, IEEE Transactions on*, vol. 16, pp. 12, 2001.

[78] S. D. Frazier and C. Bonham, "Suggested practices for reducing animal-caused outages," *Industry Applications Magazine, IEEE*, vol. 2, pp. 25, 1996.

[79] P. H. Patrick and J. S. Poulton, "Development and evaluation of environmentally sustainable technologies for animal exclusion at transmission stations," in *Power Engineering Society Summer Meeting, 1999. IEEE*, 1999, pp. 298.

[80] J. Burnham, R. Carlton, E. A. Cherney, G. Couret, K. T. Eldridge, M. Farzaneh, S. D. Frazier, R. S. Gorur, R. Harness, D. Shaffner, S. Siegel, and J. Varner, "Preventive measures to reduce bird-related power Outages-part I: electrocution and collision," *Power Delivery, IEEE Transactions on*, vol. 19, pp. 1843, 2004.

[81] E. Cinieri and F. Muzi, "Lightning induced overvoltages, improvement in quality of service in MV distribution lines by addition of shield wires," *Power Delivery, IEEE Transactions on*, vol. 11, pp. 361, 1996.

[82] A. Porrino, I. Alexandri, M. Clement, G. S. Finlay, T. Henriksen, J. Hoeffelman, M. Ishii, P. Martinez Cid, C. A. Nucci, F. Poplansky, F. Rachidi, G. P. T. Roelofs, and R. Rudolph, "Lightning protection of distribution networks. II. Application to MV networks," in *Electricity Distribution. Part 1: Contributions. CIRED. 14th International Conference and Exhibition on (IEE Conf. Publ. No. 438)*, 1997, pp. 28/1.

[83] P. Heine, M. Lehtonen, J. Niskanen, and A. Oikarinen, "Limiting the number of the most severe voltage sags in rural medium voltage networks," in *Power Quality and Supply Reliability Conference*, 2008, pp. 99.

[84] P. Heine, M. Lehtonen, and A. Oikarinen, "Overvoltage protection, faults and voltage sags," in *Harmonics and Quality of Power, 11th International Conference on*, 2004, pp. 100.

[85] P. A. Kuntz, R. D. Christie, and S. S. Venkata, "Optimal vegetation maintenance scheduling of overhead electric power distribution systems," *Power Delivery, IEEE Transactions on*, vol. 17, pp. 1164, 2002.

[86] P. J. Appelt and J. W. Goodfellow, "Research on how trees cause interruptions - applications to vegetation management," in *Rural Electric Power Conference*, 2004, pp. C6.

[87] T. A. Short, *Electric Power Distribution Handbook*. ed. New York: CRC Press, 2004.

[88] M. Radmehr, S. Farhangi, and A. Nasiri, "Effects of power quality distortions on electrical drives and transformer life in paper industries: simulations and real time measurements," presented at *IEEE IAS Pulp and Paper Conference*, 2006.

[89] C. A. Warren, T. A. Short, J. J. Burke, H. Morosini, C. W. Burns, and J. Storms, "Power quality at Champion Paper-the myth and the reality," *IEEE Transactions on Power Delivery*, vol. 14, pp. 636-641, April 1999.

[90] B. M. Nacke and R. L. Schlake, " The importance of power quality management in the pulp and paper industry," *IEEE Transactions on Industry Applications*, vol. 38, pp. 758-762, May-June 2002.

[91] D. Andrews, M. T. Bishop, and J. F. Witte, "Harmonic measurements, analysis, and power factor correction in a modern steel manufacturing facility," *IEEE Transactions on Industry Applications*, vol. 32, pp. 617-624, 1996.

[92] G. J. Miranda, "Options for the cement industry in the deregulated power era," presented at *2002 IEEE-IAS/PCA 44th Cement Industry Technical Conference*, 2002.

[93] D. Bentancur, G. Perez, A. Pardo, and A. Rondoni, "Study of a cement plant experiencing power quality problems inUruguay," presented at *CIRED 16th International Conference and Exhibition on Electricity Distribution*, 2001.

[94] M.Ahrens and Z. Konstantinovic, "Harmonic filters and power factor compensation for cement plants," presented at *2005 Cement Industry Technical Conference*, 2005.

[95] "Assessing power quality in a California food processing plant," Public Interest Energy Research Program, March 2003.

[96] K. Stockman, F. D. Hulster, M. Didden, and R. Belmans, "Embedded solutions to protect textile processes against voltage sags," in *Industry Applications Conference, 37th IAS Annual Meeting*, 2002, pp. 2561.

[97] S. A. Yin, C. N. Lu, E. Liu, Y. C. Huang, and C. Y. Huang, "A survey on high tech industry power quality requirements," presented at *IEEE/PES Transmission and Distribution Conference and Exposition*, 2001.

[98] D. Walsh and R. R. Legoy, "Multi generation enhanced power quality design for semiconductor manufacturing facilities," presented at *2001 IEEE Power Engineering Society Winter Meeting*, 2001.

[99] A. McEachern, "Samsung's "power vaccine" standard: applications and recommendations for a stringent power quality immunity standard," Power Standards Lab, California.

[100] R. Barss, "New innovations in surge suppressors-the impact on the telecommunication industry," in *Telecommunications Energy Conference, 1996. INTELEC '96., 18th International*, 1996, pp. 155.

[101] M. Vatani and S. Bayer, "Working with high-tech customers on power quality issues," presented at *57th Conference for Protective Relay Engineers*, 2004.

[102] A. Moreno-Munoz, M. Gonzalez, M. Linan, and J. J. Gonzalez, "Power quality in high-tech plants: a case study," presented at *2005 IEEE Compatibility in Power Electronics*, 2005.

[103] H. M. Ryan and M. Osborne, " Power quality: a perspective of system problems and solution considerations," presented at *IEE Colloquium on Issues in Power Quality*, 1995.

[104] R. C. Lentz, F. J. Mercede, and J. N. Mercede, Jr., "A student design project to improve power quality for a commercial facility," *Power Systems, IEEE Transactions on*, vol. 10, pp. 3, 1995.

[105] "Power quality for business," [online], APS, [cited 20 Sept., 2010], <http://www.aps.com/main/_files/services/BusWaysToSave/Power.pdf>.

[106] C. J. Melhorn, P. Hofmann, and M. Samotyj, "Characterization of power quality problems associated with large commercial customers served from large underground distribution network systems," in *IEEE Industrial and Commercial Power Systems Technical Conference*, 1994, pp. 117.

[107] M. J. Sullivan, T. Vardell, and M. Johnson, "Power interruption costs to industrial and commercial consumers of electricity," *IEEE Transactions on Industry Applications*, vol. 33, pp. 1448-1457, 1997.

[108] "Power quality for healthcare facilities using flywheel energy storage," Active Power Inc., 2003.

[109] G. A. Corner, G. D. Currie, A. L. Evans, and R. Railton, "Quality of electrical mains supplies in hospitals: Implications for microprocessor-controlled medical equipment," *Medical and Biological Engineering and Computing*, vol. 31, pp. 438-444, July 1993.

[110] S. M. Islam, T. Larsen, W. B. Lawrence, D. R. Castro, E. O. Carillo, and J. S. Perez, "Power quality issues in hospitals," presented at *Australian Universities Power Engineering Conference*, 2001.

[111] "Power quality monitoring and analysis-Evaluating power quality at medical center," S&C Electric Company, 1998.

[112] P. W. Hall, B. B. Bailey, and E. H. Camm, "Power quality evaluation at medical center," in *IEEE Transmission and Distribution Conference*, 1999, pp. 560-565.

[113] T. L. Baldwin, T. J. Hogans, S. D. Henry, F. J. Renovich, and P. T. Latkovic, "Reactive-power compensation for voltage control at resistance welders," *IEEE Transactions on Industry Applications*, vol. 41, pp. 1485-1492, 2005.

[114] D. W. Petro and R.L.Wood, "Power quality issues regarding adjustable speed drives in petroleum terminals," in *IEEE Incorporated Industry Application Society 41st Annual Petroleum and Chemical Industry Conference*, 1994, pp. 227-234.

[115] B. H. Chowdhury, "Power Quality," in *IEEE Potentials: the magazine for up-and-coming engineers*, 2001, pp. 5-11.

[116] S. Saksena and S. G. Karady, "Effects of voltage sags on household loads," presented at *IEEE Power Engineering Society General Meeting*, 2005.

[117] P. Pohjanheimo, "A Probabilistic Method for Comprehensive Voltage Sag Management in Power Distribution Systems," Doctoral thesis, Department of Electrical and Communications Engineering, Helsinki University of Technology, 2003.

[118] C. P. Gupta, J. V. Milanovic, and M. T. Aung, "The influence of process equipment composition on financial losses due to voltage sags," presented at *11th International Conference on Harmonics and Quality of Power*, Lake Placid, NY, United States, 2004.
[119] M. Delfanti, E. Fumagalli, P. Garrone, L. Grilli, and L. L. Schiavo, "Toward Voltage-Quality Regulation in Italy," *Power Delivery, IEEE Transactions on*, vol. 25, pp. 1124.
[120] D.Chapman, "The cost of poor power quality," Copper Development Association, November 2001.
[121] K. H. LaCommare and J. H. Eto, "Understanding the cost of power interruption to US electricity consumers," Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-55718, 2004.
[122] Primen, "The cost of power disturbances to industrial & digital economy companies," EPRI CEIDS, June 2001.
[123] EPRI, "Incentives and penalties for electrical power quality under performance based regulations," CEA Technologies Inc. (CEATI), T044700-5124, November 2005.
[124] J. D. Lamoree, "Cost of Outages," Enernex Corporation, October 14 2004.
[125] Y. Shih-An, L. Chan-Nan, E. Liu, H. Yu-Chang, and H. Chinug-Yi, "Assessment of interruption cost to high tech industry in Taiwan," in *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, 2001, pp. 270.
[126] N. Kee-young, C. Sang-bong, R. Hee-suk, J. Seong-hwan, L. Jae-duck, and K. Dae-kyung, "Development of criteria and calculation of Korean industrial customer interruption costs," in *Power System Technology, International Conference on*, 2004, pp. 592.
[127] G. Linhofer, P. Maibach, and F. Wong, "Power quality devices for short term and continuous voltage compensation," presented at *International power quality conference*, Singapore, 2002.
[128] J. V. Milanovic and N. Jenkins, "Power quality cost for manufacturing industries," in *EdF Workshop*, Paris, 2003, pp.
[129] L. Lawton, M. Sullivan, K. V. Liere, and A. K. J. Eto, "A framework and review of customer outage costs: Integration and analysis of electric utility outage cost surveys," Lawrence Berkeley National Laboratory, 2003.
[130] G. Tollefson, R. Billinton, G. Wacker, E. Chan, and J. Aweya, "Canadian customer survey to assess power system reliability worth," *IEEE Transactions on Power Systems*, vol. 9, pp. 443-450, 1994.
[131] *Statistical Classification of Economic Activities in the European Community*, Eurostat NACE Rev. 2, 2006.
[132] "Electricity outage cost study," Energy Research Institute, Chulalongkorn University, Bangkok, 2001.
[133] S. B. Choi, K. Y. Nam, D. K. Kim, S. H. Jeong, H. S. Ryoo, and J. D. Lee, "Evaluation of interruption costs for industrial customers in korea," in *IEEE PES Power Systems Conference and Exposition*, 2006, pp. 839-845.
[134] E. N. Dialynas, S. M. Megaloconomos, and V. C. Dali, "Interruption cost analysis for the electrical power customers in greece," in *Electricity Distribution, 16th International Conference and Exhibition on*, 2001, pp. 129-129.
[135] M. Pandey and R. Billinton, "Electric service reliability worth determination in the Nepal Power System," in *Electrical and Computer Engineering, IEEE Canadian Conference on*, 1999, pp. 1465-1470.

[136] "Glossary of statistical terms: Purchasing power parities (PPPs)," [online], Organisation for Economic Co-orperation and Development, [cited Sep. 29, 2010], <http://stats.oecd.org/glossary/detail.asp?ID=2205>.

[137] "Global purchasing power parities and real expenditures," World Bank, Washington, 2008.

[138] P. A. Tipler and G. Mosca, *Physics for Scientists and Engineers*. 6 ed.: W. H. Freeman, 2007.

[139] F. Carlsson, B. Widell, and C. Sadarangani, "Ride-through investigation for a hot mill process," presented at *International Conference on Power System Technology*, 2000.

[140] Z. Q. Chen, "Effect of voltage sags on sensitive equipment," Master thesis, Department of Electrical Engineering, National Sun Yat-sen University, Kaohsiung, 2004.

[141] J. Lamore, D. Mueller, P. Vinett, W. Jones, and M. Samotyj, "Voltage sag analysis case studies," *IEEE Transactions on Industry Applications*, vol. 30, pp. 1083-1089, July-Aug 1994.

[142] V. E. Wagner, A. A. Andreshak, and J. P. Staniak, "Power quality and factory automation," *IEEE Transactions on Industry Applications*, vol. 26, pp. 620-626, July-Aug 1990.

[143] G. Brauner and C. Hennerbichler, "Voltage dips and sensitivity of consumers in low voltage networks," presented at *CIRED 16th International Conference and Exhibition on Electricity Distribution*, 2001.

[144] E. R. Collins_Jr. and M. A. Bridgwood, "The impact of power system disturbances on AC-coil contactors," presented at *IEEE Annual Textile, Fiber, and Film Industry Technical Conference*, 1997.

[145] P.Pohjanheimo and M. Lehtonen, "Equipment sensitivity to voltage sags-test results for contactors, PCs and gas discharge lamps," presented at *10th International Conference on Harmonics and Quality of Power*, 2002.

[146] M. T. Aung and J. V. Milanovic, "The influence of transformer winding connections on the propagation of voltage sags," *IEEE Transactions on Power Delivery*, vol. 21, pp. 262, 2006.

[147] J. G. Dougherty and W. L. Stebbins, "Power quality: a utility and industry perspective," in *Textile, Fiber, and Film Industry Technical Conference, IEEE Annual*, 1997, pp. 5-10.

[148] S. S. Choi, J. D. Li, and D. M. Vilathgamuwa, "A generalized voltage compensation strategy for mitigating the impacts of voltage sags/swells," *IEEE Transactions on Power Delivery*, vol. 20, pp. 2289-2297, July 2005.

[149] S. S. Choi, J. D. Li, and D. M. Vilathgamuwa, "Dynamic voltage restoration with minimum energy injection," *IEEE Transactions on Power Systems*, vol. 15, pp. 51-57, Feb 2000.

[150] J. V. Milanovic, M. T. Aung, and S. C. Vegunta, "The influence of induction motors on voltage sag propagation-part I: accounting for the change in sag characteristics," *Power Delivery, IEEE Transactions on*, vol. 23, pp. 1063, 2008.

[151] A. Rojas, "Flywheel energy matrix systems: Today's technology, tomorrow's energy storage solution.," in *International Stationary Battery Conference*, Florida, 2003, pp.

[152] W. E. Brumsickle, R. S. Scheider, G. A. Luckjiff, D. M. Divan, and M. F. McGranaghan, "Dynamic sag correctors: cost effective industrial power line conditioning," *IEEE Transactions on Industrial Applications*, vol. 37, pp. 212, Feb 2001.

[153] W. A. Chisholm, "Outline of guide for application of transmission line surge arresters 42 to 765 kV," EPRI, 1012313, Oct. 2006.
[154] J. Sanders and K. Newman, "Polymer arresters as an alternative to shield wire," Hubbell Power Systems Inc., EU1413-H, 1992.
[155] C. Meyer, S. Schroder, and R. W. De Doncker, "Solid-state circuit breakers and current limiters for medium-voltage systems having distributed power systems," *Power Electronics, IEEE Transactions on*, vol. 19, pp. 1333, 2004.
[156] A. Cali, S. Conti, F. Santonoceto, and G. Tina, "Benefits assessment of fault current limiters in a refinery power plant: a case study," in *Power System Technology, International Conference on*, 2000, pp. 1505.
[157] Y. H. Song, *Modern Optimisation Techniques in Power Systems*. ed. Dordrecht, Netherlands: Kluwer Academic Publishers, 1999.
[158] J. Kueck, B. Kirby, T. Rizy, F. Li, and N. Fall, "Reactive power from distributed energy," *The Electricity Journal*, vol. 19, pp. 27, 2006.
[159] M. Avendano-Mora, J. V. Milanovic, B. Patel, and Y. Zhang, "The influence of model parameters and uncertainties on assessment of network wide costs of voltage sags," in *Electrical Power Quality and Utilisation, 10th International Conference on*, 2009, pp. 1.
[160] J. V. Milanovic, A. Myo Thu, and C. P. Gupta, "The influence of fault distribution on stochastic prediction of voltage sags," *Power Delivery, IEEE Transactions on*, vol. 20, pp. 278, 2005.
[161] J. A. Martinez, J. Martin-Arnedo, and J. V. Milanovic, "Load modeling for voltage sag studies," in *IEEE Power Engineering Society General Meeting*, 2003, pp. 2513.

Appendix A Typical Financial Loss due to Voltage Sags and Interruptions

Note: all Tables and Figures are taken from (E9)

Table A-1 CIC (£) values

Sector	CIC (£) for an interruption of duration						
	Momentary	1 min	20 min	1 hour	4 hour	8 hour	24 hour
Residential	-	-	0.19	0.7	4.78	-	-
Commercial	11.47	11.47	49.12	106	345	719	1.0k
Industrial	1.2k	1.5k	2.9k	4.3k	7.6k	12.0k	16.3k
Large user	216k	216k	219k	233k	329k	413k	581k

Table A-2 Estimated costs for industrial sectors

Industrial Process	Voltage Dip Cost (% of total yearly power cost)		
	Category A	Category B	Category C
Semiconductor	0 to 2	2 to 10	5 to 6
Pharmaceutical	0 to 0.8	1 to 5	2 to 4
Chemical	0 to 1	1 to 3	2 to 4
Petrochemical	0 to 1	2 to 5	1.5 to 3.5
Manufacturing	0 to 0.2	0 to 1	0.8 to 1
Metallurgy	0 to 0.2	0 to 1.5	1 to 1.5
Food	0 to 0.5	0 to 1.5	0 to 2

Table A-3 Direct cost per event per kW. Politecnico di Milano

[€/kW-event]	Entire sample (sub-sample)		
	Median	Mean	Interval
All sectors	0.8 (1.1)	2.8 (3.3)	0 (0.1) - 30
Per NACE codes			
DA – Food products	0.6	5.9	0.2 – 30
DB – Textiles	3.2	3.2	3.2
DE – Paper	0.8 (0.9)	0.9 (1.0)	0.1 – 2.2
DF – Refined petroleum products	13.3	13.3	13.3
DG – Chemicals and man-made fibers	0.6 (0.7)	0.5 (0.7)	0 (0.6) – 0.8
DH – Plastic products	1.8	2.2	0.1 – 4.2
DI – Glass and ceramic products	0.8	0.9	0.1 – 2.3
DJ – Metals products	1.1 (4.9)	3.3 (4.9)	0 (1.1) – 8.7
DL – Electrical equipment	9.3	10.6	0.1 – 22.4
DM – Auto and auto components	2.9	2.9	0.7 – 5.0

Table A-4 Financial losses due to voltage dips

Industry	Typical financial loss per event (€)
Semiconductor production	3,800,000
Financial trading	6,000,000 per hour
Computer center	750,000
Telecommunications	30,000 per minute
Steel works	350,000
Glass industry	250,000

Table A-5 Financial losses of large commercial and industrial customer for various disturbances

Scenario	Financial Losses ($)
4 hour outage without notice	74,835
1 hour outage without notice	39,459
1 hour outage with notice	22,973
Voltage dip	7,694
Momentary outage	11,027

Table A-6 Impact of voltage dip on industry

Industry	Loss per voltage dip ($)
Paper manufacturing	30,000
Chemical industry (plastic, glass, etc.)	50,000
Automobile industry	75,000
Equipment manufacturing	100,000
Credit card processing	250,000
Semiconductor industry	2.5 million

Table A-7 Summary of all outage cost studies

Study	Average cost per hour	Cost per interrupted kW or kWh	Cost per event
Population Research Systems	$61,949 for large industrial and commercial All regions - $59,983 Northwest - $28,609 Southwest - $51,908 Southeast - $86,477 West - $52,734 Midwest - $28,735		
ASCO	Cellular – $41k Telephone – $72k Airline reservation – $90k		
EDF		$0.67/kW $8/kWh up to 30MWh $17.4/kWh from 30 to 50 MWh	
ESOURCE			$583k over 800 commercial and industrial customer over 1 year
IEEE 493-1997		Industrial - $6.43/kW + $9.11/kWh Commercial – $21.77/kWh	
CEIDS EPRI	$7795 for digital establishments $14,746 for continuous process manufacturing		
Primen Mass Survey	$21,688 for 19 businesses surveyed		
ICF Consulting			80 to 100 times the cost of retail electricity

Table A-8 Comparison of interruption costs of industrial customers (in year 2000 US$/kW)

Study/Duration	2 second	1 min	20 min	1 hour	2 hour	4 hour	8 hour	24 hour
Canada (small industrial)	1.07	2.55	3.65	7.71	13.68	28.13	52.06	82.87
England (industrial)	14.49	15.24	33.62	59.5	-	170.1	283	354.3
USA (industrial)	-	-	-	9.64	-	-	-	-
Nepal (industrial	-	0.11	0.23	0.42	0.58	1.50	3.00	10.99
Greece (industrial)	2.10	2.55	7.35	12	16.75	21.80	-	46.86
Taiwan (high-tech)	37.03	55.15	60.90	87.6	118.1	167.1	242.4	425.2

Table A-9 Voltage-dip sensitivity factors for different industries

Category	Dip sensitive factor
Semiconductor (SC)	1
Computer and peripherals (CP)	0.4
Telecommunications (TC), and	0.4
Optoelectronics (OE)	0.6
Precision machinery (PM)	0
Biotechnology (BT)	0

Table A-10 Industries surveyed

Industry	Number of samples	Ratio (%)
Food and beverages	49	7.4
Textile and apparel	55	8.3
Pulp and paper products	36	5.8
Chemical and products	127	19.2
Basic/fabricated metal	52	7.9
Other machinery and equipment	49	7.4
Electric and electronic equipment	82	12.4
Electric machinery	53	8.0
Audio visual equipment	48	7.3
Motor vehicles	51	7.7
Other transport equipment	56	8.5

Table A-11 Interruption cost by duration (unit: Won)

Industry type	Interruption cost per average kW ($/kW)			
	Below 3 seconds	Below 1 minutes	Below 5 minutes	Below 30 minutes
Food and beverages	22.783	44.747	78.020	128.504
Textile and apparel	8.421	8.724	9.500	13.935
Pulp and paper products	1.660	1.678	1.781	2.100
Chemical and products	39.805	50.284	52.042	61.505
Basic/Fabricated metal	12.886	18.706	33.359	63.288
Other machinery and equipment	11.594	15.950	26.605	59.443
Electric and electronic equipment	80.335	120.718	174.493	230.076
Electric machinery	7.700	13.634	21.470	45.794
Audio visual equipment	9.547	12.709	23.045	53.517
Motor vehicles	23.699	36.683	49.706	83.612
Other transport equipment	9.316	12.862	15.782	39.420

Table A-12 Expected losses due to voltage disturbance

Industry	Losses due to voltage disturbance ($/kVA per event)
Semiconductors	80 - 120
Glass	10 - 15
Automotive	6 - 10
Plastics	4 - 7
Textile	3 - 8

Table A-13 Cost per event of interruption

Industry	Cost per Event of Interruption
Paper industry	$10,000 - $30,000
Textile industry	$10,000 - $40,000
Data processing	$10,000 - $40,000
Plastic industry	$10,000 - $50,000
Semiconductor industry	$10,000 - $50,000
Automotive manufacturing	$15000

Source: EPRI – PQ Applications Guide for Architects and Engineers

Table A-14 Average cost of outages

Industry	Average cost of downtime ($/hour)
Mobile communications	41,000
Telephone ticket sales	72,000
Airline reservation	90,000
Credit card operations	2,580,000
Brokerage operations	6,480,000

Source: U.S. Department of Energy's Strategic Plan for Distributed Energy Resources (2000)

Table A-15 Estimated voltage dip costs

Industry	Duration	Cost/dip
UK steel work	30% for 3.5 cycles	£250k
US glass plant	Less than 1 second	$200k
US computer center	2 second	$600k
US car plant	Annual exposure	$10M
South Africa	Annual exposure	$3B

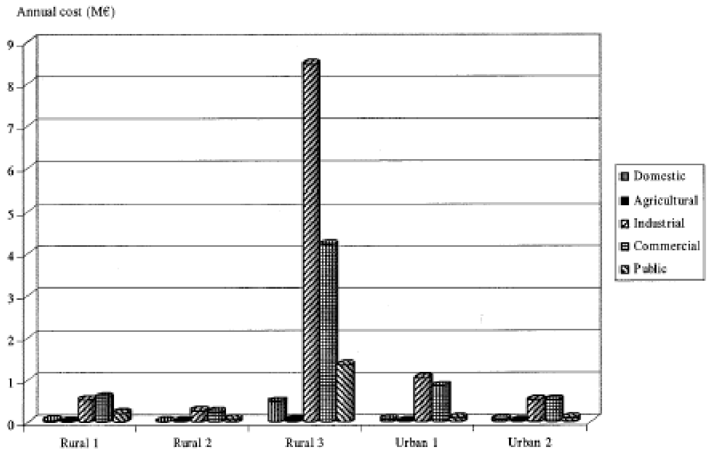


Figure A-1 Annual costs due to voltage dips for five Finnish distribution companies

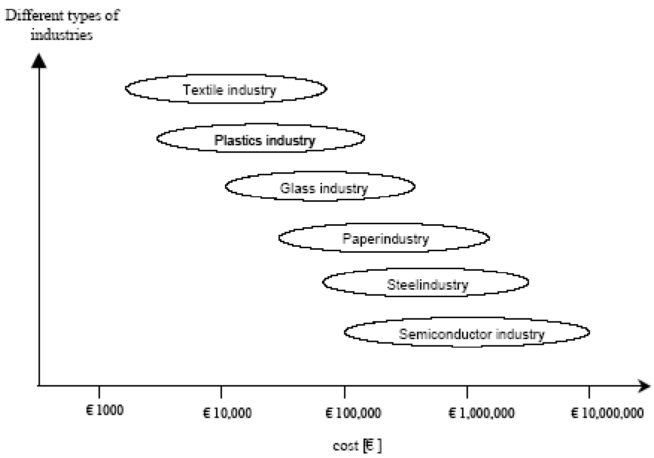


Figure A-2 Voltage dip-related cost in different industries

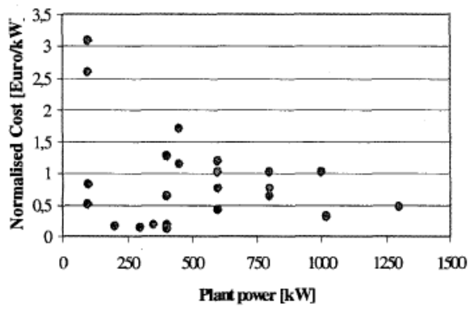


Fig. A-3 Normalized cost per dip as a function of plant power

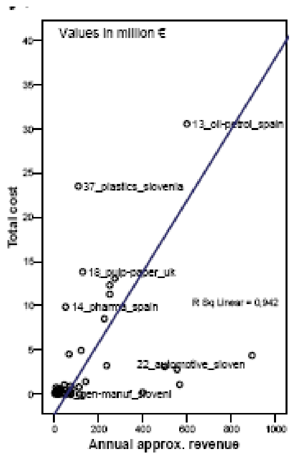


Fig. A-4 Annual costs due to power quality disturbances for the industrial sector in EU-25

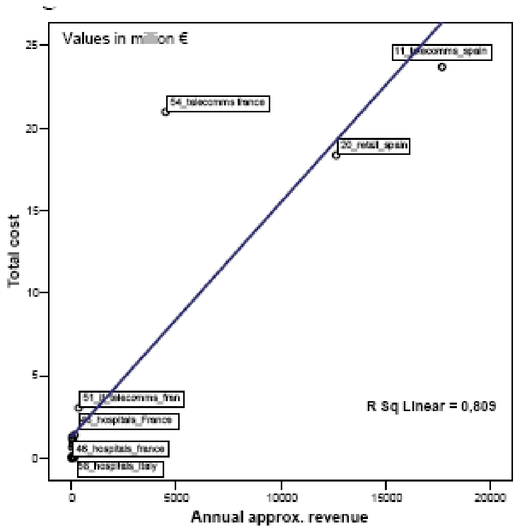


Fig. A-5 Annual costs due to power quality disturbances for the services sector in EU-25

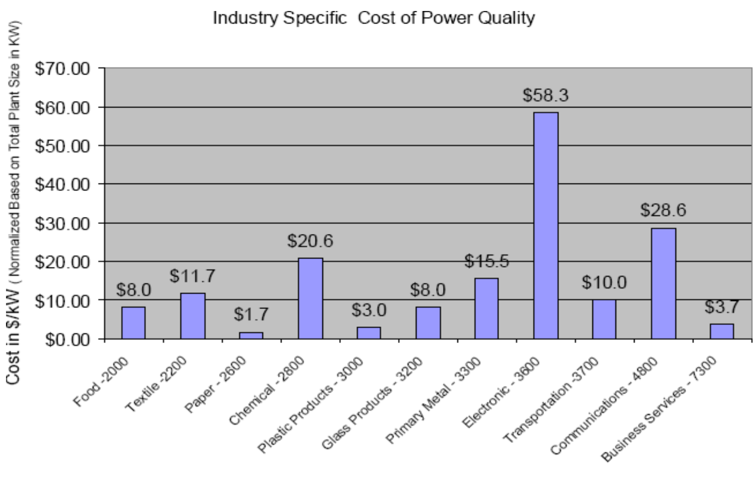


Fig. A-6 Industry-specific costs of PQ

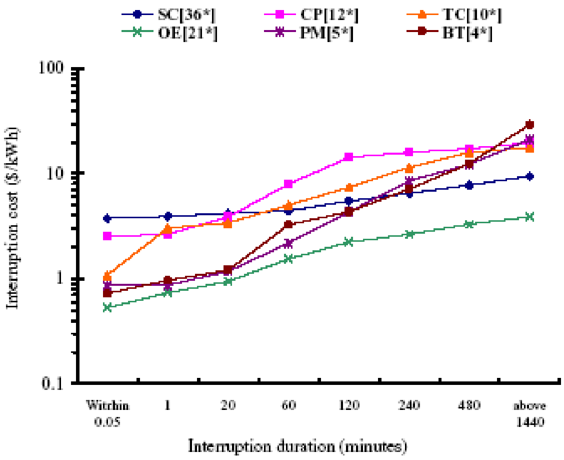


Fig. A-7 Customer damage functions for different high-tech industry categories

Appendix B Voltage Disturbance Cost Assessment Tool User Manual

Outline

- Introduction to VoDCAT v1.0
- The User Interface Tabs
- Colour Codes
- Main Functions
- Summary of Functional Buttons
- Limitations
- Warning Messages
- Exercise

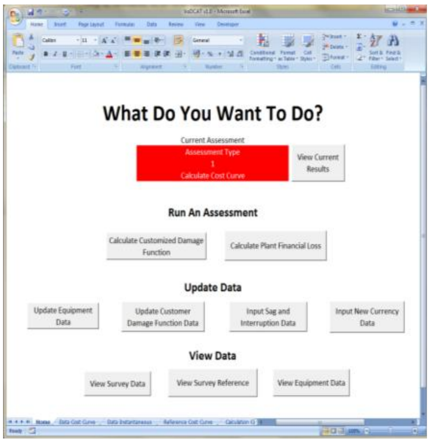
Introduction to VoDCAT v1.0

- Written in Microsoft Excel 2007
- User Interface consist of eight Excel tabs
  - Main tab a.k.a. Home
  - Two Data holding tabs
  - One Reference tab
  - Three Calculation tabs
  - Output tab
- All calculations contained in seven VBA modules of code
- Application requires Macro to be enabled

Introduction to VoDCAT v1.0

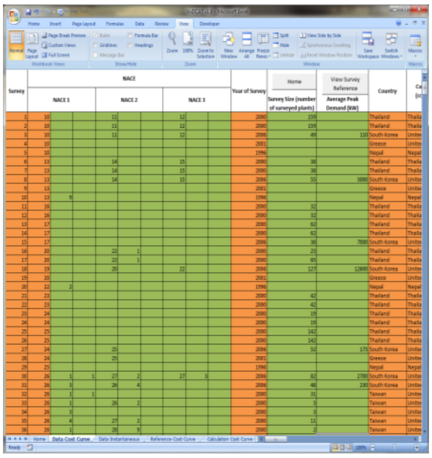
- Easy to use functions requires a few mouse click to run assessments
- Built-in links that navigate the screen to the most convenient place for the function chosen
- Developed with robustness in mind
  - Updatable database of customer cost functions
  - Updatable equipment failure characteristics

User Interface - Home



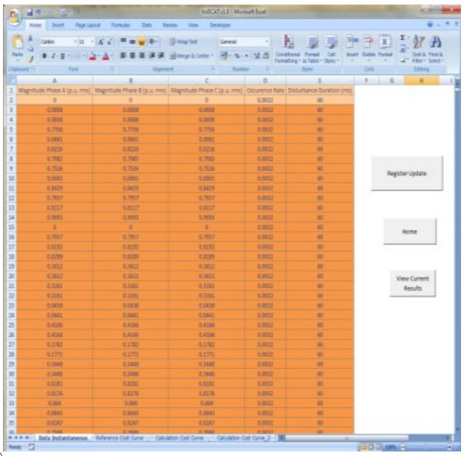
- Main control page for assessment initiation
- Outlines main functions of software
- Provides choice of assessment through functional buttons
- All assessment should initiate here
- Summarises current assessment type (area in red)

User Interface – Data Cost Curve



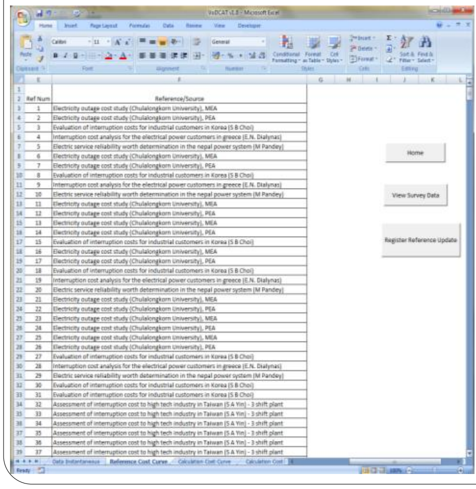
- Database of customer damage functions gathered from customer surveys
- Holds information of surveyed plants (process type, size, location, cost functions) and survey details (year, size, base currency used)
- Also contains information on inflation rates and purchasing power parity (PPP) of countries included in the surveys
- Serves as input in developing customized damage function for customers
- Can be updated when new survey data is available

User Interface – Data Instantaneous



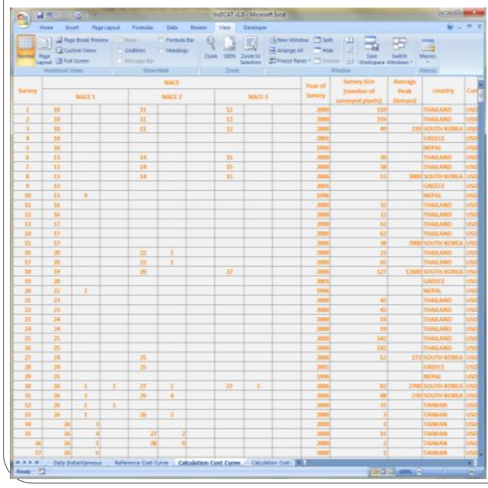
- Contains information on voltage disturbances at the assessed bus
- Serves as input for assessment of customer losses due to the disturbances

User Interface – Reference Cost Curve



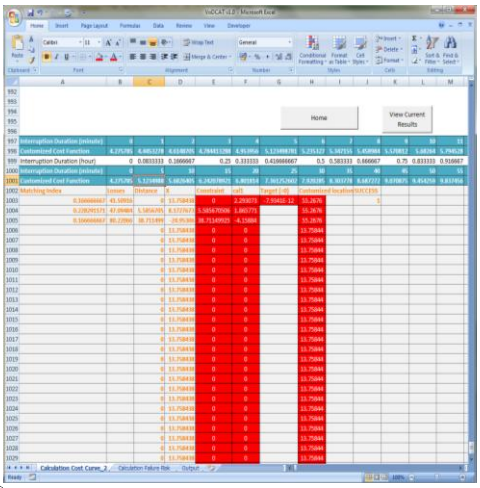
- Keeps information on the source where survey data is found
- Record keeping for future references

User Interface – Calculation Cost Curve



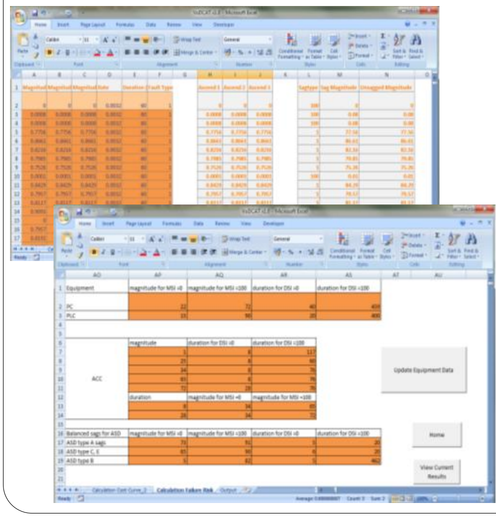
- Holds temporary information when a customized cost curve is built
- User should not modify any cell in this tab
- Treated database of customer damage functions can be found here

User Interface – Calculation Cost Curve2



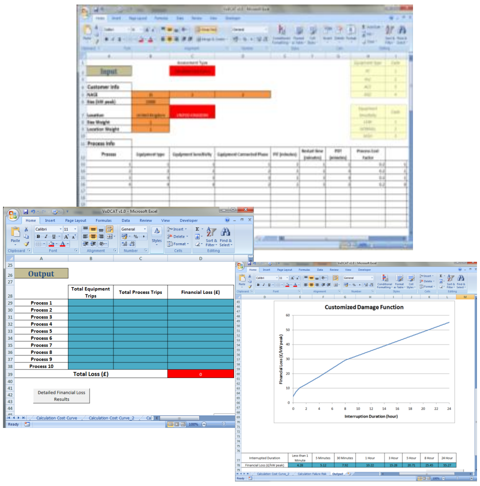
- Holds temporary information when a customized cost curve is built
- Also contains the 1 minute resolution customized cost curve if results of that detail is required

User Interface – Calculation Failure Risk



- Holds temporary information whilst assessing customer plant failure risk and financial loss
- Contains failure risk and financial loss contribution of each equipment and process for every single voltage disturbance assessed
- Also holds information on equipment failure characteristics to be modified when necessary

User Interface – Output



- Summarises main results of the assessment
- Contains link to detailed results when necessary

Colour Codes

- A set of colour codes are created to
  - Assist user in identifying the function of cells in the software
  - Assist user in filling in the required cells during assessment
  - Prevent user from moving/modifying certain cells

Optional Input

Title

Compulsory Input

Do Not Move/Modify

Explanatory Notes

Calculation Blocks (Do Not Move/Modify)

Output

Main Functions

- VoDCAT v1.0 allows user to:
  - Build customized damage functions for customer plants
  - Run assessments to determine customer failure risks and financial loss due to voltage sags, short and sustained interruptions
  - Serves as database for customer damage function surveys

Main Functions – Build Customized Damage Functions

- Purpose
  - Develop customized damage function for customer plant based on information from past surveys that matches the assessed plant
- Initiation
  - The assessment is initiated by pressing [Calculate Customized Damage Functions] in the Home page
- Input
  - Customer plant characteristics (process type, plant size and location)
  - General customer damage functions from surveys (database)
  - Currency and inflation data of countries involved

Main Functions – Build Customized Damage Functions

- Customer plant info (type, size, and location)

Customer Info			
NACE	15	2	2
Size (kW peak)	15000		
Location	United Kingdom	UNITED KINGDOM	
Size Weight	1		
Location Weight	1		

Main Functions – Build Customized Damage Functions

- General customer damage functions from surveys

Survey	NACE								
	NACE 1			NACE 2			NACE 3		
1	10	2		11			12		
2	10			11	1	1	12	3	
3	10	4	4	11	2		12	4	

Compulsory input Optional input

Year of Survey	Survey Size (number of surveyed plants)	Average Peak Demand (kW)	Country	Currency (country)	Exchange rate (equivalent to 1US$ at time of survey)
2000	159	5000	Thailand	Thailand	NA
2000	159	10000	Thailand	Thailand	NA
2006	49	110	South Korea	United States	960

Main Functions – Build Customized Damage Functions

- General customer damage functions from surveys

Cost Per Sag less than 1 minute (per kW of plant power)	Interruption Cost										
	1 min	3 min	5 min	20 min	30 min	1 hour	2 hour	4 hour	8 hour	> 8 hour	24 hour
2.34	2.97				32.96	76.43	151.68	305.47	602.69		
6.73	7.3				20.81	34.83	57.18	154.55	249.92		
22.782	44.747		78.02		128.504	182.43		410.426	896.906	1103.59	

Main Functions – Build Customized Damage Functions

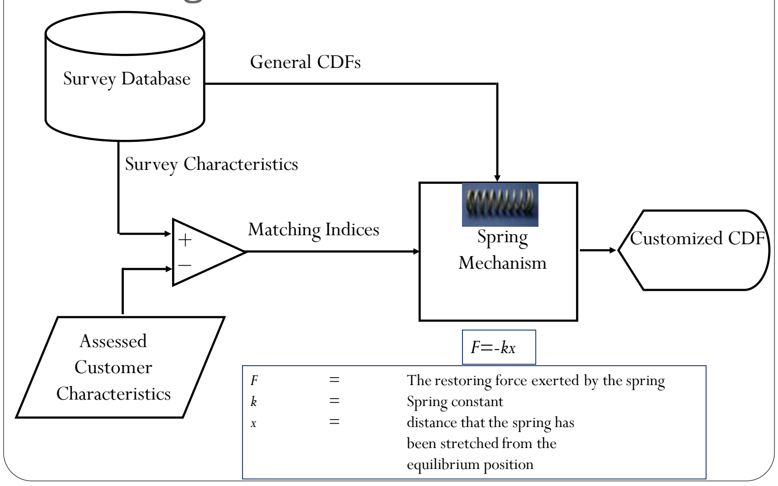
- Currency and inflation data

Year	Inflation Rate and PPP at year 2005				
	Greece	India	South Korea	Nepal	Taiwan
1996	0	0.08977	0.0493	0.081	0.03075
1997	0	0.07164	0.0449	0.07	0.00903
1998	0.0452	0.13231	0.0751	0.067	0.01682
1999	0.0214	0.0467	0.0081	0.114	0.00176
2000	0.0289	0.04009	0.0226	0.034	0.01252
2001	0.03654	0.03779	0.04067	0.024	-0.00005
2002	0.03918	0.04297	0.02762	0.029	-0.00202
2003	0.0344	0.03806	0.03515	0.048	-0.00276
2004	0.03027	0.03767	0.03591	0.04	0.01612
2005	0.0349	0.04246	0.02754	0.045	0.02307
2006	0.0331	0.06177	0.0224	0.08	0.00598
2007	0.0299	0.06372	0.0254	0.064	0.01798
2008	0.035	0.0518	0.034	0.064	0.03527
PPP 2005	0.7	14.67	788.92	22.65	19.34

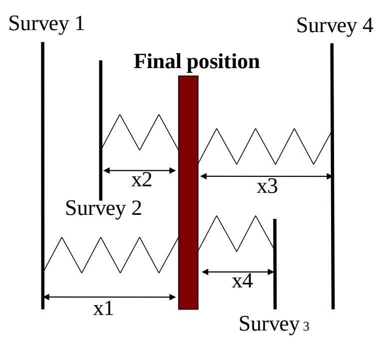
Main Functions – Build Customized Damage Functions

- What happens behind the scenes?
  - Raw survey data is treated to form a uniform format
    - Currency Conversion
    - Discounting and Compounding to a common time frame
    - Extrapolation (incomplete data)
  - A matching test to determine the similarity of survey to the assessed plant
  - Application of "Spring Theory" to build customized damage function

Main Functions – Build Customized Damage Functions



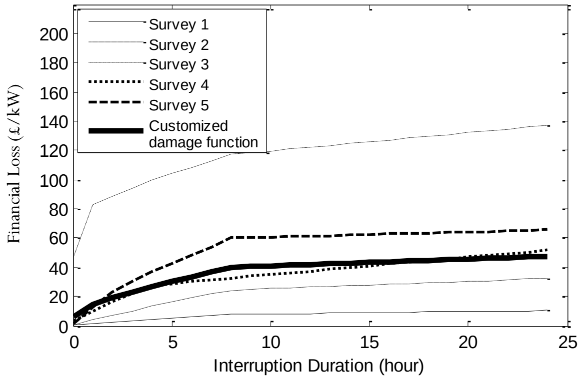
Main Functions – Build Customized Damage Functions



$$MI_1 x_1 + MI_2 x_2 = MI_3 x_3 + MI_4 x_4$$

Main Functions – Build Customized Damage Functions

- Output



Main Functions – Failure Risk and Financial Loss Assessment

- Purpose
  - Estimate number of equipment and process trip for customer plant due to voltage sag and interruption
  - Estimate customer financial loss resulting from the disturbances
- Initiation
  - The assessment is initiated by pressing [Calculate Plant Financial Loss] in the Home page
- Input
  - Customer plant info (type, size, and location)
  - Customer process info (Process Immunity Time (self and dependent), process cost factor and dependence matrix)
  - Customer equipment info (equipment type, sensitivity, connected phase and restart time)
  - Disturbances (sag, interruption) info
  - General customer damage functions from surveys (database)

Main Functions – Failure Risk and Financial Loss Assessment

- Customer process info (Process Immunity Time, process cost factor and dependence matrix)
- Customer equipment info (equipment type, sensitivity, connected phase and restart time)

Process Info

Process	Equipment type	Equipment Sensitivity	Equipment Connected Phase	PIT (minutes)	Restart time (minutes)	Process Cost Factor
1	2	3	1	0	1	0.25
2	2	2	2	0	2	0.25
3	2	1	3	0	3	0.25
4	2	3	3	0	3	0.25

Equipment type	*Code*
PC	*1*
PLC	*2*
ACC	*3*
ASD	*4*

Equipment Sensitivity	*Code*
LOW	*1*
NORMAL	*2*
HIGH	*3*

Main Functions – Failure Risk and Financial Loss Assessment

- Process Immunity Time - (PIT)
  - Time constants specifying maximum time a process can continue operation after its main equipment tripped
  - Process will not be disrupted if equipment is restarted within the buffer time

Main Functions – Failure Risk and Financial Loss Assessment

Process Dependence Matrix			
1	0	0	0
1	1	0	1
0	0	1	0
0	0	0	1

0 represents independence

Row represents process

1 represents dependence

Column represents dependence to other processes

e.g. Process 2 (row 2) is dependent on process 1, 2 and 4 but independent to process 3

Main Functions – Failure Risk and Financial Loss Assessment

- Disturbances (sag, interruption) info

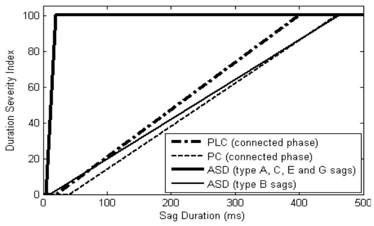
Magnitude Phase A (p.u. rms)	Magnitude Phase B (p.u. rms)	Magnitude Phase C (p.u. rms)	Occurence Rate	Disturbance Duration (ms)
1	0.79	1	1	60
1	0.74	1	3	80
1	0.82	0.81	1	150
0.81	0.86	1	2	60
0.81	0.81	1	1	60
1	0.84	0.78	1	100
1	0.74	1	0.5	60
0.78	0.78	0.78	1	80
1	0.87	0.78	1	60
0.84	0.84	0.84	0.1	60
0.80	0.80	0.80	1	200

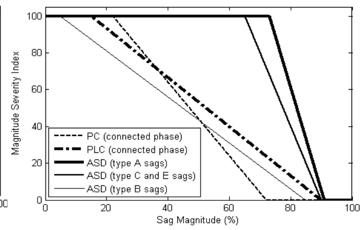
Main Functions – Failure Risk and Financial Loss Assessment

- What happens behind the scenes?
  - The impact of voltage sag is converted to Severity Indices (MSI & DSI)
  - Severity Indices is then converted to equipment failure risk
  - Plant failure risk is calculated from equipment failure risk
  - Customer financial loss is obtained from the customized damage function and plant failure risk

Main Functions – Failure Risk and Financial Loss Assessment

Severity Indices

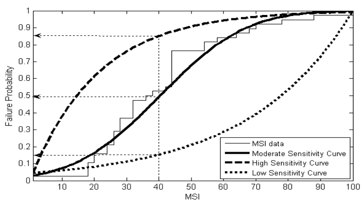


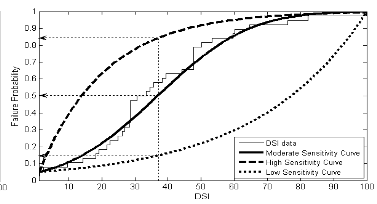


Equipment	magnitude for MSI =0	magnitude for MSI =100	duration for DSI =0	duration for DSI =100
PC	22	72	40	459
PLC	15	90	20	400

Main Functions – Failure Risk and Financial Loss Assessment

Equipment failure risk





Main Functions – Failure Risk and Financial Loss Assessment

Process Assessment – Example (Automotive plant)

Process	Sensitive Equipment	PITs	Equipment Restart Time	Process Ride Through
press shop	plc	< 1 sec	> 1sec	No
body shop	contactor	< 1 sec	> 1sec	No
paint shop	plc	< 1 sec	> 1sec	No
power train	pc	< 1 sec	> 1sec	NO
general assembly	asd	5 mins	< 5 mins	Yes

Main Functions – Failure Risk and Financial Loss Assessment

Process Assessment – Example (Automotive plant)

PIT_d Matrix	press shop	body shop	paint shop	power train	general assembly
press shop	1	0	0	0	0
body shop	1	1	0	0	0
paint shop	1	1	1	0	0
power train	1	1	1	1	0
general assembly	1	1	1	1	1

Main Functions – Failure Risk and Financial Loss Assessment

Output

	Total Equipment Trips	Total Process Trips	Financial Loss (£)
Process 1	2	2	2400
Process 2	1	5	5100
Process 3	4	6	6000
Process 4	3	7	10500
Process 5	5	8	25000
Process 6	0	0	0
Process 7	0	0	0
Process 8	0	0	0
Process 9	0	0	0
Process 10	0	0	0
Total Loss (£)			49000

Main Function - Database

- Purpose
  - To keep an up to date database of general customer damage functions, as input for developing realistic customized damage functions
- Initiation
  - The assessment is initiated by pressing [Update Customer Damage Function Data] in the Home page
- Input
  - Surveyed customer process type, size, location and damage function
  - Survey year, size and base currency used

Summary of Functional Buttons

Button	Found In	Action
Calculate Customized Damage Functions	Home	Initialize function to build customized damage function for customers
Calculate Plant Financial Loss	Home	Initialize function to calculate customer plant failure risk and financial loss
Detailed CDF Results	Output	Click to view customer damage function with resolution higher than 5 minute
Detailed Financial Loss Results	Output	Click to view customer financial loss results for individual voltage sag or interruption
Home	All Except Home	Return to Home tab
Input Sag and Interruption Data	Output	Initiate function to input new voltage sag and interruption data
Input New Currency Data	Home	Initiate function to input inflation/currency data for a new country
Register Input	Data Instantaneous	Register new disturbances input

Summary of Functional Buttons

Button	Found In	Action
Register Reference Update	Reference Cost Curve	Register new references
Register Update	Data Cost Curve	Register new survey data
Start Assessment	Output	Start running simulation
Update Customer Damage Function Data	Home	Initialize function to update new customer damage functions from surveys into database
Update Equipment Data	Home, Calculation Failure Risk	Initialize function to update new equipment failure characteristics
View Equipment Data	Home	Go to equipment data page
View Current Results	All except Reference Cost Curve and Output	Go to Output tab
View Survey Data	Home, Reference Cost Curve	Go to customer survey database
View Survey Reference	Data Cost Curve	Go to reference database

Limitations

- There are limits on some parameters due to the way the codes are written and the inherent limitation of the Excel solver
- Limits are as follow:
  - Maximum number of customer processes : 10
  - Maximum number of disturbances : 10000
  - Maximum number of surveys in database: 900
  - Maximum matching surveys: 30

Warnings Messages

- Warning messages is included to:
  - Request confirmation:

    Equipment Data Will Be Replaced! Proceed?

  - Advise further actions:

    Update Reference for Newly Inputted Customer Damage Functions?
    New Customer Damage Functions Registered! Advice Update on Reference File!

  - Notify user of a completed task

    Input Registered!
    Reference Updated!
    Assessment Completed!

  - Notify user of any errors encountered

    Assessment Failed! Solver could not find a solution!
    Assessment Could Not be Completed! None of the Surveys Matched the Assessed Plant!

Software information

- VoDCAT version 1.0
- last updated 17/05/10

Developed by Jhan Yhee Chan
Jhan.chan@postgrad.manchester.ac.uk

Appendix C Network Data

Table C-1 Bus Data

Bus	Type	Pd	Qd	Gs	Bs	Area	Vm	Va	BasekV	Zone	Vmax	Vmin
1	3	0.00	0.00	0	0	1	1.000	0.000	132	1	1.1	0.9
2	1	0.00	0.00	0	0	1	1.000	-0.016	132	1	1.1	0.9
3	1	0.00	0.00	0	0	1	1.000	-0.016	132	1	1.1	0.9
4	1	0.00	0.00	0	0	1	1.009	-5.833	33	1	1.06	0.94
5	1	0.00	0.00	0	0	1	1.017	-5.723	33	1	1.06	0.94
6	1	0.00	0.00	0	0	1	1.026	-5.755	33	1	1.06	0.94
7	1	0.00	0.00	0	0	1	1.021	-4.238	33	1	1.06	0.94
8	1	0.00	0.00	0	0	1	1.013	-2.848	33	1	1.06	0.94
9	1	0.00	0.00	0	0	1	1.014	-5.420	33	1	1.06	0.94
10	1	0.00	0.00	0	0	1	1.022	-6.737	33	1	1.06	0.94
11	1	0.00	0.00	0	0	1	1.019	-2.838	33	1	1.06	0.94
12	1	0.00	0.00	0	0	1	1.010	-3.513	33	1	1.06	0.94
13	1	20.43	7.62	0	0	1	1.022	-11.505	11	1	1.06	0.94
14	1	8.81	3.28	0	0	1	1.021	-8.371	11	1	1.06	0.94
15	1	19.86	7.41	0	0	1	1.014	-9.575	11	1	1.06	0.94
16	1	10.08	2.94	0	0	1	1.013	-8.549	11	1	1.06	0.94
17	1	5.72	2.13	0	0	1	1.005	-8.999	11	1	1.06	0.94
18	1	21.36	7.96	0	0	1	1.024	-10.718	11	1	1.06	0.94
19	1	9.00	3.35	0	0	1	1.013	-10.527	11	1	1.06	0.94
20	1	9.01	1.88	0	0	1	1.007	-12.870	11	1	1.06	0.94
21	1	2.99	0.62	0	0	1	1.022	-8.710	11	1	1.06	0.94
22	1	2.99	0.62	0	0	1	1.020	-9.254	11	1	1.06	0.94
23	1	5.97	1.24	0	0	1	1.017	-10.414	11	1	1.06	0.94
24	1	25.45	5.30	0	0	1	1.015	-11.051	11	1	1.06	0.94
25	1	9.59	2.00	0	0	1	1.014	-12.053	11	1	1.06	0.94
26	1	27.20	10.05	0	0	1	1.009	-10.159	11	1	1.06	0.94
27	1	20.26	7.49	0	0	1	1.007	-10.973	11	1	1.06	0.94
28	1	14.07	5.20	0	0	1	1.014	-11.830	11	1	1.06	0.94
29	1	12.85	4.75	0	0	1	1.020	-8.392	11	1	1.06	0.94
30	1	4.42	1.29	0	0	1	1.014	-7.436	11	1	1.06	0.94
31	1	7.49	2.18	0	0	1	1.022	-5.434	11	1	1.06	0.94
32	1	21.41	6.24	0	0	1	1.006	-10.611	11	1	1.06	0.94
33	1	6.82	1.99	0	0	1	1.005	-5.112	11	1	1.06	0.94
34	1	18.53	5.40	0	0	1	1.011	-11.627	11	1	1.06	0.94
35	1	8.22	2.85	0	0	1	1.024	-10.253	11	1	1.06	0.94
36	1	8.13	2.81	0	0	1	1.010	-12.284	11	1	1.06	0.94
37	1	16.16	5.59	0	0	1	1.017	-10.395	6.6	1	1.06	0.94
38	1	21.17	7.33	0	0	1	1.013	-10.776	11	1	1.06	0.94
39	1	3.69	1.28	0	0	1	1.015	-10.453	11	1	1.06	0.94
40	1	18.90	6.54	0	0	1	1.004	-11.705	11	1	1.06	0.94
41	1	8.22	2.85	0	0	1	1.015	-7.900	11	1	1.06	0.94
42	1	8.32	2.88	0	0	1	1.014	-8.077	6.6	1	1.06	0.94
43	1	5.67	1.96	0	0	1	1.000	-9.063	11	1	1.06	0.94
44	1	11.66	3.91	0	0	1	1.017	-9.676	11	1	1.06	0.94
45	1	22.75	7.64	0	0	1	1.023	-11.572	11	1	1.06	0.94
46	1	27.68	9.29	0	0	1	1.010	-13.431	11	1	1.06	0.94
47	1	11.38	3.82	0	0	1	1.008	-9.837	11	1	1.06	0.94
48	1	10.62	3.56	0	0	1	1.014	-10.721	11	1	1.06	0.94
49	1	9.57	3.21	0	0	1	1.015	-9.639	11	1	1.06	0.94
50	1	10.75	3.14	0	0	1	1.015	-5.814	11	1	1.06	0.94

51	1	18.05	5.26	0	0	1	1.004	-7.950	11	1	1.06	0.94
52	1	4.03	1.18	0	0	1	1.012	-3.961	11	1	1.06	0.94
53	1	9.82	3.43	0	0	1	1.012	-7.760	11	1	1.06	0.94
54	1	7.08	2.47	0	0	1	1.021	-6.821	11	1	1.06	0.94
55	1	10.67	3.73	0	0	1	1.003	-6.790	11	1	1.06	0.94
56	1	6.14	1.79	0	0	1	1.008	-5.775	11	1	1.06	0.94
57	1	6.42	2.24	0	0	1	1.012	-5.688	11	1	1.06	0.94
58	1	5.48	1.91	0	0	1	1.019	-7.682	11	1	1.06	0.94
59	1	8.97	3.13	0	0	1	1.004	-6.155	11	1	1.06	0.94
60	1	0.00	0.00	0	0	1	0.986	-0.518	132	1	1.06	0.94
61	1	0.00	0.00	0	0	1	0.986	-0.518	132	1	1.06	0.94
62	1	0.00	0.00	0	0	1	0.981	-1.714	132	1	1.06	0.94
63	1	0.00	0.00	0	0	1	0.981	-1.713	132	1	1.06	0.94
64	1	0.00	0.00	0	0	1	0.998	-0.128	132	1	1.06	0.94
65	1	0.00	0.00	0	0	1	0.998	-0.127	132	1	1.06	0.94
66	1	0.00	0.00	0	0	1	0.989	-0.937	132	1	1.06	0.94
67	1	0.00	0.00	0	0	1	0.989	-0.938	132	1	1.06	0.94
68	1	0.00	0.00	0	0	1	0.998	-0.134	132	1	1.06	0.94
69	1	0.00	0.00	0	0	1	0.998	-0.133	132	1	1.06	0.94
70	1	0.00	0.00	0	0	1	0.995	-0.340	132	1	1.06	0.94
71	1	0.00	0.00	0	0	1	0.995	-0.337	132	1	1.06	0.94
72	1	0.00	0.00	0	0	1	1.007	-5.950	33	1	1.06	0.94
73	1	0.00	0.00	0	0	1	1.007	-5.945	33	1	1.06	0.94
74	1	0.00	0.00	0	0	1	0.974	-6.923	33	1	1.06	0.94
75	1	0.00	0.00	0	0	1	0.970	-6.755	33	1	1.06	0.94
76	1	0	0	0	0	1	1.003	-6.153	33	1	1.06	0.94
77	1	0	0	0	0	1	1.003	-6.154	33	1	1.06	0.94
78	1	0	0	0	0	1	0.989	-6.595	33	1	1.06	0.94
79	1	0	0	0	0	1	0.996	-4.670	33	1	1.06	0.94
80	1	0	0	0	0	1	0.959	-7.376	33	1	1.06	0.94
81	1	0	0	0	0	1	0.956	-7.301	33	1	1.06	0.94
82	1	0	0	0	0	1	0.960	-7.321	33	1	1.06	0.94
83	1	0	0	0	0	1	1.003	-5.890	33	1	1.06	0.94
84	1	0	0	0	0	1	1.003	-5.887	33	1	1.06	0.94
85	1	0	0	0	0	1	0.996	-6.335	33	1	1.06	0.94
86	1	0	0	0	0	1	0.991	-5.972	33	1	1.06	0.94
87	1	0	0	0	0	1	1.011	-6.175	33	1	1.06	0.94
88	1	0	0	0	0	1	0.979	-7.140	33	1	1.06	0.94
89	1	0	0	0	0	1	0.966	-7.684	33	1	1.06	0.94
90	1	0	0	0	0	1	0.966	-7.684	33	1	1.06	0.94
91	1	0	0	0	0	1	0.997	-6.966	33	1	1.06	0.94
92	1	0	0	0	0	1	0.999	-6.595	33	1	1.06	0.94
93	1	0	0	0	0	1	0.999	-6.597	33	1	1.06	0.94
94	1	0	0	0	0	1	1.005	-6.209	33	1	1.06	0.94
95	1	0	0	0	0	1	1.006	-6.159	33	1	1.06	0.94
96	1	0	0	0	0	1	1.005	-6.573	33	1	1.06	0.94
97	1	0	0	0	0	1	0.999	-6.902	33	1	1.06	0.94
98	1	0	0	0	0	1	1.015	-6.191	33	1	1.06	0.94
99	1	0	0	0	0	1	1.007	-6.532	33	1	1.06	0.94
100	1	0	0	0	0	1	1.019	-5.997	33	1	1.06	0.94
101	1	0	0	0	0	1	1.019	-5.996	33	1	1.06	0.94
102	1	0	0	0	0	1	1.020	-5.978	33	1	1.06	0.94
103	1	0	0	0	0	1	1.019	-6.034	33	1	1.06	0.94
104	1	0	0	0	0	1	1.009	-4.931	33	1	1.06	0.94
105	1	0	0	0	0	1	1.010	-4.922	33	1	1.06	0.94
106	1	0	0	0	0	1	1.018	-4.279	33	1	1.06	0.94
107	1	0	0	0	0	1	1.009	-3.039	33	1	1.06	0.94

108	1	0	0	0	0	1	1.012	-4.846	33	1	1.06	0.94
109	1	0	0	0	0	1	1.004	-4.102	33	1	1.06	0.94
110	1	0	0	0	0	1	1.020	-4.253	33	1	1.06	0.94
111	1	0	0	0	0	1	1.011	-2.958	33	1	1.06	0.94
112	1	0	0	0	0	1	0.977	-5.151	33	1	1.06	0.94
113	1	0	0	0	0	1	1.002	-5.771	33	1	1.06	0.94
114	1	0	0	0	0	1	0.946	-7.615	33	1	1.06	0.94
115	1	0	0	0	0	1	1.013	-5.456	33	1	1.06	0.94
116	1	0	0	0	0	1	1.013	-5.456	33	1	1.06	0.94
117	1	0	0	0	0	1	0.964	-6.902	33	1	1.06	0.94
118	1	0	0	0	0	1	0.977	-5.152	33	1	1.06	0.94
119	1	0	0	0	0	1	1.013	-5.505	33	1	1.06	0.94
120	1	0	0	0	0	1	1.012	-5.468	33	1	1.06	0.94
121	1	0	0	0	0	1	1.010	-5.449	33	1	1.06	0.94
122	1	0	0	0	0	1	1.008	-5.571	33	1	1.06	0.94
123	1	0	0	0	0	1	1.015	-7.204	33	1	1.06	0.94
124	1	0	0	0	0	1	1.014	-7.299	33	1	1.06	0.94
125	1	0	0	0	0	1	1.020	-6.792	33	1	1.06	0.94
126	1	0	0	0	0	1	1.020	-6.790	33	1	1.06	0.94
127	1	0	0	0	0	1	1.006	-7.458	33	1	1.06	0.94
128	1	0	0	0	0	1	1.013	-7.135	33	1	1.06	0.94
129	1	0	0	0	0	1	1.015	-7.144	33	1	1.06	0.94
130	1	0	0	0	0	1	1.004	-7.282	33	1	1.06	0.94
131	1	0	0	0	0	1	1.015	-7.199	33	1	1.06	0.94
132	1	0	0	0	0	1	1.011	-7.437	33	1	1.06	0.94
133	1	0	0	0	0	1	1.021	-6.831	33	1	1.06	0.94
134	1	0	0	0	0	1	1.019	-6.931	33	1	1.06	0.94
135	1	0	0	0	0	1	1.010	-3.563	33	1	1.06	0.94
136	1	0	0	0	0	1	1.015	-3.155	33	1	1.06	0.94
137	1	0	0	0	0	1	1.018	-2.902	33	1	1.06	0.94
138	1	0	0	0	0	1	1.018	-2.902	33	1	1.06	0.94
139	1	0	0	0	0	1	0.973	-4.949	33	1	1.06	0.94
140	1	0	0	0	0	1	0.971	-5.064	33	1	1.06	0.94
141	1	0	0	0	0	1	1.007	-3.630	33	1	1.06	0.94
142	1	0	0	0	0	1	1.008	-3.589	33	1	1.06	0.94
143	1	0	0	0	0	1	1.009	-3.599	33	1	1.06	0.94
144	1	0	0	0	0	1	1.007	-3.630	33	1	1.06	0.94
145	1	0	0	0	0	1	1.007	-3.648	33	1	1.06	0.94
146	1	0	0	0	0	1	1.007	-3.646	33	1	1.06	0.94
147	1	0	0	0	0	1	1.002	-3.950	33	1	1.06	0.94
148	1	0	0	0	0	1	0.997	-4.236	33	1	1.06	0.94
149	1	0	0	0	0	1	1.006	-3.800	33	1	1.06	0.94
150	1	0	0	0	0	1	1.006	-3.796	33	1	1.06	0.94
151	1	0	0	0	0	1	1.006	-3.799	33	1	1.06	0.94
152	1	0	0	0	0	1	1.006	-3.795	33	1	1.06	0.94
153	1	0	0	0	0	1	0.980	-4.860	33	1	1.06	0.94
154	1	0	0	0	0	1	0.993	-4.264	33	1	1.06	0.94
155	1	0	0	0	0	1	0.993	-4.264	33	1	1.06	0.94
156	1	0	0	0	0	1	0.986	-4.610	33	1	1.06	0.94
157	1	0	0	0	0	1	1.004	-3.835	33	1	1.06	0.94
158	1	0	0	0	0	1	0.998	-4.180	33	1	1.06	0.94

Table C-2 Generator Data

Status	Pmax	Pmin	R1	X1	R0	X0
1	50000	1	0.1067	0.01573	0.000625	0.00625

Table C-3 Line Data

From Bus	To Bus	R	X	B	R0	X0	B0	Rate A	Rate B	Rate C	Length	Type	Status
1	2	0.000	0.000	0.000	0.000	0.000	0.000	432	0	0	0.1	1	1
1	3	0.000	0.000	0.000	0.000	0.000	0.000	432	0	0	0.1	1	1
62	63	0.000	0.000	0.000	0.000	0.000	0.000	300	0	0	0.1	1	1
2	60	0.013	0.030	0.019	0.080	0.089	0.006	300	0	0	13.5	1	1
2	62	0.006	0.046	0.019	0.038	0.139	0.006	300	0	0	20.5	1	1
2	64	0.002	0.006	0.074	0.011	0.017	0.025	300	0	0	4.5	1	1
2	66	0.005	0.036	0.009	0.027	0.107	0.003	300	0	0	16.9	1	1
2	68	0.005	0.012	0.012	0.032	0.036	0.004	300	0	0	5.2	1	1
2	70	0.010	0.028	0.009	0.062	0.084	0.003	300	0	0	14.6	1	1
3	61	0.013	0.030	0.019	0.080	0.089	0.006	300	0	0	13.5	1	1
3	63	0.006	0.046	0.020	0.037	0.138	0.007	300	0	0	20.5	1	1
3	65	0.002	0.006	0.074	0.011	0.017	0.025	300	0	0	4.5	1	1
3	67	0.005	0.036	0.009	0.027	0.107	0.003	300	0	0	16.9	1	1
3	69	0.005	0.012	0.010	0.032	0.036	0.003	300	0	0	5.2	1	1
3	71	0.010	0.028	0.009	0.062	0.084	0.003	300	0	0	14.6	1	1
4	73	0.008	0.024	0.000	0.048	0.071	0.000	35.6	0	0	1.1	1	1
4	72	0.008	0.024	0.001	0.049	0.072	0.000	35.6	0	0	1.1	1	1
4	84	0.042	0.028	0.005	0.250	0.083	0.002	20.7	0	0	3.3	1	1
4	83	0.041	0.028	0.005	0.248	0.084	0.002	21.3	0	0	3.4	1	1
4	76	0.029	0.069	0.003	0.176	0.208	0.001	23.3	0	0	3.4	1	1
4	77	0.030	0.070	0.002	0.178	0.209	0.001	20.7	0	0	3.4	1	1
4	86	0.064	0.112	0.001	0.384	0.335	0.000	20.7	0	0	3.9	1	1
4	85	0.064	0.112	0.001	0.386	0.337	0.000	21.8	0	0	4.0	1	1
74	82	0.307	0.367	0.001	1.841	1.101	0.000	13.5	0	0	11.9	1	1
75	81	0.332	0.411	0.001	1.990	1.232	0.000	13.5	0	0	13.4	1	1
82	80	0.024	0.043	0.000	0.143	0.128	0.000	22.6	0	0	1.4	1	1
85	78	0.149	0.193	0.001	0.896	0.578	0.000	16.3	0	0	6.6	1	1
85	74	0.199	0.235	0.000	1.192	0.705	0.000	16.3	0	0	7.2	1	1
86	79	0.149	0.193	0.001	0.895	0.579	0.000	16.3	0	0	6.6	1	1
86	75	0.199	0.235	0.000	1.192	0.705	0.000	16.3	0	0	7.2	1	1
5	95	0.078	0.105	0.000	0.468	0.314	0.000	15.4	0	0	3.2	1	1
5	92	0.096	0.147	0.005	0.575	0.440	0.002	20.7	0	0	7.3	1	1
5	93	0.096	0.147	0.005	0.578	0.442	0.002	20.7	0	0	7.3	1	1
5	88	0.184	0.213	0.002	1.103	0.640	0.001	16.2	0	0	7.4	1	1
5	87	0.064	0.149	0.005	0.383	0.446	0.002	23.3	0	0	7.5	1	1
87	91	0.153	0.272	0.000	0.917	0.817	0.000	22.6	0	0	9.0	1	1
88	90	0.160	0.186	0.001	0.959	0.559	0.000	16.2	0	0	6.0	1	1
89	90	0.000	0.000	0.000	0.000	0.000	0.000	35	0	0	0.1	1	1
95	94	0.013	0.013	0.001	0.077	0.040	0.000	26.9	0	0	1.1	1	1
6	101	0.027	0.042	0.001	0.159	0.127	0.000	22.6	0	0	1.8	1	1
100	101	0.000	0.000	0.000	0.000	0.000	0.000	35	0	0	0.1	1	1
6	98	0.061	0.103	0.001	0.367	0.310	0.000	21.3	0	0	4.0	1	1
6	99	0.111	0.191	0.000	0.667	0.573	0.000	20	0	0	7.1	1	1
6	103	0.071	0.098	0.004	0.425	0.295	0.001	21.3	0	0	5.5	1	1
6	102	0.071	0.098	0.004	0.424	0.295	0.001	21.3	0	0	5.5	1	1
98	96	0.050	0.088	0.001	0.300	0.263	0.000	20	0	0	3.1	1	1
99	97	0.050	0.088	0.001	0.302	0.265	0.000	20	0	0	3.2	1	1
105	104	0.007	0.006	0.001	0.040	0.017	0.000	22.6	0	0	0.7	1	1
7	110	0.036	0.043	0.002	0.216	0.130	0.001	16.1	0	0	2.6	1	1
7	108	0.026	0.085	0.001	0.157	0.255	0.000	33.6	0	0	3.7	1	1
7	106	0.070	0.072	0.007	0.422	0.217	0.002	20.7	0	0	5.6	1	1
7	112	0.081	0.077	0.012	0.483	0.231	0.004	23.3	0	0	8.9	1	1
8	111	0.037	0.044	0.002	0.223	0.131	0.001	16.1	0	0	2.6	1	1

8	109	0.026	0.085	0.001	0.157	0.256	0.000	33.6	0	0	3.7	1	1
8	107	0.070	0.073	0.007	0.420	0.218	0.002	21.3	0	0	5.6	1	1
108	105	0.041	0.042	0.002	0.245	0.127	0.001	26.9	0	0	3.6	1	1
109	79	0.056	0.057	0.003	0.335	0.172	0.001	23.3	0	0	5.0	1	1
9	115	0.005	0.008	0.002	0.028	0.025	0.001	32.3	0	0	1.0	1	1
9	116	0.005	0.008	0.002	0.029	0.025	0.001	32.3	0	0	1.0	1	1
9	119	0.003	0.019	0.005	0.015	0.058	0.002	23.9	0	0	2.7	1	1
9	120	0.026	0.020	0.005	0.157	0.059	0.002	23.3	0	0	2.7	1	1
9	121	0.041	0.023	0.004	0.244	0.068	0.001	21.3	0	0	2.9	1	1
9	122	0.026	0.026	0.004	0.157	0.077	0.001	23.5	0	0	2.9	1	1
118	112	0.000	0.000	0.000	0.000	0.000	0.000	35	0	0	0.1	1	1
117	114	0.123	0.188	0.006	0.735	0.565	0.002	22.6	0	0	9.2	1	1
121	113	0.059	0.094	0.001	0.355	0.282	0.000	22.6	0	0	3.9	1	1
122	117	0.238	0.282	0.000	1.430	0.846	0.000	16.3	0	0	8.5	1	1
128	130	0.065	0.049	0.006	0.389	0.146	0.002	16.1	0	0	2.3	1	1
10	128	0.055	0.086	0.000	0.328	0.257	0.000	16.1	0	0	3.3	1	1
10	133	0.006	0.018	0.000	0.037	0.054	0.000	35.6	0	0	0.9	1	1
10	134	0.006	0.018	0.000	0.038	0.055	0.000	35.6	0	0	0.9	1	1
10	126	0.010	0.013	0.006	0.061	0.038	0.002	39.7	0	0	2.2	1	1
10	125	0.010	0.013	0.006	0.061	0.038	0.002	39.7	0	0	2.2	1	1
129	127	0.048	0.067	0.001	0.290	0.202	0.000	16.1	0	0	3.0	1	1
129	132	0.042	0.127	0.000	0.249	0.382	0.000	22.6	0	0	4.5	1	1
133	131	0.059	0.157	0.002	0.353	0.471	0.001	22.6	0	0	6.4	1	1
134	129	0.018	0.030	0.002	0.106	0.091	0.001	23.3	0	0	1.9	1	1
134	124	0.039	0.129	0.002	0.236	0.387	0.001	26.9	0	0	5.4	1	1
133	123	0.039	0.129	0.002	0.236	0.387	0.001	26.9	0	0	5.4	1	1
135	157	0.039	0.073	0.003	0.232	0.220	0.001	22.6	0	0	4.4	1	1
11	138	0.029	0.066	0.001	0.175	0.198	0.000	24.5	0	0	2.2	1	1
11	137	0.029	0.066	0.001	0.175	0.198	0.000	24.5	0	0	2.2	1	1
11	136	0.035	0.110	0.003	0.208	0.329	0.001	33.6	0	0	4.9	1	1
11	135	0.035	0.110	0.003	0.209	0.331	0.001	33.6	0	0	4.9	1	1
157	147	0.048	0.078	0.001	0.287	0.234	0.000	18.4	0	0	3.2	1	1
158	148	0.048	0.078	0.001	0.287	0.234	0.000	18.4	0	0	3.2	1	1
143	158	0.116	0.174	0.005	0.697	0.523	0.002	22.6	0	0	8.4	1	1
144	141	0.003	0.004	0.000	0.020	0.012	0.000	16.2	0	0	0.1	1	1
144	156	0.117	0.210	0.000	0.703	0.631	0.000	22.6	0	0	6.9	1	1
151	149	0.001	0.001	0.000	0.006	0.002	0.000	21.9	0	0	0.1	1	1
152	150	0.001	0.001	0.000	0.005	0.002	0.000	21.9	0	0	0.1	1	1
155	154	0.055	0.099	0.000	0.332	0.297	0.000	21.8	0	0	3.3	1	1
155	139	0.254	0.334	0.000	1.523	1.003	0.000	16.3	0	0	10.4	1	1
156	153	0.055	0.099	0.000	0.332	0.298	0.000	21.8	0	0	3.3	1	1
156	140	0.198	0.235	0.000	1.190	0.704	0.000	16.3	0	0	7.1	1	1
158	148	0.049	0.081	0.001	0.296	0.242	0.000	22.6	0	0	3.3	1	1
12	143	0.014	0.025	0.000	0.086	0.075	0.000	22.6	0	0	0.9	1	1
12	142	0.015	0.025	0.000	0.088	0.075	0.000	22.6	0	0	0.9	1	1
12	144	0.015	0.026	0.000	0.091	0.078	0.000	22.6	0	0	1.0	1	1
12	145	0.034	0.058	0.000	0.201	0.174	0.000	21.8	0	0	2.1	1	1
12	146	0.033	0.058	0.000	0.200	0.174	0.000	20.7	0	0	2.1	1	1
12	152	0.050	0.174	0.001	0.301	0.522	0.000	23.3	0	0	6.1	1	1
12	151	0.055	0.178	0.001	0.328	0.533	0.000	23.3	0	0	6.6	1	1
12	155	0.188	0.335	0.001	1.125	1.006	0.000	20.7	0	0	11.1	1	1

Table C-4 Transformer Data

From Bus	To Bus	R	X	B	F_W	T_W	Tap	Shift	Rate A	Rate B	Rate C	Status
60	4	0.0112	0.2523	0	1	0	0.92	0	78	0	0	1

61	4	0.011	0.2525	0	1	0	0.92	0	78	0	0	1
62	6	0.009	0.2083	0	1	0	0.92	0	78	0	0	1
62	6	0.0088	0.205	0	1	0	0.92	0	78	0	0	1
63	5	0.0137	0.2622	0	1	0	0.94	0	58.5	0	0	1
63	5	0.014	0.2629	0	1	0	0.94	0	58.5	0	0	1
2	7	0.0124	0.2933	0	1	0	0.94	0	58.5	0	0	1
2	8	0.0149	0.2933	0	1	0	0.98	0	58.5	0	0	1
3	7	0.0158	0.2667	0	1	0	0.94	0	58.5	0	0	1
3	8	0.0159	0.2667	0	1	0	0.98	0	58.5	0	0	1
64	9	0.0074	0.2483	0	1	0	0.94	0	117	0	0	1
65	9	0.0076	0.25	0	1	0	0.94	0	117	0	0	1
66	10	0.0076	0.2378	0	1	0	0.92	0	117	0	0	1
67	10	0.0076	0.2378	0	1	0	0.92	0	117	0	0	1
68	11	0.0067	0.2444	0	1	0	0.96	0	117	0	0	1
69	11	0.0067	0.2444	0	1	0	0.96	0	117	0	0	1
70	12	0.0108	0.2492	0	1	0	0.96	0	78	0	0	1
71	12	0.0109	0.2517	0	1	0	0.96	0	78	0	0	1
123	44	0.0492	0.7876	0	0	1	0.98	0	24	0	0	1
124	44	0.0492	0.7734	0	0	1	0.98	0	24	0	0	1
74	14	0.0448	0.6586	0	0	1	0.94	0	21.8	0	0	1
75	14	0.0448	0.6564	0	0	1	0.94	0	21.8	0	0	1
6	26	0.0167	0.3045	0	0	1	0.98	0	70.4	0	0	1
104	30	0.0435	1.0462	0	0	1	0.98	0	24	0	0	1
76	15	0.0471	0.6541	0	0	1	0.96	0	24	0	0	1
77	15	0.0471	0.6541	0	0	1	0.96	0	21.8	0	0	1
87	20	0.0835	101797	0	0	1	0.94	0	12	0	0	1
88	20	0.0835	1.1797	0	0	1	0.94	0	12	0	0	1
106	31	0.068	0.9024	0	0	1	0.98	0	14.5	0	0	1
107	31	0.0685	0.887	0	0	1	0.98	0	14.5	0	0	1
139	53	0.0685	1.0514	0	0	1	0.94	0	14.5	0	0	1
140	53	0.0685	1.0437	0	0	1	0.94	0	14.5	0	0	1
89	21	0.0582	0.6422	0	0	1	0.94	0	14.5	0	0	1
90	22	0.0709	0.9767	0	0	1	0.94	0	14.5	0	0	1
142	54	0.0874	0.8843	0	0	1	0.96	0	10.9	0	0	1
145	55	0.0466	1.0688	0	0	1	0.98	0	24	0	0	1
146	55	0.0469	1.0832	0	0	1	0.98	0	24	0	0	1
78	16	0.0707	1.0819	0	0	1	0.96	0	14.5	0	0	1
79	16	0.0708	1.0775	0	0	1	0.96	0	14.5	0	0	1
135	50	0.0663	0.851	0	0	1	0.98	0	14.5	0	0	1
136	50	0.0663	0.8587	0	0	1	0.98	0	14.5	0	0	1
114	36	0.0982	1.0973	0	0	1	0.9	0	12	0	0	1
91	23	0.1139	1.087	0	0	1	0.96	0	12	0	0	1
9	37	0.0239	0.5847	0	0	1	0.96	0	48	0	0	1
108	32	0.044	1.0516	0	0	1	0.96	0	24	0	0	1
109	32	0.0507	1.0831	0	0	1	0.96	0	24	0	0	1
147	56	0.0648	1.01	0	0	1	0.98	0	14.5	0	0	1
148	56	0.0655	0.9914	0	0	1	0.98	0	14.5	0	0	1
149	57	0.0678	1.0909	0	0	1	0.98	0	14.5	0	0	1
150	57	0.0678	1.0909	0	0	1	0.98	0	14.5	0	0	1
92	24	0.0452	0.6542	0	0	1	0.96	0	26.4	0	0	1
93	24	0.0452	0.6542	0	0	1	0.96	0	26.4	0	0	1
96	27	0.0442	0.7824	0	0	1	0.96	0	26.4	0	0	1
97	27	0.0442	0.7824	0	0	1	0.96	0	26.4	0	0	1

125	45	0.0531	0.795	0	0	1	0.96	0	24	0	0	1
126	45	0.0531	0.8344	0	0	1	0.96	0	24	0	0	1
10	46	0.0174	0.4587	0	0	1	0.96	0	70.4	0	0	1
72	13	0.0433	1.0374	0	0	1	0.94	0	24	0	0	1
73	13	0.0438	1.0713	0	0	1	0.94	0	24	0	0	1
100	28	0.4463	0.9941	0	0	1	0.9	0	24	0	0	1
115	38	0.0369	0.9469	0	0	1	0.96	0	35.2	0	0	1
116	38	0.0381	0.9523	0	0	1	0.96	0	35.2	0	0	1
80	17	0.0702	1.0633	0	0	1	0.94	0	14.5	0	0	1
81	17	0.0708	1.0633	0	0	1	0.94	0	14.5	0	0	1
117	39	0.1979	1.8557	0	0	1	0.92	0	8	0	0	1
110	33	0.0489	0.8029	0	0	1	1	0	24	0	0	1
111	33	0.0492	0.7985	0	0	1	1	0	24	0	0	1
118	40	0.0445	0.6587	0	0	1	0.92	0	21.8	0	0	1
112	34	0.0438	0.6664	0	0	1	0.92	0	21.8	0	0	1
153	58	0.0721	0.981	0	0	1	0.94	0	14.5	0	0	1
94	25	0.0532	1.1364	0	0	1	0.96	0	24	0	0	1
119	41	0.055	1.0653	0	0	1	0.98	0	24	0	0	1
119	42	0.0488	1.1444	0	0	1	0.98	0	21.8	0	0	1
120	41	0.0393	1.1174	0	0	1	0.98	0	24	0	0	1
120	42	0.0487	1.1666	0	0	1	0.98	0	21.8	0	0	1
127	47	0.0499	0.7722	0	0	1	0.98	0	24	0	0	1
127	47	0.0499	0.7722	0	0	1	0.98	0	24	0	0	1
83	18	0.0507	0.8795	0	0	1	0.94	0	24	0	0	1
84	18	0.0507	0.8795	0	0	1	0.94	0	24	0	0	1
11	51	0.0256	0.5229	0	0	1	0.98	0	48	0	0	1
137	52	0.0347	0.9535	0	0	1	1	0	35.2	0	0	1
138	52	0.0353	0.9557	0	0	1	1	0	35.2	0	0	1
102	29	0.0316	0.7754	0	0	1	0.98	0	26.4	0	0	1
103	29	0.0471	0.6409	0	0	1	0.98	0	26.4	0	0	1
130	48	0.0736	0.6241	0	0	1	0.96	0	24	0	0	1
131	49	0.0676	0.9288	0	0	1	0.98	0	14.5	0	0	1
132	49	0.0721	0.8911	0	0	1	0.98	0	14.5	0	0	1
122	43	0.0727	1.13	0	0	1	0.98	0	14.5	0	0	1
86	19	0.073	0.97	0	0	1	0.94	0	14.5	0	0	1
157	59	0.0671	0.8806	0	0	1	0.98	0	14.5	0	0	1
158	59	0.0671	0.8806	0	0	1	0.98	0	14.5	0	0	1
113	35	0.1131	1.0761	0	0	1	0.94	0	12	0	0	1

Table C-5 Fault data for lines

From Bus	To Bus	Lightning	Animal	Tree	Dig-in	Others	Cable/Overhead Ratio	Fault Occurrence Rate
1	2	0	0	0	0	1	0	1
1	3	0	0	0	0	1	0	1
62	63	0	0	0	0	1	0	1
2	60	0.25	0.15	0.15	0	0.45	1	3
2	62	0.25	0.15	0.15	0	0.45	1	2
2	64	0.25	0.15	0.15	0	0.45	1	1
2	66	0.25	0.15	0.15	0	0.45	1	2
2	68	0.25	0.15	0.15	0	0.45	1	1
2	70	0.25	0.15	0.15	0	0.45	1	1

3	61	0.25	0.15	0.15	0	0.45	1	2
3	63	0.25	0.15	0.15	0	0.45	1	2
3	65	0.25	0.15	0.15	0	0.45	1	3
3	67	0.25	0.15	0.15	0	0.45	1	1
3	69	0.25	0.15	0.15	0	0.45	1	2
3	71	0.25	0.15	0.15	0	0.45	1	2
4	73	0.15	0.15	0.15	0.15	0.4	0.7	2
4	72	0.15	0.15	0.15	0.15	0.4	0.7	3
4	84	0	0	0	0.5	0.5	0	1
4	83	0	0	0	0.5	0.5	0	2
4	76	0.15	0.2	0.15	0.1	0.4	0.7	2
4	77	0.15	0.2	0.15	0.1	0.4	0.7	2
4	86	0.2	0.2	0.2	0	0.4	1	1
4	85	0.2	0.2	0.2	0	0.4	1	2
74	82	0.2	0.2	0.2	0	0.4	1	2
75	81	0.2	0.2	0.2	0	0.4	1	1
82	80	0.2	0.2	0.2	0	0.4	1	3
85	78	0.2	0.2	0.2	0	0.4	1	3
85	74	0.2	0.2	0.2	0	0.4	1	2
86	79	0.2	0.2	0.2	0	0.4	1	2
86	75	0.2	0.2	0.2	0	0.4	1	2
5	95	0	0	0	0.5	0.5	0	3
5	92	0.15	0.15	0.1	0.2	0.4	0.6	2
5	93	0.15	0.15	0.1	0.2	0.4	0.6	2
5	88	0.15	0.15	0.1	0.2	0.4	0.6	2
5	87	0.15	0.15	0.1	0.2	0.4	0.6	1
87	91	0.2	0.2	0.2	0	0.4	1	2
88	90	0.2	0.2	0.2	0	0.4	1	2
89	90	0	0	0	0	1	0	1
95	94	0	0	0	0.5	0.5	0	2
6	101	0.15	0.2	0.15	0.1	0.4	0.7	3
100	101	0	0	0	0	1	0	3
6	98	0.2	0.2	0.15	0.05	0.4	0.8	2
6	99	0.2	0.2	0.15	0.05	0.4	0.8	1
6	103	0.1	0.1	0.1	0.3	0.4	0.5	2
6	102	0.1	0.1	0.1	0.3	0.4	0.5	2
98	96	0.2	0.2	0.15	0.05	0.4	0.9	2
99	97	0.2	0.2	0.15	0.05	0.4	0.9	2
105	104	0	0	0	0.5	0.5	0	1
7	110	0.1	0.05	0.05	0.4	0.4	0.3	2
7	108	0.15	0.15	0.1	0.2	0.4	0.6	1
7	106	0.1	0.05	0.05	0.4	0.4	0.3	2
7	112	0	0	0	0.5	0.5	0	2
8	111	0.1	0.05	0.05	0.4	0.4	0.3	3
8	109	0.15	0.15	0.1	0.2	0.4	0.6	3
8	107	0.1	0.05	0.05	0.4	0.4	0.3	1
108	105	0	0	0	0.5	0.5	0	1
109	79	0	0	0	0.5	0.5	0	2
9	115	0	0	0	0.5	0.5	0	2
9	116	0	0	0	0.5	0.5	0	2
9	119	0	0	0	0.5	0.5	0	3
9	120	0	0	0	0.5	0.5	0	1
9	121	0	0	0	0.5	0.5	0	1

9	122	0	0	0	0.5	0.5	0	2
118	112	0	0	0	0	1	0	1
117	114	0.15	0.15	0.1	0.2	0.4	0.6	2
121	113	0.15	0.2	0.15	0.1	0.4	0.7	2
122	117	0	0	0	0.5	0.5	0	3
128	130	0	0	0	0.5	0.5	0	2
10	128	0	0	0	0.5	0.5	0	3
10	133	0.15	0.2	0.15	0.1	0.4	0.7	2
10	134	0.15	0.2	0.15	0.1	0.4	0.7	1
10	126	0	0	0	0.5	0.5	0	2
10	125	0	0	0	0.5	0.5	0	2
129	127	0	0	0	0.5	0.5	0	3
129	132	0.2	0.2	0.2	0	0.4	1	3
133	131	0.2	0.2	0.2	0	0.4	1	2
134	129	0.1	0.1	0.05	0.35	0.4	0.4	2
134	124	0.15	0.2	0.15	0.1	0.4	0.7	2
133	123	0.15	0.2	0.15	0.1	0.4	0.7	1
135	157	0.1	0.05	0.05	0.4	0.4	0.3	1
11	138	0.2	0.2	0.2	0	0.4	1	2
11	137	0.2	0.2	0.2	0	0.4	1	2
11	136	0.2	0.2	0.15	0.05	0.4	0.8	2
11	135	0.2	0.2	0.15	0.05	0.4	0.8	2
157	147	0.2	0.2	0.15	0.05	0.4	0.8	2
158	148	0.2	0.2	0.15	0.05	0.4	0.8	2
143	158	0.1	0.1	0.1	0.3	0.4	0.5	3
144	141	0	0	0	0	1	0	1
144	156	0.2	0.2	0.2	0	0.4	1	2
151	149	0	0	0	0	1	0	1
152	150	0	0	0	0	1	0	1
155	154	0.2	0.2	0.2	0	0.4	1	2
155	139	0.2	0.2	0.2	0	0.4	1	3
156	153	0.2	0.2	0.2	0	0.4	1	2
156	140	0.2	0.2	0.2	0	0.4	1	2
158	148	0.2	0.2	0.15	0.05	0.4	0.8	1
12	143	0.2	0.2	0.2	0	0.4	1	1
12	142	0.2	0.2	0.2	0	0.4	1	1
12	144	0.2	0.2	0.2	0	0.4	1	1
12	145	0.2	0.2	0.2	0	0.4	1	2
12	146	0.2	0.2	0.2	0	0.4	1	2
12	152	0.2	0.2	0.2	0	0.4	1	2
12	151	0.2	0.2	0.2	0	0.4	1	1
12	155	0.2	0.2	0.2	0	0.4	1	1

Appendix D Data for HQPZ

Table D-1 Customer Process Demand

Plant	Total Size (MVA)	Power Factor	Process	Power usage factor	Process size (MVA)	Process MW	Process MVAR
1	0.92	0.75	1	0.15	0.14	0.10	0.09
		0.75	2	0.2	0.18	0.14	0.12
		0.75	3	0.1	0.09	0.07	0.06
		0.75	4	0.15	0.14	0.10	0.09
		0.75	5	0.2	0.18	0.14	0.12
2	3.14	0.7	1	0.2	0.63	0.44	0.45
		0.7	2	0.2	0.63	0.44	0.45
		0.7	3	0.3	0.94	0.66	0.67
		0.7	4	0.2	0.63	0.44	0.45
3	0.99	0.75	1	0.2	0.20	0.15	0.13
		0.75	2	0.2	0.20	0.15	0.13
		0.75	3	0.6	0.59	0.45	0.39
4	2.85	0.75	1	0.3	0.86	0.64	0.57
		0.75	2	0.3	0.86	0.64	0.57
		0.75	3	0.1	0.29	0.21	0.19
		0.75	4	0.2	0.57	0.43	0.38
5	5.71	0.7	1	0.2	1.14	0.80	0.82
		0.7	2	0.1	0.57	0.40	0.41
		0.7	3	0.15	0.86	0.60	0.61
		0.7	4	0.15	0.86	0.60	0.61
		0.7	5	0.1	0.57	0.40	0.41
		0.7	6	0.1	0.57	0.40	0.41
		0.7	7	0.1	0.57	0.40	0.41
		0.7	8	0.1	0.57	0.40	0.41
6	4.67	0.75	1	0.2	0.93	0.70	0.62
		0.75	2	0.2	0.93	0.70	0.62
		0.75	3	0.2	0.93	0.70	0.62
		0.75	4	0.2	0.93	0.70	0.62
		0.75	5	0.15	0.70	0.53	0.46
7	4.2	0.75	1	0.15	0.63	0.47	0.42
		0.75	2	0.75	3.15	2.36	2.08
8	5.36	0.7	1	0.25	1.34	0.94	0.96
		0.7	2	0.1	0.54	0.38	0.38
		0.7	3	0.25	1.34	0.94	0.96
		0.7	4	0.1	0.54	0.38	0.38
9	10.43	0.7	1	0.75	7.82	5.48	5.59
Total					32.62	23.46	22.63

Table D-2 Customer Process Data

Process	Equipment	Equipment Sensitivity	Equipment Connected Phase	PIT (s)	Equipment Restart Time (s)	Cost Factor
1	ACC	Moderate	B	60	10	0.1
	ASD	Moderate	A	60	100	0.1
	ASD	Moderate	A	60	60	0.2
	ASD	Moderate	A	60	60	0.25
	ASD	Moderate	A	60	60	0.35
2	ASD	Moderate	A	60	100	0.15
	PLC	Moderate	C	60	100	0.2
	ASD	Moderate	A	60	100	0.25
	ASD	Moderate	A	60	60	0.4
3	ASD	Moderate	A	60	100	0.25
	PLC	Moderate	B	60	60	0.35
	ACC	Moderate	C	60	60	0.4
4	PLC	Moderate	A	60	100	0.1
	PLC	Moderate	B	60	100	0.25
	ACC	Moderate	C	60	10	0.3
	ASD	Moderate	A	60	10	0.35
5	PLC	Moderate	A	60	10	0.05
	PLC	Moderate	B	60	10	0.1
	ASD	Moderate	A	60	100	0.1
	PLC	Moderate	C	60	10	0.1
	PLC	Moderate	A	60	60	0.1
	PLC	Moderate	C	60	10	0.1
	PLC	Moderate	B	60	100	0.2
	PLC	Moderate	B	60	100	0.25
6	PLC	Moderate	A	60	100	0.1
	ACC	Moderate	B	60	100	0.1
	PLC	Moderate	C	60	100	0.2
	PC	Moderate	B	60	100	0.25
	ASD	Moderate	A	60	60	0.35
7	PC	Moderate	B	60	60	0.5
	ASD	Moderate	A	60	100	0.5
8	ASD	Moderate	A	60	60	0.1
	ACC	Moderate	A	60	100	0.2
	ASD	Moderate	A	60	10	0.3
	ACC	Moderate	B	60	10	0.4
9	ASD	Moderate	A	60	100	1

Table D-3 Customer Process Dependence Matrix

Process	Process Dependence Matrix							
1	1	0	0	0	0			
	0	1	0	0	0			
	0	0	1	0	0			
	0	0	0	1	1			
	0	0	0	0	1			
2	1	0	0	0				
	0	1	0	0				
	0	0	1	0				
	0	0	0	1				
3	1	1	1					
	1	1	1					
	1	1	1					
4	1	0	0	0				
	0	1	0	0				
	0	0	1	1				
	0	0	1	1				
5	1	0	0	0	0	0	0	0
	0	1	1	1	1	1	1	0
	0	1	1	1	1	1	1	0
	0	1	1	1	1	1	1	0
	0	1	1	1	1	1	1	0
	0	1	1	1	1	1	1	0
	0	1	1	1	1	1	1	0
	0	0	0	0	0	0	0	1
6	1	0	0	0	0			
	0	1	0	0	0			
	0	0	1	0	0			
	0	0	0	1	0			
	0	0	0	0	1			
7	1	1						
	1	1						
8	1	0	0	0				
	0	1	1	1				
	0	0	1	1				
	0	0	0	1				
9	1							

Table D-4 Independent Supplies for HQPZ Assessment

Independent Supply	Voltage Level (kV)	Coordinate X	Coordinate Y	Available capacity
1	33	460040	379212	5.3
2	11	457505	380066	7.8
3	11	459362	379394	4
4	11	460376	377894	7.9
5	33	460040	363570	47.8
6	11	457490	369152	12.5
7	11	460376	370180	2.8
8	11	456433	361452	5.7
9	11	459705	360366	13.8
10	11	466119	362009	15.4
11	11	471033	353852	5.4
12	11	458862	345937	7.4
13	11	458862	345937	10.7
14	11	461147	343466	9.9
15	33	442862	347294	14
16	11	447390	347552	3.2
17	11	438362	346609	4.9
18	11	435219	346594	2.4
19	11	430158	360261	11.4
20	11	429230	356189	13.8
21	11	426230	354661	13.2
22	11	419430	346318	9.2
23	11	420826	368880	2.8

Table D-5 DVR sizes considered in HQPZ Assessment

Case	P (MW)	Q (MVAr)	Case	P (MW)	Q (MVAr)
1	1	1	**17**	17	17
2	2	2	**18**	18	18
3	3	3	**19**	19	19
4	4	4	**20**	20	20
5	5	5	**21**	21	21
6	6	6	**22**	22	22
7	7	7	**23**	23	23
8	8	8	**24**	24	24
9	9	9	**25**	25	25
10	10	10	**26**	26	26
11	11	11	**27**	27	27
12	12	12	**28**	28	28
13	13	13	**29**	29	29
14	14	14	**30**	30	30
15	15	15	**31**	31	31
16	16	16	**32**	32	32

Table D-6 Transmission Level Sags

Number	10% transmission sags					30% transmission sags				
	Phase A (pu)	Phase B (pu)	Phase C (pu)	Rate	Duration (ms)	Phase A (pu)	Phase B (pu)	Phase C (pu)	Rate	Duration (ms)
1	0.83	0.83	0.83	0.1	60	0.83	0.83	0.83	0.33	60
2	0.79	0.79	0.79	0.1	60	0.79	0.79	0.79	0.33	60
3	0.81	0.81	0.81	0.1	60	0.81	0.81	0.81	0.33	60
4	0.77	0.77	0.77	0.1	60	0.77	0.77	0.77	0.33	60
5	1.00	0.80	1.00	0.1	60	1.00	0.80	1.00	0.33	60
6	1.00	0.75	1.00	0.1	60	1.00	0.75	1.00	0.33	60
7	1.00	0.83	1.00	0.1	60	1.00	0.83	1.00	0.33	60
8	1.00	0.87	1.00	0.1	60	1.00	0.87	1.00	0.33	60
9	1.00	0.82	1.00	0.1	60	1.00	0.82	1.00	0.33	60
10	1.00	0.84	1.00	0.1	60	1.00	0.84	1.00	0.33	60
11	1.00	0.75	1.00	0.1	60	1.00	0.75	1.00	0.33	60
12	1.00	0.78	1.00	0.1	60	1.00	0.78	1.00	0.33	60
13	1.00	0.87	1.00	0.1	60	1.00	0.87	1.00	0.33	60
14	1.00	0.85	1.00	0.1	60	1.00	0.85	1.00	0.33	60
15	1.00	0.80	1.00	0.1	60	1.00	0.80	1.00	0.33	60
16	1.00	0.82	1.00	0.1	60	1.00	0.82	1.00	0.33	60
17	1.00	0.87	1.00	0.1	60	1.00	0.87	1.00	0.33	60
18	1.00	0.71	1.00	0.1	60	1.00	0.71	1.00	0.33	60
19	1.00	0.83	1.00	0.1	60	1.00	0.83	1.00	0.33	60
20	1.00	0.71	1.00	0.1	60	1.00	0.71	1.00	0.33	60
21	1.00	0.79	1.00	0.1	60	1.00	0.79	1.00	0.33	60
22	1.00	0.77	1.00	0.1	60	1.00	0.77	1.00	0.33	60
23	1.00	0.89	1.00	0.1	60	1.00	0.89	1.00	0.33	60
24	1.00	0.70	1.00	0.1	60	1.00	0.70	1.00	0.33	60
25	1.00	0.87	1.00	0.1	60	1.00	0.87	1.00	0.33	60
26	1.00	0.91	1.00	0.1	60	1.00	0.91	1.00	0.33	60
27	1.00	0.92	1.00	0.1	60	1.00	0.92	1.00	0.33	60
28	1.00	0.87	1.00	0.1	60	1.00	0.87	1.00	0.33	60
29	0.80	1.00	1.00	0.1	60	0.80	1.00	1.00	0.33	60
30	0.81	1.00	1.00	0.1	60	0.81	1.00	1.00	0.33	60
31	0.75	1.00	1.00	0.1	60	0.75	1.00	1.00	0.33	60
32	0.84	1.00	1.00	0.1	60	0.84	1.00	1.00	0.33	60
33	0.77	1.00	1.00	0.1	60	0.77	1.00	1.00	0.33	60
34	0.91	1.00	1.00	0.1	60	0.91	1.00	1.00	0.33	60
35	0.86	1.00	1.00	0.1	60	0.86	1.00	1.00	0.33	60
36	0.79	1.00	1.00	0.1	60	0.79	1.00	1.00	0.33	60
37	0.86	1.00	1.00	0.1	60	0.86	1.00	1.00	0.33	60
38	0.76	1.00	1.00	0.1	60	0.76	1.00	1.00	0.33	60
39	0.80	1.00	1.00	0.1	60	0.80	1.00	1.00	0.33	60
40	0.91	1.00	1.00	0.1	60	0.91	1.00	1.00	0.33	60
41	0.85	1.00	1.00	0.1	60	0.85	1.00	1.00	0.33	60
42	0.75	1.00	1.00	0.1	60	0.75	1.00	1.00	0.33	60
43	0.88	1.00	1.00	0.1	60	0.88	1.00	1.00	0.33	60
44	0.84	1.00	1.00	0.1	60	0.84	1.00	1.00	0.33	60
45	0.73	1.00	1.00	0.1	60	0.73	1.00	1.00	0.33	60
46	0.75	1.00	1.00	0.1	60	0.75	1.00	1.00	0.33	60
47	0.83	1.00	1.00	0.1	60	0.83	1.00	1.00	0.33	60
48	0.84	1.00	1.00	0.1	60	0.84	1.00	1.00	0.33	60

49	0.78	1.00	1.00	0.1	60	0.78	1.00	1.00	0.33	60
50	0.83	1.00	1.00	0.1	60	0.83	1.00	1.00	0.33	60
51	0.80	1.00	1.00	0.1	60	0.80	1.00	1.00	0.33	60
52	0.71	1.00	1.00	0.1	60	0.71	1.00	1.00	0.33	60
53	1.00	1.00	0.71	0.1	60	1.00	1.00	0.71	0.33	60
54	1.00	1.00	0.77	0.1	60	1.00	1.00	0.77	0.33	60
55	1.00	1.00	0.70	0.1	60	1.00	1.00	0.70	0.33	60
56	1.00	1.00	0.78	0.1	60	1.00	1.00	0.78	0.33	60
57	1.00	1.00	0.85	0.1	60	1.00	1.00	0.85	0.33	60
58	1.00	1.00	0.72	0.1	60	1.00	1.00	0.72	0.33	60
59	1.00	1.00	0.71	0.1	60	1.00	1.00	0.71	0.33	60
60	1.00	1.00	0.83	0.1	60	1.00	1.00	0.83	0.33	60
61	1.00	1.00	0.83	0.1	60	1.00	1.00	0.83	0.33	60
62	1.00	1.00	0.70	0.1	60	1.00	1.00	0.70	0.33	60
63	1.00	1.00	0.70	0.1	60	1.00	1.00	0.70	0.33	60
64	1.00	1.00	0.74	0.1	60	1.00	1.00	0.74	0.33	60
65	1.00	1.00	0.83	0.1	60	1.00	1.00	0.83	0.33	60
66	1.00	1.00	0.71	0.1	60	1.00	1.00	0.71	0.33	60
67	1.00	1.00	0.78	0.1	60	1.00	1.00	0.78	0.33	60
68	1.00	1.00	0.84	0.1	60	1.00	1.00	0.84	0.33	60
69	1.00	1.00	0.86	0.1	60	1.00	1.00	0.86	0.33	60
70	1.00	1.00	0.85	0.1	60	1.00	1.00	0.85	0.33	60
71	1.00	1.00	0.72	0.1	60	1.00	1.00	0.72	0.33	60
72	1.00	1.00	0.80	0.1	60	1.00	1.00	0.80	0.33	60
73	1.00	1.00	0.80	0.1	60	1.00	1.00	0.80	0.33	60
74	1.00	1.00	0.78	0.1	60	1.00	1.00	0.78	0.33	60
75	1.00	1.00	0.73	0.1	60	1.00	1.00	0.73	0.33	60
76	1.00	1.00	0.85	0.1	60	1.00	1.00	0.85	0.33	60
77	1.00	1.00	0.85	0.1	60	1.00	1.00	0.85	0.33	60
78	0.86	0.79	1.00	0.1	60	0.86	0.79	1.00	0.33	60
79	0.81	0.83	1.00	0.1	60	0.81	0.83	1.00	0.33	60
80	0.82	0.82	1.00	0.1	60	0.82	0.82	1.00	0.33	60
81	0.73	0.86	1.00	0.1	60	0.73	0.86	1.00	0.33	60
82	0.80	0.81	1.00	0.1	60	0.80	0.81	1.00	0.33	60
83	0.86	1.00	0.87	0.1	60	0.86	1.00	0.87	0.33	60
84	0.90	1.00	0.81	0.1	60	0.90	1.00	0.81	0.33	60
85	0.76	1.00	0.74	0.1	60	0.76	1.00	0.74	0.33	60
86	0.76	1.00	0.85	0.1	60	0.76	1.00	0.85	0.33	60
87	0.89	1.00	0.92	0.1	60	0.89	1.00	0.92	0.33	60
88	0.75	1.00	0.88	0.1	60	0.75	1.00	0.88	0.33	60
89	1.00	0.85	0.88	0.1	60	1.00	0.85	0.88	0.33	60
90	1.00	0.81	0.90	0.1	60	1.00	0.81	0.90	0.33	60
91	1.00	0.73	0.75	0.1	60	1.00	0.73	0.75	0.33	60
92	1.00	0.85	0.75	0.1	60	1.00	0.85	0.75	0.33	60
93	1.00	0.78	0.71	0.1	60	1.00	0.78	0.71	0.33	60
94	1.00	0.73	0.72	0.1	60	1.00	0.73	0.72	0.33	60
95	0.84	0.82	1.00	0.1	60	0.84	0.82	1.00	0.33	60
96	0.74	0.88	1.00	0.1	60	0.74	0.88	1.00	0.33	60
97	0.89	1.00	0.85	0.1	60	0.89	1.00	0.85	0.33	60
98	0.74	1.00	0.92	0.1	60	0.74	1.00	0.92	0.33	60
99	1.00	0.91	0.74	0.1	60	1.00	0.91	0.74	0.33	60
100	1.00	0.71	0.92	0.1	60	1.00	0.71	0.92	0.33	60

Appendix E List of Publications

E.1 Journal Papers

[1] J. Y. Chan, J. V. Milanovic, and A. Delahunty, "Generic failure risk assessment of industrial processes due to voltage sags," *IEEE Transactions on Power Delivery*, vol. 24, pp. 2405, 2009.

[2] J. Y. Chan, J. V. Milanovic, and A. Delahunty, "Risk based assessment of financial losses due to voltage sag," *IEEE Transactions on Power Delivery*, to be published.

E.2 International Conference Papers

[1] J. Y. Chan and J. V. Milanovic, "Severity indices for assessment of equipment sensitivity to voltage sags and short interruptions," in *IEEE PES General Meeting 2007*, Tampa, Florida, 2007.

[2] J. Y. Chan and J. V. Milanovic, "Methodology for assessment of financial losses due to voltage sags and short interruptions," in *9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, 2007.

[3] J. Y. Chan, J. V. Milanovic, A. Delahunty, and C. D. Horne, "Estimating customer voltage sag performance through analysis of monitoring records," in *6th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion*, Thessaloniki, Greece, 2008.

[4] J. Y. Chan and J. V. Milanovic, "Methodology for development of customized customer damage functions for evaluation of financial losses due to voltage sags and interruptions," in *PowerTech, 2009 IEEE Bucharest*, 2009.

[5] J. Y. Chan, J. V. Milanovic, and A. Delahunty, "Risk based financial assessment of voltage sag mitigation options," in *Electricity Distribution. CIRED 2009. 20th International Conference and Exhibition on*, 2009.

E.3 Technical Reports

[8] "Economic framework for power quality - draft report," CIGRE/CIRED Joint Working Group C4.107, October, 2009.

E.4 Industrial Software

[9] Voltage Disruption Cost Assessment Tool (VoDCAT), version 1.0, updated 17/05/2010.