EQUIVALENT DYNAMIC MODEL OF DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATION

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ABSTRACT

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Today’s power systems are based on a centralised system and distribution networks that are considered as passive terminations of transmission networks. The high penetration of Distributed Generation (DG) at the distribution network level has created many challenges for this structure. New tools and simulation approaches are required to address the subject and to quantify the dynamic characteristics of the system. A distribution network or part of it with DG, Active Distribution Network Cell (ADNC), can no longer be considered as passive. An equivalent dynamic model of ADNC is therefore extremely important, as it enables power system operators to quickly estimate the impact of disturbances on the power system’s dynamic behaviour. A dynamic equivalent model works by reducing both the complexity of the distribution network and the computation time required to run a full dynamic simulation. It offers a simple and low-order representation of the system without compromising distribution network dynamic characteristics and behaviour as seen by the external grid. This research aims to develop a dynamic equivalent model for ADNC. It focuses on the development of an equivalent model by exploiting system identification theory, i.e. the grey-box approach. The first part of the thesis gives a comprehensive overview and background of the dynamic equivalent techniques for power systems. The research was inspired by previous work on system identification theory. It further demonstrates the theoretical concept of system identification, system load modelling and the modelling of major types of DG. An equivalent model is developed, guided by the assumed structure of the system. The problem of equivalent model development is then formulated under a system identification framework, and the parameter estimation methodology is proposed. The validation results of the effectiveness and accuracy of the developed model are presented. This includes the estimation of the parameter model using a clustering algorithm to improve the computational performance and the analysis of transformer impedance effects on the ADNC responses. The evaluation of probability density function, eigenvalue analysis and parameter sensitivity analysis for the model parameters are also presented. Typical model parameters for different network topologies and configurations are identified. Finally, the developed equivalent model is used for a large power system application. The accuracy and robustness of the developed equivalent model are demonstrated under small and large disturbance studies for various types of fault and different fault locations.
DECLARATION

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1 Introduction

1.1 Background

Modern electrical systems are centralised, feed into interconnected large power stations via the high voltage transmission network, and transmit power to customers via the lower voltage distribution network. The rapid growth of various types of distributed generation (DG), connected at the lower voltage supply, has created many challenges to this structure. The wider integration of DG into the distribution network increases requirements for operation and control of the network due to the complexity and variety of the new technology devices. This also leads to increasing difficulty in modelling the distribution network for system dynamic studies, in particular to model various distribution network’s components in detail, because of significantly increased
complexity and order of the model and consequently excessive computation time needed for system level dynamic studies.

Traditionally, the distribution network has been represented by simple equivalent load model for power systems dynamic studies. The conventional dynamic equivalent model approach for large power systems is to make use of simple equivalent load model of the distribution network. However, with the increasing number of small generation units at the distribution network level, simple equivalent load modelling is no longer adequate or reliable in representing the dynamic characteristics of the network. Moreover, the detailed data for the components of the distribution network is not always available. This lack of component data and the increase in network complexity limit the applicability of the conventional methodology for development of dynamic equivalents of the distribution network.

The flexible operation of the power networks of the future, both distribution and transmission, will depend even more on adequate modelling of all network components. There is, therefore, a need for new modelling tools and equivalent models for distribution networks that represent the behaviour of the network at the point of connection accurately, without significantly increasing computational effort. The new tools and models need in particular to handle effectively the increased complexity of the distribution network caused by the increasing penetration of various types of DGs.

1.2 Motivation and Problem Statement

The increasing penetration of DGs has renewed interest in modelling the dynamic behaviour of power systems, at both transmission and distribution level. New tools and
Chapter 1

Introduction

Simulation approaches are required to address this subject and to quantify the dynamic characteristics of the system. Rapid changes in DGs are altering nature of distribution networks as passive terminations of transmission networks. A distribution network in which DG units are connected to the grid, the so called Active Distribution Network Cell (ADNC), can no longer be considered as passive. Therefore, in the future it will not be possible to use simple equivalents of ADNC for power system dynamic modelling, as was done before. However, the whole ADNC cannot be represented in a detailed manner because of the huge dimensions of the system and the computational time constraints associated with dynamic simulations of large power networks. Thus, the equivalent dynamic model of ADNC is extremely important, as it enables power system operators to quickly estimate the impact of disturbances on the power system’s dynamic behaviour. A dynamic equivalent model works by simplifying the complexity of the distribution network and reducing the computation time required to run a full dynamic simulation. It offers a simple and low-order representation of the system without compromising distribution network dynamic characteristics and behaviour as seen by the external grid.

1.3 Review of Past Work

1.3.1 Dynamic Equivalent Models of Large Power Systems

Dynamic equivalent models of large power systems are typically used in simulating transient rotor angle stability of synchronous machine (transient stability simulations). This type of dynamic equivalent falls under the category of low frequency equivalents [1]. Most of the research works on the development of dynamic equivalent
models have been done in 1970s and 1980s which were based on the ideas proposed by Ward [2] and empirical methods [3, 4].

In the late 1960’s, the modal equivalent approach was first reported [5, 6] and later in the 1980’s [7-9]. This method suggested the elimination of those modes of oscillation that are not be easily excited by disturbances in particular areas of the system. Due to the difficulty to find the modes to be eliminated, and the need to modify stability simulation programs to use a state matrix form of the equations of the equivalent, the modal analysis methods have not been widely used [10, 11].

Later, the coherency concept was developed in the 1970’s, as an alternative approach [12-16]. Following a remote disturbance, certain groups of generators will tend to swing together. These groups, called coherent groups, can be represented by a single equivalent machine. Chang et al. [14] originally proposed the coherency concept, which was later developed further by Podmore [15] and incorporated in the Dynamic Equivalencing software package, DYNEQ, developed under the American Electric Power Research Institute (EPRI) [10, 17].

The modal-coherency technique is a method which has been used to supplement the coherency methods [18-22]. In this method, the coherent groups are identified using modal methods. The rigorous mathematical basis of the method is benefited to overcome the disadvantages of the coherency method. On the other hand, the modal equivalent does not depend on the perturbation chosen to determine the equivalent. In [22], the modal-coherency method using frequency response is applied to identify coherent generators.

Lately, Artificial Neural Network (ANN) has been used to develop a dynamic equivalent model of power systems [23-27]. The ANN-based models were derived from
measurements at points connecting both the study system and external subsystems. This technique involved two different neural networks that are used to extract states of the reduced order equivalent and to predict the new state values of the external system. Similar techniques successfully applied to derive dynamic equivalents for large systems are also presented in [28]. In these studies, the external system is represented through an input-output formulation and only one neural network is used to predict its dynamic behaviour.

Apart from those previous methods mentioned, the identification of dynamic equivalents is proposed based on the approach using measurement and simulation-based techniques. The Maximum Likelihood technique[29, 30] and least-square algorithm [31] were used as the optimisation algorithm. In these works, an equivalent model is estimated using the optimisation algorithm and re-evaluated against the original system until the cost function has reached the minimum and all equivalent parameters have been identified. A similar principle is suggested in [25, 32-34]. The main interest is to search for the best parameter vector which minimises an error index that is taken to be a square function of the difference between measured output and the simulated/calculated output.

Another approach based on the Extended Two Particle Swarm optimisation algorithm is proposed in [35] using the measurements obtained from Phasor Measurement Units (PMU). More recently, the identification-based equivalent from online measurements, using the interpretation of coherency from the graph model of a power system, has been proposed in [36]. The knowledge of coherent generators from a graph model gives the number of equivalent generators and attaching locations. The parameters of equivalent generators are identified using the identification procedure built into the Power System Analysis Toolbox (PSAT) and MATLAB software.
Chapter 1

Introduction

1.3.2 Modelling of loads

The major source of inaccuracy in dynamic power simulation arises from the model used to represent loads, due to their stochastic nature. Traditionally, loads are represented as simple static load model on the basis of constant impedance (Z), constant current (I), constant power (P) or static polynomial load models. A general overview on load representation for dynamic power simulation was reported in [37]. Next, standard load models for power flow and dynamic simulations programs were given in [38], with the recommendations on the structure of multiple load types connected to a load bus for transient stability, longer-term dynamics and small-disturbance stability studies. Improved structures for static loads, dynamic IM models, dynamic synchronous motor models and transformer saturation have been proposed for more accurate load modelling.

To overcome the drawbacks of linearity, a dynamic load model has been developed. Currently, the composite load model comprised of a static part and dynamic part is widely used in power system dynamic simulations [39-47]. The static part of the composite load model is represented by the combination of constant impedance (Z), constant current (I) and constant power (P) known by ZIP model [39-43, 45, 46], the static polynomial model [44] or a voltage dependent impedance which depends on supply voltage and load current [47]. The static part of the composite load model is connected in parallel with the dynamic part, which is represented by an induction motor (IM) model.

In [48], the behaviour of three simplified composite load models were compared: a generic non-linear dynamic model of the first order, a static exponential load plus a dynamic first order model for IM and a static exponential load plus a dynamic third-order model of IM. It was shown that for the same disturbance, the simulation results
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were quite different from each other and only the third-order IM model correctly predicted the voltage collapse at the load bus.

The effect of dynamic versus static load modelling in large transient stability studies are presented in [49]. The model used a composite load model comprising of an equivalent IM in parallel with a static load model. Two cases were considered in the study. Case one was a severe disturbance in a strong interconnected system. Case two was severe disturbance in a system with heavy industrial loads and weak interconnections, and therefore, having significantly higher number of frequency and voltage deviations. The results in the first study demonstrated that the differences between the calculated response and the actual response of static and dynamic load model are marginally small. In the second case, however, significantly larger differences between the results obtained with the static and dynamic load model were observed and the dynamic model showed much better accuracy. Therefore, it was concluded that for weak systems with high frequency and voltage deviations, dynamic load model should be used.

1.3.3 Dynamic Equivalent Models of Distribution Networks with DG

Most work in the past in this area concentrated on the development of dynamic equivalents of distribution network that contains wind farms [50-53]. There are a very few papers, however, reporting the development of the dynamic equivalent of ADNC [54-67] which can be divided into six groups of authors. The Hankel-norm approximation is used to derive the dynamic equivalent of ADNC as reported in [54-56]. The equivalent model is developed by combination of two linearised model, i.e., the state space model of the generator and the model of the network. The model
reduction is then performed using Hankel-norm approximation based on the specified error boundary. In this method, the dynamic equivalents produced are valid only for a given operating condition. Thus, the procedures for obtaining dynamic equivalents need to be repeated for different conditions.

A dynamic equivalent of ADNC based on the system identification approach was proposed in [57, 58]. Since the detailed information on the network structure and parameters are not available, the ADNC was modelled using the black-box approach. The parameter identification is then performed by importing the input (voltage and frequency) and output (real and reactive power) data into the MATLAB System Identification toolbox. The state space and auto-regressive model with exogenous input (ARX) model are used to represent the equivalent model. The main advantage of this method is its simplicity of implementation, as it does not require detailed network information. This model, however, is highly dependent on the type and location of the disturbance.

Under the same approach, the further development of the model in [57, 58] is presented in [59]. The state space model in the MATLAB System Identification toolbox is used to represent the dynamic equivalent of ADNC. The model’s order is identified by the singular value diagram. The singular value diagram of signals obtained from system under the disturbance, which does not excite the modes of transmission network much, can reflect the order of the distribution network easier. Simulations done in [59] have suggested that this order, or an order slightly higher, is enough for a subspace state-space model to represent the distribution network.

The development of dynamic equivalent models for microgrids (MG) as reported in [64, 66, 67] also adopted the system identification theory. The developed model is
formed into two parts, i.e., fast dynamic response and slow dynamic response. The
detailed model of Voltage Source Inverter (VSI) is used to represent the fast dynamic
response part. The MG slow dynamic response is represented by reduced order models
that can be derived from two different approaches: black box and grey box modelling.
In [64], a black box modelling approach based on ANN was used to represent the MG
dynamic equivalent. The Levenberg-Marquardt method and Mean Square Error (MSE)
criterion in the MATLAB Neural Network Toolbox was used to train the equivalent
model. In [66, 67], the MG dynamic equivalent was derived using a grey-box approach
in combination with an Evolutionary Particle Swarm Optimization (EPSO) algorithm.
The model was developed in MATLAB/Simulink. The parameters were estimated using
an EPSO algorithm and the Sum Square Error (SSE) was used to measure the closeness
of the estimated model response to the real system response.

A recurrent Artificial Neural Networks (ANN) is adopted to derive a generic
nonlinear dynamic equivalent model of ADNC [60-62]. All the active elements in the
ADNC are represented by the ANN. The ANN training in time series is performed
using the suitable patterns from the complex voltages, power transfer and injected
currents during the fault simulation. The main advantages of this method are that no
prior detailed specifications are needed and that the developed model accuracy is not
depended on certain operating conditions.

A state space model for stand-alone MG was introduced in [63]. The model,
which incorporated the composite load model, was divided into three components:
plants, controllers and reference frames (RF). A vector valued function is then produced
that describes all plants in a similar form using a generic vector valued function to
model the RL (resistance inductance) branch dynamics in rotating RFs. For more
realistic results with oscillations and load margin, the bifurcation theory used in this study shown that the composite loads should be included in the MG modelling.

In [65], a dynamic model of MG for small signal studies is proposed. The model is developed from the electro-mechanical dynamics of a synchronous generator (exciter and governor), and the dynamics of a voltage-sourced converter (VSC), together with a power controller and the network dynamics. The ordinary differential equations (ODEs) for each element in their respective local dq0 reference frames are used to derive the equivalent model. A linearisation at an operating point is performed before the equations are re-arranged in form of a state space model. The linearised model is validated with a detailed model developed in the PSCAD/EMTDC software package.

1.4 Summary of Past Work

In summary, the static loads are considered as the load models in most of the past studies of ADNC dynamic equivalent model [54-56, 61, 62, 65]. Only a few papers, however, take into account dynamic loads in their modelling [63]. The induction motors are usually the most significant contributors to load dynamic characteristics as motors consume 60 to 70% of the total energy supplied by a power system [68]. Furthermore, it was suggested by [49] that for transient stability analysis in weak interconnected power systems and high frequency and voltage deviations (like ADNC), the load model should include a combination of static and dynamic part reflecting dynamics of induction motors. As a general conclusion, the dynamic load models should be considered in ADNC modelling, together with static load models. For the dynamic load models, the
third-order model of IM is sufficient to represent the dynamic characteristics of power systems as suggested in [48].

Approximating the dynamics of ADNC using passive lumped loads, as it was done before, is no longer applicable because of the dynamics introduced by DGs. Therefore, replacing ADNC with suitable dynamic equivalent model is essential for dynamic system studies as detailed network models are not appropriate due to the huge dimensions of the system and computational time constraints. The conventional dynamic equivalent techniques, i.e., the modal analysis method and coherency-based identification, are not suitable for deriving ADNC equivalents since DGs connected to the distribution network through power electronic interfaces are not characterised by angle and angular speeds [67]. Moreover, linearisation and model reduction of a distribution network with DG are only appropriate and reliable under certain conditions [54-56]. The linearisation process involved in model reduction methods limits the obtained simulation results from being generalised for large disturbance studies [54-56, 63]. In order to obtain the desired ADNC model, a suitable dynamic equivalent technique is needed. System identification techniques in combination with some general knowledge of network structure, if applied adequately, seem capable of handling the model derivation problems, as they involve building mathematical models based on observed system responses and can be easily validated [57-59, 64, 66, 67].

1.5 Aims of the Research

The increased complexity of distribution networks due to higher penetration level of DG resulted in need to develop new modelling tools and equivalent models that adequately represent the dynamic behaviour of the network. The main aim of this
research is, therefore, to develop an equivalent model of distribution network with DG capable of describing the steady state and dynamic behaviour of the ADNC for large system stability studies. In order to achieve the above aim, the research has the following objectives:

1. A dynamic equivalent model offers a reduced order network model with less computational time needed for dynamic simulation studies. The first objective of this research is to develop a simple, low-order dynamic equivalent model of ADNC. The developed equivalent model should be used for large power system stability studies.

2. The dynamic equivalent methods reported in the literature indicate that the conventional dynamic equivalent techniques, such as modal analysis and coherency methods, are not suitable for development of ADNC equivalent model. System identification theory seems a promising method to be adopted. The second objective of this research is to develop robust parameter estimation method for developed equivalent model based on application of system identification theory. The methodology should be also applicable for parameter estimation of equivalent models of other forms of active distribution networks, such as microgrids.

3. The third objective of the research is to propose suitable range of equivalent model parameters for different, typical, compositions of ADNC. Appropriate case studies should be developed for this purpose, in order to produce the generic range of ADNC responses.

4. In dynamic equivalencing, the equivalent model performance and the accuracy of the model is typically evaluated through dynamic system studies. The forth
objective of this research is, therefore, to validate developed equivalent model in large power systems stability studies under small and large disturbances. The robustness and accuracy of the equivalent model should be demonstrated by comparing the simulated responses obtained using full non-linear ADNC model and those obtained using developed equivalent model.

1.6 Major Contributions of the Research

The research presented in this thesis contributes to several areas of dynamic equivalencing of electrical power networks. The main contributions are listed below.

(Note: References given in parentheses indicate that the related results are published in international journals or in proceedings of international conferences. A full list of author’s thesis-based publications is given in Appendix F.)

1. Detailed overview of past methodologies for development of equivalent dynamic models of part or whole power network is presented with clear identification of advantages and disadvantages of each of those.

2. A steady state model of ADNC in the form of second-order transfer function is developed using Prony analysis and nonlinear least square optimisation. The developed model is applicable in small signal stability studies (F5).

3. A low-order dynamic equivalent model of ADNC in state space form is developed using the grey-box approach. The developed equivalent model is suitable for use in both steady state and dynamic system studies (F1, F3 and F4).
4. Sensitivity analysis was carried out to establish model sensitivity to accuracy of different parameters. This helps identifying parameters that need to be carefully tuned in order to get overall best performance of the model (F2).

5. Statistical and probabilistic analysis was carried out to establish ranges of parameters of equivalent model for typical configurations/compositions of ADNC (F1 and F2). Suitable look-up table is also developed detailing model parameters for different ADNC compositions and structures.

6. Potential improvement of the parameter estimation procedure in terms of computational time is proposed by implementing the clustering algorithm before performing the parameter estimation. The clustering algorithm significantly improves computation time with the same accuracy as the individual parameter estimation procedure (F6).

7. The ADNC model, originally developed in MATLAB/Simulink environment, is appropriately modified and applied in commercially available software, DIgSILENT PowerFactory, so that it can be readily used by other researchers working in this area and using DIgSILENT PowerFactory in their studies. Although developed model is not included in standard DIgSILENT PowerFactory library, there is enough information in this thesis to build such a model if needed.

8. Developed ADNC model is applied in sufficiently large transmission system and validated through small and large disturbance stability studies using DIgSILENT PowerFactory. The performance and accuracy of the equivalent model are validated under various types of symmetrical and asymmetrical faults, different fault locations and different types of small and large disturbances (F2).
1.7 Outline of the Thesis

The thesis is organised in seven chapters as follows.

Chapter 1: Introduction

This chapter provides the background motivation and the problem statement for development of the dynamic equivalent model of distribution networks with distributed generation. An overview and summary of previous work is also presented here. This is followed by the aims of the research, identified from the review of previous work, and the main contributions of the research.

Chapter 2: Distributed Generation

The most common DG technologies are presented and briefly discussed in this chapter. A description of their structure as well as the operation of each type is presented. The penetration level of DG in distribution networks is also discussed. Finally, the concepts of active distribution network and Microgrids (considered to be a special case of ADNC in this thesis) are discussed as well in this chapter.

Chapter 3: Techniques for Development of Dynamic Equivalent Models

This chapter provides overview of historical development of dynamic equivalent techniques used to derive dynamic equivalents for large power systems and distribution networks with DG. Their advantages and disadvantages are clearly discussed. Some of the techniques presented here inspired the development of the dynamic equivalent model for ADNC.
Chapter 4: Dynamic Equivalent Model of ADNC

This chapter presents the background knowledge on system identification theory. The modelling of loads and major types of DG is also discussed here as DG represent one of the main component of the ADNC structure. Following this, a preliminary ADNC model in the form of the second order transfer function is described. The initial model is developed based on a combination of Prony analysis and nonlinear least square optimisation and applicable for small disturbance stability studies. All the relevant results of model performance and accuracy are presented to show the effectiveness of the preliminary model. Further, the chapter presents detailed development of the ADNC model based on the grey-box approach. The parameter estimation procedure by employing nonlinear least square optimisation is also discussed here.

Chapter 5: Validation of Dynamic Equivalent Model of ADNC

The ADNC model validation results were presented in this chapter. The performance of developed model is evaluated for different disturbances, various fault locations and different network configurations, and the results of simulations compared with those obtained using full non-linear model of ADNC developed in DlgsILENT PowerFactory. This is followed by the estimation of model parameters using a clustering procedure and estimation of the effects of connecting transformer impedance on ADNC responses. The probability density function (PDF) of model parameters is then established and sensitivity of the model response to parameter values evaluated. Finally, the chapter presents typical model parameters for different network topologies and compositions.
Chapter 6: Application of ADNC Model in Power System Stability Studies

This chapter presents the application of the developed equivalent model in a large power system network. The model is accessed using small and large disturbances, different fault types and fault locations. The results of simulation using full nonlinear ADNC network are compared with those obtained using developed equivalent model. Both, small and large disturbance stability analysis were carried out. Finally, the eigenvalues of the system obtained with full non-linear model, and with the equivalent model of ADNC, are compared in order to evaluate the suitability of the model for the use in small disturbance stability studies.

Chapter 7: Conclusions and Future Work

First part of this chapter presents summary of the research presented in the thesis along with the main conclusions of the research. The second part of the chapter presents suggestions for future research in this area and discusses possible improvements of the equivalent models and methodologies developed.
2 Distributed Generation

2.1 Introduction

Recently, factors such as the need to reduce carbon emissions, a general desire to improve the quality of the environment and the rising price and reducing availability of fossil fuels lead to an increase in alternative generating technologies such as wind, landfill gas, wave and tidal energy. Generation projects that have harnessed these new technologies have typically been small in comparison to traditional fossil fuel generating plant. For economic reasons, such projects have tended to connect at distribution voltages. These new types of generating plant based on renewable energy sources and connected to distribution level voltages are generally called Distributed Generation (DG). Therefore, DGs are small electrical power generation units connected directly to the distribution network or connected to the network on the customer site of the meter [69, 70]. DG embraces a broad range of prime mover technologies, such as
internal combustion (IC) engines, gas turbines, microturbines, photovoltaic systems, fuel cells, wind generators etc. Most of the DG like microturbines, wind generators, photovoltaic systems and fuel cells has power electronic converters (inverters) to interface with the distribution network system.

DG is gaining a lot of attention as it brought about economic benefits to the development and operation of the total power systems in terms of the increase of system efficiency and the improvements in the power quality and reliability, as well as wider environmental benefits. However, the increasing numbers of DG units connected to distribution network also posed challenges to owners of those systems. Many technical and operation challenges like the control strategies for electrical network and dynamic interaction between the high voltage and low voltage network have to be resolved before DG becomes feasible. Consequently, the suitable static and dynamic models of DG units and the whole distribution network with DGs are required in order to simulate the behaviour of modern electrical networks. These issues related to high penetration of DG within distribution network must be resolved to permit the wider applications of DG in modern electricity supply systems.

2.2 The importance of DG

A distributed electricity system is one in which small and micro generators (i.e. DG) are connected directly to factories, offices, households and to lower voltage distribution networks. Electricity not demanded by the directly connected customers is fed into the active distribution network to meet demand elsewhere. Electricity storage systems may be additionally utilised to store any excess generation. Large power stations and large-scale renewables, e.g. offshore wind, remain connected to the high
voltage transmission network providing national back up and ensuring quality of electricity supply. Again, electricity storage may be also utilised to accommodate the variable output of some forms of generation. A distributed electricity system is represented in Figure 2-1.

As mentioned above, DG refers to generation connected to the distribution network rather than the transmission network. In [71], DG is referred to as generation connected to the distribution network at medium voltage, MV, (30 – 1kV) or low voltage, LV, (< 1kV). Generation connected to the high voltage transmission system (above 69kV), including large wind parks, is not included in this category. According to several research studies, some universally accepted common attributes of DG have been identified as [69-71]:

- not centrally planned
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- not centrally despatched
- normally smaller than 50 to 100 MW
- usually connected to the distribution system

The use of renewable DG sources for the generation of electricity is seen as one of the important ways of reducing carbon dioxide emissions. In many applications, DG can provide valuable benefits for both the consumers and the Distribution network operator (DNO). Since DGs are relatively small in size, they are more conveniently and cheaply utilised in a wider range of applications. The downstream location of DG units in distribution systems has brought the generation close to the loads, and consequently, reduced energy losses. The benefits of utilising DG can be summarised as follows [70]:

- improving availability and reliability of utility system
- voltage support and improved power quality (the effect of increasing the network fault level by adding generation often leads to improved power quality [94])
- reduction of the transmitted power and as the result, the transmission and distribution expenditures are postponed or avoided
- power-loss reduction as DG is connected closer to the loads
- possibility of co-generation applications
- wide application of DG will reduce fossil fuel consumptions and consequently contribute to the emission reduction

In 2003, the UK’s electricity generation map changed, as documented in the UK government’s Energy White Paper [72]. It accepts the need to reduce carbon dioxide (CO₂) emissions significantly and provides the long-term framework to deliver UK environmental, security of supply, competitiveness and social goals. In reducing CO₂ emissions, the priority is to strengthen the contribution of energy efficiency and
renewable energy sources. The Energy White Paper set a target of 10% of electricity from renewable sources by 2010, and an aspiration for sourcing 20% of the overall electricity consumption comes from renewable sources by 2020 [72]. Currently, based on provisional data, renewable, including large scale hydro generation, accounted for 6.6% of total electricity generated in the UK in 2010 [73, 74].

Various renewable technologies will contribute to this target. Certain technologies, such as onshore and offshore wind, landfill gas and industrial combined heat and power (CHP) have developed significantly in recent years, resulting in reductions in unit costs which further encouraged the development of DG. Wind generation will majorly contribute to accomplish the target since there is huge wind resource available and its leading competitive position among renewable technologies. The development of micro and alternative renewable technologies, such as biomass, is probably to ensure that the mix of DG will broaden over time. The high level overview indicates that demand for connections of electricity generation at distribution voltage is unlikely to reduce in the foreseeable future and that such projects are necessary in order to contribute towards the meeting of UK energy policy goals.

2.3 DG Technologies

There are several different types of generators that could be used for DG. These can be split into three main categories, i.e., synchronous generators, asynchronous generators and power electronic converter (inverter) based generators. The following sub-sections will describes each of the three main categories of DG.
2.3.1 Synchronous Generators

The alternating current (AC) on the electricity distribution and transmission system in the UK oscillates at a frequency of 50 cycles per second. Synchronous generators are capable of being controlled such that their output is synchronised with this frequency. They can generate both active and reactive power, thus providing voltage stability for the network. Synchronous generators are typically utilised for large centralised generation schemes, such as fossil-fuel fired plants, nuclear or hydro power plants, though they are also employed in DG systems in the case of diesel/gas engines, gas turbine and combined cycle gas turbine (CCGT) driven generators.

2.3.2 Asynchronous Generators

Asynchronous generators are more commonly used for DG applications, i.e., with individual generator capacities less than a few MW, such as wind generators, solar dish engines or solar thermal systems. Asynchronous generators cannot generate reactive power on their own. Therefore, they cannot operate independently of the grid, unless a source of reactive power is provided (e.g., power factor correction capacitors or synchronous compensator). The most common form of asynchronous generator applied as DG is the induction generator used for fixed speed wind generation.

2.3.3 Power Electronic Converter (Inverter) Based Generators

Certain generating technologies are generally connected to the electricity network via power electronics. Direct current (DC) sources (photovoltaics batteries, fuel cells) need power electronic inverters to convert DC to AC for grid connection. In terms of existing DG, these power electronic technologies are being applied increasingly for
connections of larger wind turbines. Traditional asynchronous wind generators and fixed speed induction generators are being superseded by Doubly Fed Induction Generators (DFIGs) that power electronic inverters for much greater control of active and reactive power output and operation with wider range of wind speeds. The generator types used for wind generation are permanent magnet synchronous generator (PMSG), asynchronous generator, DFIG and wound field synchronous generator [75]. PMSGs are favourable in small scale wind generation designs, because of their high efficiency and self-exciting capabilities. DFIGs are suitable for high power wind generator application with a reduced converter cost. The synchronous generators allow for independent control of both active and reactive power. As for the asynchronous generators, they are less expensive, robust and have simple design of wind generation system.

2.3.4 Generation types and Energy Resources

DG can be classified by the primary energy source to be converted to electrical power. By virtue of the lower power transfer capacity of distribution networks, compared with transmission networks, DG tends to be of relatively low power outputs. The following sub-sections will be describing the different generation types and energy recourse of DG.

2.3.4.1 Wind

Wind power is gaining increasing significance for electricity generation in regions throughout the world that have reasonable wind speeds. The characteristics of power network operation with DG have been addressed and largely solved through experience with clusters of wind turbines formed into wind farms. Both onshore and
offshore wind farms have been built and a number of large industrial users of power have installed wind turbines for their sole use. The turbines used for these applications are in the range 500 kW to 3 MW [76]. The electricity generated by wind turbines is very much, if not completely dependent on the wind conditions in the area where they are located.

Micro-wind generators are small-scale wind turbines aimed at domestic housing electricity generation in the range of 1-10 kW. Micro-wind generators produce electricity when the wind blows at speeds in the range from 3-4 m/s up to 15 m/s. Most micro-wind generators aimed at domestic housing have a capacity of up to 1 kW. However, there are larger generators available from 10 kW and above for offices and industrial buildings. Micro-wind technology utilises synchronous or asynchronous generators as part of their design.

Wind turbine generators can operate at fixed speeds or variable speeds. Fixed speed generators are more robust and cheaper than the variable speed ones, because they typically require fewer parts and do not use power electronic inverters. Generally, fixed speed wind generators use an induction generator as the electrical power component. Variable speed wind generators, however, are more efficient than the fixed speed wind generators. The electricity produced by micro-wind generators is generally DC, which has to be converted to AC using inverters in order to be connected to the network [70, 77]. Typical electrical power generators used for variable speed wind generators are the doubly feed induction generator and permanent magnet synchronous generator [70, 77].

2.3.4.2 Oil or gas powered combined heat and power (CHP)

Combined heat and power (CHP) techniques generate useful heat and electricity. There are two possible CHP configurations; either electricity or heat is the main product, with heat or electricity, respectively, as the by-product. There are three main
sizes of CHP, i.e., industrial CHP, district/community CHP and micro CHP. The CHP plants in the UK mainly are located in industrial complexes. Most of large industrial CHP is gas or steam turbine based, fuelled by oil or gas. District or community CHP plant produce heat as the main product. The heat is distributed using hot water to local residential and commercial units. District CHP units are sized to provide the required heat load and supply electrical power as a by-product. Micro CHP refers to any CHP unit that is used within a domestic house and is defined, by engineering recommendation G83 [78, 79], as being a generator within a maximum electrical rating of 3.6 kW. Typical electrical power generators used for CHP are reciprocating engines, combustion or gas turbines and steam turbines.

Steam turbines are widely used for CHP applications. The oil or gas is burned in a boiler, and the electricity is generated when the resulting high-pressure steam is passed through the turbine. The two types of steam turbines most widely used are the backpressure turbine and extraction-condensing turbine depends mainly on the quantities of power and heat, quality of heat and economic factors. Steam turbine CHP units are available with power outputs of 0.5 MW upwards [80].

Gas turbine cogeneration systems can produce all or a part of the energy requirement of the site, and the energy released at high temperature (400 – 550°C) in the exhaust stack can be recovered for various heating and cooling applications. Though natural gas is most commonly used, other gaseous fuels, such as biogas, landfill gas and mine gas can also be employed. The typical range of gas turbines varies from a fraction of a MW to more than 200 MW [80].

Reciprocating engines dominated the CHP applications for industrial, commercial, and institutional facilities. Reciprocating engines start quickly, follow load well, have good part-load efficiencies, and generally have high reliabilities. In many
cases, multiple reciprocating engine units further increase overall plant capacity and availability. Reciprocating engines have higher electrical efficiencies than gas turbines of comparable size, and thus lower fuel-related operating costs. They are readily available in sizes that range from 0.5 kW to 6.5MW [77].

2.3.4.3 Hydro

There are two main types of small-scale hydro generators, i.e., low head and medium head. Large scale hydro is typically connected at higher transmission voltage levels and is therefore not relevant to this section. Medium head hydro generators are considered to be those that generate between 100 kW and 30 MW while the low head hydro generators are smaller than 100 kW. Low head small-scale hydro generators utilise the existing “run-of-river” water flow, that is, they use the flow of water from existing weirs or locks using a penstock to divert the water through a turbine.

Most small-scale hydro is low head. Medium head systems most usually take water from dams, again via a penstock. Typical electrical power generators used for small-scale hydro generators are synchronous generator and induction generators [70]. The induction generators are usually used for isolated areas and single facility [81]. The synchronous generators are generally used for medium head systems and supply the electricity to a community distribution system [77]. On the other hand, home-size low head hydro generators usually generate dc which is used to charge batteries in battery bank for daily use of electricity.

2.3.4.4 Energy from waste (EfW)

There are several different technologies available to generate electricity from waste. The most prevalent of these are the combustion (incineration) of raw and processed waste, landfill gas and gas produced from the anaerobic digestion of agricultural and animal waste [82]. The gas produced by these technologies is known as
biogas. The biogas is used for direct combustion in cooking or lighting and to generate electricity. Some energy from waste (EfW) plants produce heat for customers and have additional gas firing to increase output use at times of high load demand. The combustion engine or CHP are usually used in this case for electricity generation [82].

2.3.4.5 Oil or gas powered diesel engines

These generating schemes are usually employed as standby installations for occasional emergency use, and particularly prevalent in remote areas and islands to back up or support the supply from the grid. The diesel engines are a type of reciprocating internal combustion engine. Generally diesel engines are four-stroke reciprocating engines that are piston-driven engines connected to induction generators or synchronous generators [83].

2.3.4.6 Photovoltaics (PV)

Photovoltaics (PV) systems convert sunlight directly into electricity. An array of PV panels generates a DC power output, which is converted to AC power by a power electronics converter (inverter). There are two types of PV system which are stand-alone system and grid connected system [83]. A stand-alone system is a PV system that is not connected to the grid and is used to supply an independent load. Such units can typically supply part of a housing or small business load. On the other hand, a grid-connected system is a PV system that connected to the grid and can feed powers into the grid. Typically, this type of PV system is installed at the buildings, residential and PV power plant. In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met by the PV system. Only the excess is fed into the grid.
2.3.4.7 Tidal

There are two generating technologies available to generate electricity from the movements of tidal waters, i.e., tidal stream and tidal barrage. Tidal streams are fast flowing volumes of water caused by the bulk movement of sea water under the influence of tides, usually occurring in shallow seas where a natural constriction forces the speed of water flow to reach a maximum. An example of a tidal stream generator under development is a hydroplane [84], which is caused to oscillate by the tidal stream, driving hydraulic cylinders to power a generator. Tidal stream generators operate under bi-directional tidal stream flows.

On the other hand, tidal barrage technology is similar to hydro generation. A dam or barrage is built across an estuary or bay, but in this case the barrage incorporates gates feeding tidal water to bi-directional water turbines that generate power from both ebbing and flowing tides [77]. Tidal barrage technology is basically similar with the low head hydro system and is using the synchronous generator for the electrical power generation.

2.3.4.8 Wave

At the moment, wave generation technology is at an early stage of development, but there is a significant wave resource available in the UK, when the technology is developed to harness it. Examples of technologies under consideration for commercial use include a four-sided permanent magnet linear generator, which is taking into consideration the features of the incident waves and the behaviour of the floating buoy [85].
2.4 Penetration Level of DG in Distribution Networks

The penetration level of DG into power networks has increased significantly worldwide in recent years. The growth in DG’s volume is due to the Governments’ strive to meet the environmental constraints in response to Kyoto Protocol and the need to enhance generation diversity. The environmental, commercial and national/regulatory factors are determined as the primary drivers for the DG growth worldwide [86].

The UK Government, through its energy regulator, the Office of Gas and Electricity Markets (Ofgem), faces the challenge under the initiative named ‘Rewiring Britain’. Different parties, including Ofgem, Department of Trade and Industry (DTI) and the local electricity networks, currently face the joint challenge of ‘rewiring’ Britain to meet the Government’s energy and environmental policies. Annual reports produced by Department of Energy and Climate Change (DECC) indicated an increasing level of DG installed in UK. Figure 2-2 and Table 2-1 show the UK electricity generation from renewable sources for year 1990 to 2009 [87]. From the data, it can be seen that renewables accounted for 6.7 % of electricity generated in the UK in 2009, up from 5.6% in 2008. Overall generation from renewables increased by 16.9% between 2008 and 2009; generation from wind increased by 31.1%, while generation from all forms of biomass was 14.4% higher; generation from hydro rose only marginally.

The National Grid Electricity Transmission Ltd (NGET) Seven Year Statement (SYS) for 2011 [88] lists DG plants installed in the various Distribution Network Operator (DNO) regions in England and Wales. These figures have been categorised by fuel type and set down in Figure 2-3. (Note: the numbers in the figure represent total power generation in MW).
Figure 2-2: Electricity generation of UK in year 1990 to 2009. Adopted from [87]

Table 2-1: Renewable electricity generation in UK. Adopted from [87]

<table>
<thead>
<tr>
<th>Renewable electricity generation TWh</th>
<th>1990</th>
<th>2000</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>-</td>
<td>0.9</td>
<td>5.3</td>
<td>7.1</td>
<td>9.3</td>
</tr>
<tr>
<td>Hydro</td>
<td>5.2</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>0.1</td>
<td>2.2</td>
<td>4.7</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Other Biomass</td>
<td>0.2</td>
<td>1.7</td>
<td>4.9</td>
<td>4.5</td>
<td>5.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.8</strong></td>
<td><strong>9.9</strong></td>
<td><strong>19.7</strong></td>
<td><strong>21.6</strong></td>
<td><strong>25.2</strong></td>
</tr>
</tbody>
</table>

Figure 2-3: Main type of renewables generation for NETS region. Adopted from [88]
Scottish Renewables publishes data, equivalent to the Seven Year Statement (SYS) renewables generation data, in their Summary of Renewable Energy Project in Scotland [89]. This data is summarised in Table 2-2.

Table 2-2: DG plant installed in Scotland. Adopted from [89]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Installed Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>2575.01</td>
</tr>
<tr>
<td>Hydro</td>
<td>1395.06</td>
</tr>
<tr>
<td>EfW</td>
<td>131.66</td>
</tr>
<tr>
<td>Biomass/CHP</td>
<td>313.65</td>
</tr>
<tr>
<td>Wave</td>
<td>1.6</td>
</tr>
<tr>
<td>Tidal</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4418.98</strong></td>
</tr>
</tbody>
</table>

Based on these figures, an observation can be made that in England and Wales, wind generation accounts for around 33% of the total DG profile. In Scottish Power (SPDL)’s authorised area, wind accounts for more than 58% of the DG profile. Therefore, wind generation dominates the overall UK electricity generation from renewables.

Provisional figures for 2010 [73, 74] show that the UK renewable generation, excluding non-biodegradable wastes, was 25,335 GWh (Table 2-3). This represents an increase of 0.4% on 2009’s figure of 25,222 GWh. Wind generation grew 7.1%, from 9,304 GWh in 2009 to 10,021 GWh in 2010. Meanwhile, particularly low rainfall throughout 2010 meant that hydro output fell by around one third on 2009’s level, from 5,662 GWh to 3,557 GWh.

Based on these figures, the UK failed to meet the 2010 target of generating 10% of electricity from renewable sources set by the Energy White Paper [90]. Renewables accounted for only approximately 6.6% of all electricity demand in 2010 [74]. The UK will need to source over 30% of energy from renewable sources by 2020 if they are to
meet the current targets set by the EU [73]. Reasons for the low number have been put down to low wind load factors leading to a lack of wind power generation [73, 74].

Table 2-3: Provisional data for UK renewable generation in 2010. Adopted from [74]

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind generation (GWh)</td>
<td>9,304</td>
<td>10,021</td>
</tr>
<tr>
<td>Hydro generation (GWh)</td>
<td>5,262</td>
<td>3,557</td>
</tr>
<tr>
<td>Other renewable generation (GWh)</td>
<td>10,656</td>
<td>11,757</td>
</tr>
<tr>
<td>Total renewable generation(GWh)</td>
<td>25,222</td>
<td>25,335</td>
</tr>
<tr>
<td>Total electricity generation (GWh)</td>
<td>375,665</td>
<td>381,247</td>
</tr>
<tr>
<td><strong>Renewable share (%)</strong></td>
<td><strong>6.7%</strong></td>
<td><strong>6.6%</strong></td>
</tr>
</tbody>
</table>

In March 2007, the European Council agreed to a common strategy for energy security and tackling climate change. An element of this was adopted binding target of 20% renewable energy from final energy consumption by 2020 [91, 92]. In January 2008, the European Commission presented a draft Directive on the promotion of the use of energy from Renewable Energy Sources (RES) which contains a series of elements to create the necessary legislative framework for making 20% renewable energy become a reality. The Directive sets the legislative framework that should ensure the increase of the 8.5% renewable energy share of final energy consumption in 2005 to 20% in 2020 [92]. The Renewables Directive sets mandatory national targets in the range from 10% to 49% for renewable energy shares of final energy consumption in 2020 which are calculated on the basis of the 2005 share of each country as outlined in the Table2-4 [91, 92].

Figure 2-4 shows the position of EU and the member states in 2008 (the latest year for which figures for all EU member states are available), with respect to percentage of renewable sources use out of total energy. It can be seen that the share of energy from renewables in the EU increased from 9.7% in 2007 to 10.3% in 2008.
Based on these figures, the Renewables Directive targets can be met along with a higher contribution by some of the more successfully technologies.

Table 2-4: Targets for renewable energy share of final energy consumption. Adopted from [91, 92].

<table>
<thead>
<tr>
<th>Country</th>
<th>Share of energy from renewable sources in final consumption of energy in 2005 (%)</th>
<th>Target for share of energy from renewable sources in final consumption of energy in 2020 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>2.2</td>
<td>13</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>9.4</td>
<td>16</td>
</tr>
<tr>
<td>The Czech Republic</td>
<td>6.1</td>
<td>13</td>
</tr>
<tr>
<td>Denmark</td>
<td>17</td>
<td>30</td>
</tr>
<tr>
<td>Germany</td>
<td>5.8</td>
<td>18</td>
</tr>
<tr>
<td>Estonia</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Ireland</td>
<td>3.1</td>
<td>16</td>
</tr>
<tr>
<td>Greece</td>
<td>6.9</td>
<td>18</td>
</tr>
<tr>
<td>Spain</td>
<td>8.7</td>
<td>20</td>
</tr>
<tr>
<td>France</td>
<td>10.3</td>
<td>23</td>
</tr>
<tr>
<td>Italy</td>
<td>5.2</td>
<td>17</td>
</tr>
<tr>
<td>Cyprus</td>
<td>2.9</td>
<td>13</td>
</tr>
<tr>
<td>Latvia</td>
<td>34.9</td>
<td>42</td>
</tr>
<tr>
<td>Lithuania</td>
<td>15.0</td>
<td>23</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>0.9</td>
<td>11</td>
</tr>
<tr>
<td>Hungary</td>
<td>4.3</td>
<td>13</td>
</tr>
<tr>
<td>Malta</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>2.4</td>
<td>14</td>
</tr>
<tr>
<td>Austria</td>
<td>23.3</td>
<td>34</td>
</tr>
<tr>
<td>Poland</td>
<td>7.2</td>
<td>15</td>
</tr>
<tr>
<td>Portugal</td>
<td>20.5</td>
<td>31</td>
</tr>
<tr>
<td>Romania</td>
<td>17.8</td>
<td>24</td>
</tr>
<tr>
<td>Slovenia</td>
<td>16.0</td>
<td>25</td>
</tr>
<tr>
<td>The Slovak Republic</td>
<td>6.7</td>
<td>14</td>
</tr>
<tr>
<td>Finland</td>
<td>28.5</td>
<td>38</td>
</tr>
<tr>
<td>Sweden</td>
<td>39.8</td>
<td>49</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1.3</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 2-4: Proportional of total final energy consumption of energy from renewable sources in 2007 and 2008. Adopted from [91].
The figures of Table 2-5 outline the new targets for 2020 with the expected annual growth rates and the necessary growth rate to increase the share of RES-Electricity significantly. Based on Table 2-5, the wind generation is still expected to contribute as the highest renewable generation to electricity consumption in European countries.

Table 2-5: Contribution of renewable energy to Electricity Consumption in Europe. Adopted from [92]

<table>
<thead>
<tr>
<th></th>
<th>2005 Eurostat TWh</th>
<th>2006 Eurostat TWh</th>
<th>2010 Projections TWh</th>
<th>2020 Targets TWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>70.5</td>
<td>82.0</td>
<td>176</td>
<td>477</td>
</tr>
<tr>
<td>Hydro</td>
<td>346.9</td>
<td>357.2</td>
<td>360</td>
<td>384</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>1.5</td>
<td>2.5</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Biomass</td>
<td>80.0</td>
<td>89.9</td>
<td>135</td>
<td>250</td>
</tr>
<tr>
<td>Geothermal</td>
<td>5.4</td>
<td>5.6</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td>electricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total RES</strong></td>
<td><strong>504.3</strong></td>
<td><strong>537.2</strong></td>
<td><strong>704</strong></td>
<td><strong>1370</strong></td>
</tr>
<tr>
<td><strong>Share of RES</strong></td>
<td><strong>15.2 %</strong></td>
<td><strong>16.0 %</strong></td>
<td><strong>19.7 %</strong></td>
<td><strong>33.6 – 40.4 %</strong></td>
</tr>
</tbody>
</table>

On the other hand, renewable energy supplies 19% of global final energy consumption (Figure 2-5), counting traditional biomass, large hydropower, and ‘new’ renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) [93]. New renewable energy includes small hydropower (less than 10 MW as a common threshold), modern biomass, wind, solar, geothermal and biofuels, providing 2.7% and are growing very rapidly in the developed countries and in some developing countries. Based on Table 2-6, about 45% of the new renewable generating capacity added between 2008 and 2009 worldwide was hydropower, which means that non-hydro renewables (dominated by wind power) made up a majority of renewable capacity additions during those years.
Despite of global economic crisis, the installed wind generations capacity reached worldwide 196 630 MW in 2010 as shown in Figure 2-6 [94]. China accounted for more than half of the world wind market 2010. In the year 2010, altogether 83 countries, one more than in 2009, used wind energy for electricity generation. 52 countries increased their total installed wind generation capacity compared to 49 countries in the previous year.
In 2010, the Chinese wind market became a class of its own, representing more than half of the world market for new wind turbines adding 18.9 GW, which equals a market share of 50.3% (Refer to Figure 2-7). The top five countries (USA, China, Germany, Spain and India) represented 74.2% of the worldwide wind capacity, significantly more than 72.9% in the year 2009. The USA and China together represented 43.2% of the global wind capacity (up from 38.4% in 2009).

![Figure 2-6: World wind power capacities. Adopted from [94]](image)

![Figure 2-7: Top 10 countries by total capacity (MW). Adopted from [94]](image)
2.5 Active Distribution Network Cell (ADNC)

Electricity produced in the world at present, as in the past, is mostly generated as part of a centralised power system designed mainly around large fossil fuel or nuclear power stations. This electricity is then fed into an interconnected high voltage transmission and lower voltage distribution networks. Distribution networks have traditionally been designed to be ‘passive’, meaning to pass power from bulk supply points to end users. This has resulted in distribution networks principally dedicated to uni-directional. The energy and system balance across all networks was controlled predominantly by the system operators responsible for the high voltage transmission systems. The responsibility of the owners of lower voltage distribution systems was to ensure that electricity was conveyed to end-users. In this respect distribution systems have formerly been considered as ‘passive’.

Nowadays, there is a growing interest in the high volume of DG integration at distribution network level due to the emergence of DG technologies, increase environmental concerns and economy factors. With the increasing penetration level of different DG units, the distribution network, cannot be treated as passive anymore. The distribution network becomes “active” when large number of DGs get connected to it, thus leading to bidirectional power flows in the network. In this thesis, the active distribution network or part of it is referred to as Active Distribution Network Cell (ADNC).

According to [71], an active distribution network is defined as system in place to control a combination of distributed energy resources (DER), mainly generators, loads and storage. Distribution network operators (DNOs) thus have the possibility of managing the electricity flows. DNOs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection
agreement. The consequence of having an active distribution network is reduction in the physical and electrical distance between generation and loads. This leads to the improvement of network operation by reduction of distribution and transmission “bottlenecks”, lower losses and enhancement of the voltage profile. The main technical features of active distribution network are summarised in Table 2-7 [71].

Table 2-7: Main features of active distribution networks. Adopted from [71]

<table>
<thead>
<tr>
<th>Infrastructure needs / specifications</th>
<th>Application</th>
<th>Driver/benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Protection</td>
<td>• Power flow congestion management</td>
<td>• Improved reliability</td>
</tr>
<tr>
<td>• Communication</td>
<td>• Data collection and management</td>
<td>• Increased asset utilisation</td>
</tr>
<tr>
<td>• Integration into existing systems</td>
<td>• Voltage management</td>
<td>• Improved access for DG</td>
</tr>
<tr>
<td>• Flexible network topology</td>
<td>• DG and load control</td>
<td>• Alternative to network reinforcement</td>
</tr>
<tr>
<td>• Active network management capable</td>
<td>• Fast reconfiguration</td>
<td>• Network stability</td>
</tr>
<tr>
<td>equipment</td>
<td></td>
<td>• Improved network efficiency (loss reduction)</td>
</tr>
<tr>
<td>• Smart metering technologies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Microgrids can be considered as an ADNC. A microgrid is a small-scale power supply network, i.e., low voltage (LV) network that is designed to provide power for a small community as shown in Figure 2-8. Small community are typically housing estate or neighbourhoods, isolated rural communities, electrical areas embedded in high-rise buildings, retail shopping areas, or commercial parks. They are generally located inside a single electrical utility’s service territory, and they rely on the utility for many services. The power sources will generally be mixed, mainly renewable sources such as small wind generators and photovoltaics, microturbines, fuel cells as well as storage devices, such as flywheels and batteries.
The connection between this network and the wider electrical power network will be through a hierarchical control and management system comprising two main control levels, as it can be observed from Figure 2-8. The local control level, i.e., Microsource Controllers (MC) and Load Controllers (LC) is used for controlling voltage and frequency based on local information. The MG hierarchical control and management system is led by the MicroGrid Central Controller (MGCC) involving functions of monitoring the active and reactive power of microgeneration systems and assuming full responsibility of the MG operation by sending set points to the MC and LC in order to control microgeneration systems and controllable loads. Hence, it enables MG to operate as a flexible active cell either when interconnected with the MV distribution network or when isolated from it [95]. The MG is operated in two modes, i.e., grid-connected and stand-alone. In grid-connected mode, the MG is completely or partly linked to the grid, and either imports or exports power from or to the grid. In
stand-alone mode, the MG disconnected from the grid, while still feeding power to the local loads [70].

The MGs are not totally new where most large facilities such as military bases, and refineries depend on their own on-site generation and remain connected to the local utility for supplemental power and other services. On the contrary, the new MGs take the benefits from combination of distributed microgeneration and local battery or other energy storage to fulfil the local demands of electricity. The microgrid is responsible for servicing the needs of its consumers, ensuring a quality of supply and possibly controlling some of the non-critical loads.

The key features that differentiate a MG from a conventional power utility can be summarised as follows [70]:

- the power generators are small (often referred to as microgenerators, of a similar size as the loads within the microgrid).
- the microgenerators are distributed and normally located in close proximity to the energy users, so that the electricity/heat can be efficiently supplied and reduced the line losses.
- the microgenerators and possibly also loads, are controlled to achieve a local energy and power balance.

The wide range of potential generators within the microgrid share one common feature: they are small, and comparable in size to the loads within the microgrid. It is also likely that several different types of generators will be present, adding a diversity of generation to the diversity of loads. The microgrid concept is made possible by the recent advances in small scale, reliable generators, power electronics and digital controllers that make it possible to reverse the trend from large scale generation and bulk supply. From the grid point of view, the MG is treated as an independent entity and
can be operated as a single aggregated load. From the user’s point of view, the advantage of MG is that it can meet their electrical/heat demand with continuous power supply without interruptions. MGs also can improve local reliability, reduce line losses and provide local voltage support [70].

As have been described in this chapter, both ADNC and MG have similar concept and network structure. The only difference is in the control interfaces and strategies that are available in MG structure, which they may not be applied in ADNC. However, these control interfaces and strategies are not taken into account in developing the dynamic equivalent model of ADNC in this thesis. Therefore, a MG can be categorised as a form of more “actively managed” ADNC in this thesis.

### 2.6 Summary

DG is becoming more widespread and is alterning the structure and operation of power system network right down to the medium voltage (MV) and LV network. Today, it is widely accepted that present architecture and operation of power systems will be facing considerable transition from passive distribution networks (with uni-directional electricity power flows) to active distribution networks (with bi-directional electricity power flows). The power systems will have to bear with the increased flexibility, increased uncertainty and also higher quality of supply requirements due to the transition. Distribution network becomes active when bi-directional power flows of DG units added to the network. The MGs are also considered as a form of ADNC in this thesis due to the similar concept and structure. The dynamics introduced by DG connected to both MV and LV distribution networks cannot be neglected in system
studies and requires detailed analysis of the system dynamic behaviour. Hence, dynamic
equivalent models of ADNC and MGs are becoming essential for future system studies,
both steady state and dynamic.
3.1 Introduction

Over recent decades, modern power system networks have greatly increased in size and complexity due to the growing demand for electricity. Consequently, much effort has been put into the development of efficient computational techniques for system stability studies of complex power systems. The most popular method is to reduce the complexity of the large network to the computationally feasible size of an equivalent system, which retains the dynamic characteristics of the power system with reasonable accuracy. The process of reducing a large power system network into an equivalent model for dynamic system studies is called dynamic equivalent process or dynamic equivalencing.
Generally, when developing a dynamic equivalent, the system network can be divided into an internal system and an external system. The internal system is the detailed representation of the researched system that is retained. The rest of the power system, the external system, as shown in Figure 3-1 [96], has to be reduced by the dynamic equivalencing process and is generally defined by a set of nodes/buses which are continuously interconnected and linked to the internal system via boundary nodes/buses [96]. Dynamic equivalencing is the process of reducing the order of the external system, and the resulting dynamic equivalent model represents the external system during studies of the internal system. The most important feature of a dynamic equivalent model is the ability to represent the dynamic behaviour of the original external system.

Figure 3-1: Internal and external subsystem: \{B\}, boundary nodes, \{L\}, load nodes, \{G\}, generator nodes of external subsystem. Adopted from [96]

Two main approaches to the development of dynamic equivalents are reported in the literature: conventional methods, and measurement- and simulation-based methods. The conventional methods include coherency and modal analysis methods. Coherency methods identify coherent generators, which are then represented by an equivalent generator. The modal method represents the external system by an approximate linear model.
In the measurement- and simulation-based methods, the external system’s response is either measured or simulated and curve fitting techniques are used to determine the model parameters. Detailed descriptions of the two approaches to dynamic equivalencing are presented in Sections 3.2 and 3.3

3.2 Conventional Techniques

The conventional dynamic equivalent techniques are basically the coherency methods and modal analysis methods. Both are based on the model reduction approach, which involves an elimination or aggregation of some components of the existing model.

3.2.1 Modal analysis methods

Modal methods [97] are based on the linearised state space model of the external system,

\[
G: \begin{cases} 
\dot{x} = Ax + Bu, & x(0) = x_0 \\
y = Cx + Du
\end{cases}
\]

(3-1)

where \(G\) is a state space system, \(A, B, C\) and \(D\) are the system matrices, \(u\) and \(y\) represent the vectors of the input and output variables and \(x\) is the state of the model.

Using the modal method, the reduced order system of \(G\) represents by \(G_r\), is defined as:

\[
G_r: \begin{cases} 
\dot{z} = A_r x + B_r u, & z(0) = z_0 \\
y_r = C_r x + D_r u
\end{cases}
\]

(3-2)
where $Gr$ should be of lower order than $G$. $A_r$, $B_r$, $C_r$, and $D_r$ represent the reduced system matrices, $y_r$ is the output variable for reduced system and $z$ is the state of the reduced model.

Eigenvalues of the system matrix $A$ give the modes of the dynamic system. The complex conjugate eigenvalues give oscillatory modes and the real eigenvalues give non-oscillatory modes. When a system undergoes transient behaviour due to a disturbance, the oscillation modes with high damping decay faster than the modes with lower damping. Modal methods try to extract the relatively less damped modes (represented by eigenvalues of $A$ which are closer to the origin) and remove the highly damped modes (represented by eigenvalues of $A$ which are furthest away from the origin). The relatively less damped modes are present in the system time responses over a longer period and hence determine the overall system response.

Since the modal analysis method is typically based on the linearisation of the external system, the reduced model is described as the linear state space formulation by depression of the order. Thus, it is not based on the real electrical power system parameters, so the resulting dynamic equivalents cannot be visualised as a simplified system. The reduced models cannot be integrated into most standard simulation programs, since they require data being converted from/to a simulation program during the simulation studies.

In the modal analysis method, different model reduction techniques can be applied depending on the properties of the external system that have to be retained in the reduced order model. Therefore, there is technique based on directly identifying and preserving certain modes of interest; this is modal truncation [6, 97]. Balanced realisation [97] is a technique focused on the observability and controllability properties.
of the system to be reduced. On the other hand, the optimal Hankel-norm approximation [54-56] is a model reduction technique that tries to achieve a compromise between a small worst case error and a small energy error. Singular perturbation theory is the most popular technique, lying between the previously mentioned techniques and exploiting the different time scale of power systems [97].

3.2.1.1 Modal Truncation

Modal truncation was the first model reduction technique to be applied to electric power systems [6]. It is based on the pole location of the linear system. The state variables are transformed to modal variables and the fast decay poles and/or those associated with high frequencies are neglected, thus enabling a reduced order of the system. Modal truncation actually neglects fast dynamic phenomena and it is suitable for steady state application. However, in transient behaviour, fast dynamic elimination leads to inaccuracy in the model’s performance [50, 53].

Good approximation of $G_r$ can often be obtained by means of modal truncation. Firstly, change the coordinates of $x(t)$. That is, find a suitable invertible matrix $T \in \mathbb{R}^{n \times n}$ and transform the state space model of (3-1) according to,

$$
\begin{align*}
\bar{A} &= T^{-1}AT = \begin{pmatrix} \bar{A}_{11} & \bar{A}_{12} \\ \bar{A}_{21} & \bar{A}_{22} \end{pmatrix}, \bar{A}_{11} \in \mathbb{R}^{r \times r}, \bar{B} = T^{-1}B = \begin{pmatrix} \bar{B}_1 \\ \bar{B}_2 \end{pmatrix}, \bar{B}_1 \in \mathbb{R}^{r \times m}, \\
\bar{C} &= CT = \begin{pmatrix} \bar{C}_1 & \bar{C}_2 \end{pmatrix}, \bar{C}_1 \in \mathbb{R}^{r \times r}, \bar{D} = D
\end{align*}
$$

Modal truncation is therefore define by $G_r$ in (3-2) as,

$$
\begin{align*}
A_r &= \bar{A}_{11}, \quad B_r = \bar{B}_1, \\
C_r &= \bar{C}_1, \quad D_r = D
\end{align*}
$$
3.2.1.2 Balanced Realisation

The Balanced realisation technique uses a slightly different approach, because it is based on the input/output behaviour of the system [97]. Generally, the state space system is transformed into a new representation, such that the property of each state space variable is both controllable and observable. In order to achieve a reduced order model, states that are strongly influenced by the inputs and strongly connected to the outputs are retained, whereas states that are weakly controllable and observable are truncated or removed.

The Controllability Gramian, $P$, is a measure of how much the input energy is coupled to the states. The Observability Gramian, $Q$, is a measure of how the states and the output are coupled to each other. For the given state-space model of $G$ in (3-1), the Controllability and Observability Gramians, $P$ and $Q$ are defined as [97]:

\[
P = \int_{0}^{\infty} e^{At} BB^T e^{A^T \tau} d\tau \tag{3-5}
\]

\[
Q = \int_{0}^{\infty} e^{A^T \tau} C^T C e^{At} d\tau \tag{3-6}
\]

$P$ and $Q$, respectively, can be obtained by solving the following Lyapunov equations [97]:

\[
AP + PA^T + BB^T = 0
\]

\[
A^T Q + QA + C^T C = 0 \tag{3-7}
\]

The Hankel singular values of $G$ are denoted as:

\[
\sigma_i(G(s)) = \sqrt{\lambda_i(PQ)}, \quad i = 1, 2, \ldots, n \tag{3-8}
\]
where $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_n \geq 0$. Usually the $\sigma_i$ are placed in a matrix as:

$$
\Sigma = \begin{bmatrix}
\sigma_1 & 0 & 0 \\
0 & \ddots & 0 \\
0 & 0 & \sigma_n
\end{bmatrix}
$$

(3-9)

The balanced realisation is achieved when $P$ and $Q$ become equal to each other and to the $\Sigma$ matrix as shown in (3-10).

$$
\bar{P} = \bar{Q} = \Sigma
$$

(3-10)

Then the balanced system of $G$ is partitioned as:

$$
A = \begin{bmatrix}
\tilde{A}_{11} & \tilde{A}_{12} \\
\tilde{A}_{21} & \tilde{A}_{22}
\end{bmatrix}, B = \begin{bmatrix}
\tilde{B}_1 \\
\tilde{B}_2
\end{bmatrix}, C = \begin{bmatrix}
\tilde{C}_1 & \tilde{C}_2
\end{bmatrix}, D = \tilde{D} \text{ and } \Sigma = \begin{bmatrix}
\Sigma_1 & 0 \\
0 & \Sigma_2
\end{bmatrix}
$$

(3-11)

where $\Sigma_1 = \text{diag}(\sigma_1, \sigma_2, \ldots, \sigma_k)$ and $\Sigma_2 = \text{diag}(\sigma_{k+1}, \sigma_{k+2}, \ldots, \sigma_n)$.

The reduced model of $G_r$ is defined as:

$$
A_r = \tilde{A}_{11}, \quad B_r = \tilde{B}_i, \\
C_r = \tilde{C}_i, \quad D_r = \tilde{D}
$$

(3-12)

### 3.2.1.3 Optimal Hankel-norm

The Hankel-norm [54-56, 97] is a measure of how much energy can be transferred from past inputs into future outputs through the system $G$. If the transfer function of the system described by (3-1) is denoted by $H(s)$, the reduced order method based on the Hankel norm attempts to find a transfer function of $k$–th order truncated system, $H_k(s)$, which minimises the error of the approximation as,

$$
\|H(s) - H_k(s)\|_\infty = \sigma_{k+1}
$$

(3-13)
Based on (3-13), the largest error between the transfer function of the original and reduced system for all frequencies will be less than or equal to \( k+1 \) of Hankel singular value.

Both optimal Hankel-norm and balanced realisation have the drawback that they are not suitable to steady state application [50, 53]. Generally, both methods are inapplicable to systems with very high dimensions, since singular values of the unreduced system have to be computed and such a computation might pose a computational burden [54-56].

### 3.2.1.4 Singular Perturbation Theory

In the singular perturbation theory method, the external system is divided into fast and slow dynamics systems. The fast dynamics system can be ignored and its effect will be reintroduced as a boundary layer correction obtained using a separate time scale. Thus, the method seems to be a more appropriate reduction technique than those described previously. The advantages of this technique are that it retains the physical meaning of variables and can predict both steady state and transient behaviour of the system because the effects of fast dynamics are reintroduced in the reduced model [50, 53].

The state space model of \( G_r \) in (3-2) using singular perturbation method is defined as,

\[
A_r = \overline{A}_1 - \overline{A}_2 \overline{A}_2^{-1} \overline{A}_{21}, \quad B_r = \overline{B}_1 - \overline{A}_2 \overline{A}_2^{-1} \overline{B}_2
\]
\[
C_r = \overline{C}_1 - \overline{C}_2 \overline{A}_2^{-1} \overline{A}_{21}, \quad D_r = \overline{D} - \overline{C}_2 \overline{A}_2^{-1} \overline{B}_2
\]

(3-14)

following from (3-3).
3.2.2 Coherency-based Methods

Coherency-based methods involve a dynamic equivalencing process in which the coherent generators (synchronous generators only) in the external area are aggregated and replaced by equivalent models. This approach is based on observation of the generators’ response in post-fault transient disturbance. In the event of disturbance, only those generators closer to the fault behave as individual units, whereas the group of generators further from the fault tend to oscillate together, i.e., the angular difference of generators in each group remains constant within a certain tolerance [98].

In coherency methods [96], coherent grouping of generators is obtained by analysing the system response to perturbation. An equivalent of the external system is then obtained by replacing each such coherent group by an equivalent generator. This method retains the physical models of generators in an equivalent form. The equivalent generator models are non-linear. As a result, the coherent generators in the external area are equivalanced. Network reduction is then applied at the boundary nodes between the internal and external area to suitably interconnect the equivalent generators. Therefore, coherency-based methods involve the following steps:

1. identification of the coherent generator groups

2. aggregation of generator and associated control devices

3. network reduction.

3.2.2.1 Identification of Coherent Groups

In order to determine the coherency, a swing equation is used to compute rotor speed. The generator swing equation [17] is given by:

$$\frac{d}{dt} \delta_i = \omega_i$$  

(3-15)
where $\delta_i$ : rotor angle

$\omega_i$ : speed

$P_{mi}$ : mechanical input power

$P_{ei}$ : electrical output power

$M_i$ : inertial constant

$D'_i$ : damping constant

By linearising the above equation at an initial operating point, the following linearised system model can be obtained:

$$M_i \frac{d^2}{dt^2} \Delta \delta_i = \Delta P_{mi} - \Delta P_{ei} - D' \Delta \omega_i$$  \hspace{1cm} (3-17)

where $\Delta \delta_i$ : change in rotor angle

$\Delta \omega_i$ : change in speed

$\Delta P_{mi}$ : change in mechanical input power.

For a given disturbance, coherent generators are determined if every generator within the group have the same angular speed and a constant complex ratio of the terminal bus voltage \[99\]. The following measure is proposed for identification of coherent groups \[96\], in which two terminal generator buses $i$ and $j$ are defined to be coherent if

$$\frac{V_i(t)}{V_j(t)} = \frac{V_i(t)}{V_j(t)} e^{i[\delta_i(t) - \delta_j(t)]} = \frac{V_i(t)}{V_j(t)} e^{i[\delta_i - \delta_j]} = \mathcal{G}$$  \hspace{1cm} (3-18)

If the voltage magnitude can be assumed to be constant, the coherency condition (3-18) simplifies to $\delta_i(t) - \delta_j(t) = \delta' \Delta$ where $\delta' = \delta_i - \delta_j$ are the initial values.
For the classical model of generators, the generator *emf* behind its own transient reactance is assumed to be constant. For these generator nodes, the coherency condition (3.18) [96] simplifies to $\delta'_i(t) - \delta'_j(t) = \tilde{\delta}'_y$ where $\tilde{\delta}'_y = \delta'_i - \delta'_j$ are the initial values. This condition is known as electromechanical coherency [96].

Thus, two generators are electromechanically coherent if the response curves of their rotor angles are similar in wave shape and the differences between their rotor angles is almost constant.

### 3.2.2.2 Aggregation of Generator and Associated Control Devices

The process of developing an equivalent model of the external system is illustrated in Figure 3-2. The original model of the external subsystem contains a large number of load nodes and a large number of generator nodes $\{G\} = \{G_1\} + \{G_2\} + \ldots + \{G_g\}$. The generator nodes are divided into groups of coherent generator nodes $\{G_1\}$, $\{G_2\}$, $\ldots$, $\{G_g\}$ and each of the groups is replaced by an equivalent generating unit.

![Figure 3-2: Generator aggregation. Adopted from [96].](image)

After identification of the coherent generator groups, the generators in the same group can be aggregated as an equivalent generator. Generally, the generator aggregation can be divided into classical aggregation and detailed aggregation. In
classical aggregation, the coherent groups are represented by an equivalent classic
generator model. The equivalent generator model includes the sum of the inertia and the
equivalent transient reactance. On the other hand, the detailed aggregation involves a
detailed generator model with an equivalent excitation, stabiliser and governor. Further
details of the aggregation of generator controls can be found in [100, 101].

In classical generator aggregation, the criterion of aggregation is that the
mechanical and electromagnetic power of the equivalent generator is equal to the sum
of corresponding values, i.e., torques and powers, of each generator in the group, as
shown in Figure 3-3.

\[
\begin{align*}
\sum_{i=1}^{n} M_i \frac{d\omega}{dt} &= \sum_{i=1}^{n} P_m - \sum_{i=1}^{n} P_e - \left( \sum_{i=1}^{n} D_i \right) \omega \\
M_a &= \sum_{i=1}^{n} M_i \\
D_a &= \sum_{i=1}^{n} D_i
\end{align*}
\] 3-19

The motion equation of the equivalent generator rotor is represented as [17]:

The inertia of the equivalent generator, \( M_a \), is obtained as:

\[ M_a = \sum_{i=1}^{n} M_i \] 3-20

and the damping coefficient of the equivalent generator, \( D_a \), is:

\[ D_a = \sum_{i=1}^{n} D_i \] 3-21
The mechanical power input and electrical power output is defined as

\[ P_{ma} = \sum_{i=1}^{n} P_{mi} ; \quad P_e = \sum_{i=1}^{n} P_{ei} \]  (3-22)

Thus, the equation (3-23) becomes:

\[ M_a \frac{d\omega}{dt} = P_a - P_e - D_a \omega \]  (3-23)

In (3-19), the electrical power is represented as:

\[ P_{ei} = \frac{E_i'U_i}{X_{\Sigma i}} \sin \delta_i \]  (3-24)

where \( E_i' \): transient electromotive force

\( U_i \): generator terminal voltage

\( \delta_i \): the power angle.

\( X_{\Sigma i} \) is the sum of individual generators’ reactance, \( X_{d}' \), i.e., the transient reactance of the equivalent generator is:

\[ X_{\Sigma i} = \frac{1}{\sum_{i=1}^{n} \frac{1}{X_{d}'} } \]  (3-25)

3.2.2.3 Network Reduction

After aggregation of coherent generators, the remaining nodes and transmission lines also need to be reduced. As illustrated in Figure 3-4 [96], when nodes are eliminated from the network model, set \{A\}, they must be removed in such a way that the currents and nodal voltages at the retained nodes, set \{R\}, are unchanged.

The network is described by the following nodal equation [96]:

\[
\begin{bmatrix}
I_R \\
I_A
\end{bmatrix} =
\begin{bmatrix}
Y_{RR} & Y_{RA} \\
Y_{AR} & Y_{AA}
\end{bmatrix} \begin{bmatrix}
V_R \\
V_A
\end{bmatrix}
\]  (3-26)

where, \( I_R \): the injection current vector of the remaining node
\( \dot{I}_A \): the injection current vector of the eliminated node

\( \dot{V}_R \): the voltage vector of the remaining node

\( \dot{V}_A \): the voltage vector of the eliminated node

\( Y_{RR} \): the self-admittance of the remaining system

\( Y_{AA} \): the self-admittance of the eliminated system

\( Y_{RA} \): the mutual-admittance of the remaining system

\( Y_{AR} \): the mutual-admittance of the eliminated system.

Figure 3-4: Elimination of nodes: (a) network before elimination; (b) network after elimination.

\{A\}, set of eliminated nodes, \{R\}, set of retained nodes. Adopted from [96]

The eliminated voltages and currents can be swapped using simple matrix algebra to give

\[
\begin{bmatrix}
I_R \\
I_A
\end{bmatrix} =
\begin{bmatrix}
Y_{RR} & Y_{Ra} \\
Y_{AR} & Y_{AA}
\end{bmatrix}
\begin{bmatrix}
V_R \\
V_A
\end{bmatrix}
\]

(3-27)

where

\[ Y_{Ro} V_R + Y_{RA} V_A = Y_{Ro} V_R + Y_{Ro} V_A \cdot \]

The square matrix in equation (3-27) is the partial inversion of the admittance matrix.

The nodal currents in the set \{R\} are,

\[ I_R = Y_R V_R + \Delta L_R \]

(3-28)
where $\Delta I_R = Y_{Rd} I_E$ is the vector consisting of the equivalent currents replacing the eliminated nodes.

Equation (3-28) describes the relationship between the currents and voltages of the retained nodes in the reduced network. If the electrical network is represented by its admittance matrix, the matrix $Y_R$ corresponds to a reduced equivalent network that consists of the retained nodes and equivalent branches linking them. These networks are often referred to as the transfer networks and the matrices describing them as the transfer admittance matrices. Matrix $Y_{Rd}$ passes the nodal currents from the eliminated nodes to the retained nodes and is referred to as the distribution matrix. Each equivalent current is a combination of the eliminated currents.

### 3.3 Measurement- and Simulation-Based Techniques

Measurement- and simulation-based techniques use either real-time measurements or simulated responses of the power system. Typically, curve-fitting techniques are used to determine the model parameters.

#### 3.3.1 Artificial Neural Network (ANN)-Based Method

A neural network dynamic equivalent is a model with a large number of parameters, which can be adjusted by a suitable training process to develop the dynamic of a complex system. A neural network can be trained to produce the dynamics of a given system. Knowing present and past input values and the past output values, the present value of the outputs is a nonlinear function of former signals.
Chapter 3  Techniques for Development of Dynamic Equivalent Model

The time domain simulation of a dynamic nonlinear system can be obtained by solving the following set of nonlinear differential and algebraic equations [28]:

$$\dot{x} = f(x(t), u(t))$$
$$y(t) = g(x(t), u(t))$$ (3-29)

where \( x \) is the state vector and \( u \) is the vector of inputs.

The system representation in (3-29) given in the continuous time domain can be discretised, resulting in the following representation:

$$x(k+1) = x(k) + hf(x(k), u(k+1))$$
$$y(k+1) = g(x(k), u(k+1)) \quad \text{for } k = 0, 1, \ldots, N_k$$ (3-30)

where \( h \) is the length of the adopted time step, \( k \) represents the step and \( N_k \) is the total number of steps.

From (3-30) it follows that:

$$y(k+1) = g\left(x(k) + hf\left(x(k), u(k+1)\right), u(k+1)\right)$$
$$= g\left(x(k), u(k+1)\right)$$
$$= g\left(x(k-1) + hf\left(x(k-1), u(k)\right), u(k+1)\right)$$
$$= \phi\left(x(k-n), u(k+1-n), \ldots, u(k), u(k+1)\right)$$ (3-31)

The output at the time step \( k + 1 \) can be determined by input and output values. A neural network can be trained to estimate the function \( g \) and to identify the nonlinear system by setting the training set with inputs \( y(k), u(k+1) \) and outputs \( y(k+1) \) for \( k=0,1,\ldots, N_k-1 \).

### 3.3.2 System Identification Method

The system identification method refers to the determination of the essential characteristics of a dynamic system by observing the response of system variables to
random system inputs, either natural or intentional. The objective is to estimate a set of parameters belonging to a model that is believed to represent some part of a total system, based on input and output measurements. Therefore, the method does not need identification of detailed information about the subsystem. Thus, the essence of system identification consists of matching signals from a real system that is undergoing random perturbations with the same signals calculated on a model of the system, and optimising the model to reduce the difference.

System identification is a parameter estimation method, as shown in Figure 3-5 [102]. The quality of the model is examined by comparing between the system output, \( y \), and the model output, \( y_M \), after both, the system and the model, are subjected by the same input signal, \( u \). The measurable system output, \( y \), usually consists of the unmeasurable output signal, \( y_S \), and the noise, \( r_S \). The optimal model for the unknown system is achieved when the output signal error, \( e = y - y_M \), is small enough. However, if this is not obtained, then the variable model parameters represented by the estimated parameter vector, \( \theta \), must be tuned by a parameter adjustment algorithm. This tuning continues until the error, \( e \), becomes minimal, i.e., less than a predefined threshold.

After conditioning the measured input and output signals, the identification procedure can be performed by the following steps:

1. model structure selection
2. estimation of the model parameters
3. model validation.

There are many ways to describe the system in form of mathematical model that are depend on the system nature. Generally, the model should have similar dynamic and static behaviour of the investigated system. The most common model structure for linear and nonlinear systems is the state space model.
Figure 3-5: Principle of system identification procedure. Adopted from [102]

State space models can be uniquely transformed to input/output models but not vice versa [102]. A linear system can always be represented in state space form, as in (3-32).

\[
\begin{align*}
x(t+1) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) + Du(t) + v(t)
\end{align*}
\]  

(3-32)

where \( u \) and \( y \) represent the vectors of the input and output variables, \( x \) describes the state of the model and \( v(t) \) is the noise in the output. By transforming the matrices \( A, B, C \) and \( D \), different canonical or non-canonical forms of the model structure can be obtained [102, 103].

For the parameter vector \( \theta \) of the system described by the model equation (3-32), the square error function given by (3-33) is used as the performance index in the estimation process.

\[
V_N(\theta, Z^n) = \frac{1}{N} \sum_{i=1}^{N} \frac{1}{2} \varepsilon^2(t, \theta) 
\]  

(3-33)
This function is to be minimised to obtain required values of $\theta$. The solution to optimisation in (3-33) can be obtained by various optimisation procedures such as the least-square method and maximum likelihood method [102, 103].

After the identification of the model parameters, the validation process is performed to evaluate the model performance and design purposes. The simplest method for evaluating the quality of a model is to compare the measured system output with the model output using the actual input signal for the model [102, 103]. Based on the visualised difference of the simulated model output and the measured system output, the user can evaluate the obtained model performance.

For a model structure that is parameterised in terms of physical parameters, a natural and important validation is to confront the estimated values and their estimated variances with what is reasonable from prior knowledge. It is also good practice to evaluate the sensitivity of the input-output behaviour with respect to these parameters to check their practical identifiability [103].

### 3.4 Dynamic Equivalent Models of Large Power Systems

The development of dynamic equivalent models has a long history and most of the research works have been done in 1970s and 1980s. Early work on dynamic equivalents for large power systems was based on the ideas proposed by Ward [2]. These included empirical methods, such as replacement of all the generators within the external subsystem by one equivalent generator [3], or determination of equivalent generators, one for each boundary bus, from an empirical distribution of active powers and inertias of the external subsystem generators [4].
The development of the modal equivalent approach was first reported in the late 1960’s [5, 6] and later in the 1980’s [7-9]. This approach recognised that some modes of oscillation will not be excited by disturbances in particular areas of the system and therefore can be eliminated. This method was never used extensively due to difficulty in determining the modes to be eliminated, and to the need to modify stability simulation programs to use a state matrix form of the equations of the equivalent [10, 11].

An alternative approach developed in the 1970’s was based on the coherency concept [12-16]. Coherency means that certain groups of generators will tend to swing together for remote disturbances and can, therefore, be represented by a single equivalent machine. Chang et al. [14] originally proposed the coherency concept, which was later developed further by Podmore [15] and incorporated in the Dynamic Equivalencing software package, DYNEQ, developed under the American Electric Power Research Institute (EPRI) [10, 17].

An improved method for the coherency-based approach was proposed in [104] in the early 1980s, and known as the slow coherency or two-time scale method. It was further improved in [105] and has been widely applied for coherency-based identification [98]. Slow coherency is motivated by the observation that when a large power system is subjected to disturbance, a slow oscillation appears which is caused by two groups of strongly coherent generators. These groups of generators form slow coherent areas which are connected through weak ties. In Padmore’s algorithm [15], the generator terminal nodes within a coherent area are of infinite admittance. This process stiffens the resulting reduced network [105]. The slow coherency method modified the impedance to more accurately represent the coherent generators connected with finite admittance [105].
A special class of coherency methods is combined with structure preserving techniques [101, 106, 107]. The procedure starts with the identification of a coherent group using the slow coherency approach, followed by the nodal aggregation of generator terminal buses along with the elimination of load buses, and finally the aggregation of generating units. The structure preservation technique is applied on the coefficient matrices of the generators and associated controls in the time domain.

Various coherency measures to identify groups of coherent generators have been proposed based on linearised models. They include swing curve of linearised system [15], pattern recognition [108], Root Mean Square (RMS) coherency measures [20, 109] and coherency measure based on the electromechanical distance measure [110, 111]. Several other methods are also reported in the literature which are based on the rate of change of kinetic energy of the faulted system [112] and using the Lyapunov function [113]. The Lyapunov function method was improved in [114], where coherency of generators is determined through some proposed coherency identification criteria based on critical energy function during the post-fault period. Other works [115] proposed the computation of the singular point and admittance distance to recognize coherent generators. This method was significantly improved in [116] through a combination of faulted system dynamics, unstable equilibrium points and electrical coupling measure between generators. The faulted generator angles are estimated through a Taylor series expansion [117]. In recent years, several works proposed other coherency measures based on artificial neural networks [17, 118, 119], fuzzy approach [120], spectrum analysis based on Taylor series expansion [121] and epsilon decomposition [122, 123]. Synchronic modal equivalencing (SME) technique has been proposed in [124, 125] based on the selective modal analysis [126] and synchrony concept in order to identify the coherent groups of generators.
Several works implemented the clustering algorithm into the coherency identification procedure. In [127], the fuzzy C-Means clustering algorithm is used to identify the coherent groups for Taiwan power systems. The rotor angle of generator was applied as the coherency measures. Taking into benefits of Phasor Measurement Unit (PMU) measurements, the hierarchical clustering algorithm technique has been used in [128] to classify the generators into coherent groups. The generator’s rotor measurements from PMU was utilised as the coherency measures. The proposed clustering method could be integrated into wide-area measurement system for fast identification of coherent generators.

An application of coherency-based dynamic reduction for a large power system using the DYNRED program was developed by EPRI in 1993 [10, 17, 100]. The program included the techniques from the DYNEQ program and the slow coherency method [105]. DYNRED has had many successful applications in large power system studies. The program has been applied to perform dynamic reduction on three large North American power networks, to compare the stability performances of the reduced order models to those of the base model, by considering different operating conditions, power flow limits on critical interfaces, and sensitivity to fault location [10]. The DYNRED program was used in [100] to perform the aggregation of an excitation system using a trajectory sensitivity method to tune the equivalent parameters. However, the algorithm for parameter aggregation purposes has not been extensively tested [101, 106].

Recently, a software tool integrated with the Research Center for Electric Energy’s (CEPEL) software package for determination of dynamic equivalents has been proposed in [129]. This software tool was developed to automate three steps of the dynamic equivalents process: identification of power plants that present coherence;
static reduction of the network; and dynamic aggregation of the coherent generating unit models. The tools were applied to partially obtain a dynamic equivalent to the Brazilian National Interconnected System (SIN), and successfully reduced the size and complexity of the system with less time and computational effort.

A simulation program Network Torsion Machine Control (NETOMAC) [130] offers a wide range of applications for power systems studies. The program incorporates an optimisation/identification tool [131] for solving several optimisation tasks and parameter identification problems. Three optimisation algorithms, Quasi-Newton, Modified Powell and Least Square, are available in the program, offering robust identification and optimisation of any linear and nonlinear problem in either the time or frequency domain [130].

Modal methods have also been used to supplement the coherency methods where coherent groups are identified using modal methods [18-22]. The modal-coherency technique used the rigorous mathematical basis of the modal method to overcome the disadvantages of the coherency method. In contrast to the coherency equivalent, the modal equivalent does not depend on the perturbation chosen to determine the equivalent. In [22], the modal-coherency method using frequency response is applied to identify coherent generators.

More recently, ANN-based models were proposed [23-27] to directly derive dynamic equivalents from measurements at points connecting both the study system and external subsystems. In these works, a neural network is used to extract states of the reduced order equivalent and another neural network is used to predict the new state values of the external system. Similar techniques successfully applied to derive dynamic equivalents for large systems are also presented in [28]. In these studies, the external
system is represented through an input-output formulation and only one neural network is used to predict its dynamic behaviour.

Another approach in determining the dynamic equivalent is the identification approach using measurement and simulation-based techniques. The Maximum Likelihood technique is applied for online measurements in [29, 30] to identify parameter values for a specified equivalent structure, which is suitable for use in standard transient stability programs. In [31], parameter identification is carried out using a least-square algorithm with an adaptive step-size scheme. Firstly, an equivalent model is estimated and re-evaluated against the original system until the cost function has reached the minimum and all equivalent parameters have been identified. A similar principle is suggested in [25, 32-34]. The main interest is to search for the best parameter vector which minimises an error index that is taken to be a square function of the difference between measured output and the simulated/calculated output.

The Extended Two Particle Swarm optimisation algorithm is applied in identification of the equivalent parameters for large power systems [35]. This method applied the measurements obtained from Phasor Measurement Units (PMU). More recently, the identification-based equivalent from online measurements, using the interpretation of coherency from the graph model of a power system, has been proposed in [36]. The knowledge of coherent generators from a graph model gives the number of equivalent generators and attaching locations. At first, the graph model of the power system is established. Later, the coherent groups of generators are identified from the weak link of the graph model. Then, the aggregation of coherent generator buses is performed. Finally, the parameters of equivalent generators are identified using the identification procedure built into the Power System Analysis Toolbox (PSAT) and MATLAB software.
3.5 Dynamic Equivalent Models of Distribution Networks with DG

A number of works reported on the development of dynamic equivalents of distribution network that contains wind farms [50-53]. In [50], several model reduction techniques have been compared and the singular perturbation theory has been suggested for dynamic equivalent of wind farms. The time variables of the detailed wind farm model are separated into slow variables and fast variables, then the reduced model is obtained by first ignoring the fast dynamic terms. The effects of fast dynamics are then reintroduced as boundary layer corrections calculated in a separated time scale. The reduced order model gives a good performance under small perturbation around the steady state operating point caused by wind speed variations.

The integral manifold technique has been used as an extension of [50] to obtain the reduced order of wind farms [53]. The technique was introduced to gain all the advantages from using singular perturbation theory, in addition to higher model accuracy. The reduced model is compared with the reduced model obtained by singular perturbation theory and proven to have a high degree of accuracy and faster computational time.

In [52], an aggregated wind farm model of the MV network is presented. The reduced network consists of an equivalent wind farm and an approximate equivalent MV feeder. The equivalent wind farm is represented by an aggregated asynchronous machine with summation of aggregated nominal and active power for each wind generator. The equivalent network represents the wind farm under small disturbances. However, the equivalent model has shown less accuracy under crucial contingency cases like sequential disturbances and longer critical clearing times.
System identification has been used to model wind turbines in state space form as reported in [51]. The equivalent wind turbine is derived with the measurements of $dq$-axis voltages and the wind speed as the input, and the measurements of $dq$-axis current as the output. The advantage of this technique is that the state space equivalent model of a wind farm can be easily obtained from the derived equivalent wind turbines since it is in a state space form.

There are a very few papers, however, reporting the development of the dynamic equivalent of ADNC [54-67]. There were mainly written by six groups of authors. A dynamic equivalent of ADNC using Hankel-norm approximation is reported in [54-56]. The model was based on calculating the specific operating point data using the load flow calculation. A linearised model is produced by combining the state space model of the generator and the model of the network into one linear model. The model reduction is then performed using Hankel-norm approximation based on the specified error boundary. The proposed model is tested on a distribution network containing WTGs (squirrel cage induction generator and doubly-fed induction generator), microturbine, combined heat and power (CHP) plants and a diesel generator. The loads in ADNC are represented as constant impedances. However, the dynamic equivalents produced are valid only for a given operating condition, so the procedures for obtaining dynamic equivalents need to be repeated for different conditions.

The system identification approach proposed in [57, 58] has been used to develop a dynamic equivalent of ADNC. The ADNC was modelled as a black box, due to a lack of detailed information on the network structure and parameters. The black-box approach means that the dynamic equivalent of the distribution network is calculated from observed input and output data. The voltage and frequency are used as the input, and active and reactive power demands as the output. The parameter identification is
then performed by importing the input and output data into the MATLAB System Identification toolbox. The model is developed in the form of a state space and auto-regressive model with exogenous input (ARX). Its main advantage is its simplicity of implementation, as it does not require detailed network information. This model, however, is highly dependent on the type and location of the disturbance.

The extension of the model presented in [57, 58] is presented in [59], still adopting the same approach. The developed model used the state space model in the MATLAB System Identification toolbox to represent the dynamic equivalent of ADNC and the singular value diagram is used to identify the model’s order. The singular value diagram of signals obtained from system under the disturbance, which does not excite the modes of transmission network much, can reflect the order of the distribution network easier. Simulations done in [59] have suggested that this order, or an order slightly higher, is enough for a subspace state-space model to represent the distribution network.

From the findings in [59], there are several factors that may affect the quality of the model during the dynamic equivalent procedure using the MATLAB System Identification Toolbox. The identified factors are:

1. double input and single input model – single input model using the bus voltage input was proven to perform better than double input model. (Note: double input model has been used in this thesis as the initial simulations, following recommendations from [58] with single input model showed to underperform compared to double input model).

2. Subspace state-space identification (N4SID) and Prediction Error Methods (PEM) model – the 4th order of N4SID model is suggested to be used as dynamic equivalent model of distribution network.
3. Disturbance used to derive dynamic equivalent – a line fault close to the distribution network was proven to be an appropriate disturbance for deriving the dynamic equivalent of distribution network.

4. Distribution network size influence – a small distribution network can be represented as a constant power load, whereas the dynamic equivalent model is more suitable to represent larger distribution networks.

5. Type of embedded generation – for distribution network with DFIG wind generation, dynamic equivalent model proposed in [59] has no significant advantage over the constant power model. However, when the distribution network comprises conventional synchronous generator, the dynamic equivalents perform better than the constant power model. Therefore, the model proposed in [59] is not suitable for ADNC network which contains different types of distributed generators.

System identification theory has also been exploited in developing the dynamic equivalent models for microgrids (MG) [64, 66, 67]. The MG equivalent model is basically derived into two parts, taking into account the dynamics going on the several active devices, i.e. fast dynamic response and slow dynamic response. The MG fast dynamic response is represented by the detailed model of the Voltage Source Inverter (VSI), interfacing a constant voltage source that represents the main storage device. On the other hand, the MG slow dynamic response is represented by reduced order models that can be derived from two different approaches: Black box and grey box modelling.

A black box modelling approach based on ANN was used in [64]. The MG dynamic equivalent is based on a Time Delay Neural Network (TDNN) model structure combining a Nonlinear Finite Impulse Response (NFIR) input structure with a Multilayer Perceptron (MLP) neural network as the nonlinear mapping. The TDNN
A generic nonlinear dynamic equivalent model based on recurrent Artificial Neural Networks (ANN) is presented in [60-62]. The ANN, used to represent all active elements in the distribution network, has to be trained by a time series. The complex voltages, power transfer and injected currents during the fault simulation are used to prepare suitable patterns for ANN training. The development of dynamic equivalent does not require the specification of a particular model configuration in advance. The target model is defined through both the structure and parameter description of the ANN. Regarding the lack of detailed information and the difficulty of modelling a large number of different active sources, using ANN can be considered as an advantage. In addition, the accuracy of the developed model is not significantly affected by changing
the operating point. Thus, it is not restricted to certain initial power flow conditions. Nevertheless, this work only considered fuel cells and microturbines as DG in the network.

In [63], a state space model that incorporates composite loads in stand-alone MG was introduced. The model was developed by separately treating the plants in the form of RL grid elements from reference frames and the control system. The MG is divided into three components: plants, controllers and reference frames (RF). The plants comprise output filter, grid lines, static loads and induction motors. The static loads are represented by the constant impedance type. The induction motor equations are rearranged to be integrated within the model. A vector valued function is then produced that describes all plants in a similar form using a generic vector valued function to model the RL (resistance inductance) branch dynamics in rotating RFs. The dynamics of RFs must be considered by introducing state variables corresponding to the RF displacement during transient behaviour. The number of RFs is equal to the number of generating units connected to the grid. The bifurcation theory is used to show that composite loads are needed for MG modelling if more realistic results with oscillations and load margin are pursued.

A small signal dynamic model of MG that incorporates a synchronous machine and power electronic interfaced DG unit is proposed in [65]. The model represents the electro-mechanical dynamics of a synchronous generator (exciter and governor), and the dynamics of a voltage-sourced converter (VSC), together with a power controller and the network dynamics. The synchronous machine equipped with excitation and governor control system may represent either a diesel generator or a gas-turbine generator unit. The VSC represents a dispatchable source, e.g. micro-turbine generator unit, fuel-cell generation unit or wind generation unit including battery storage. The
lines and the constant loads are represented by series-connected RL branches in each phase. The operational modes and control strategies are also studied. The model is constructed from ordinary differential equations (ODEs) for each element in their respective local $dq_0$ reference frames. Then the equations are transformed to a MG global $dq_0$ frame, linearised about an operating point and arranged in the state space form of a linearised mathematical model. The linearised model is validated with a detailed model developed in the PSCAD/EMTDC software package. The model can be applied to investigate small-signal dynamics behaviour of MG and design/optimise controllers of the electronically interfaced DG unit during grid-connected and islanded modes of operation.

Generally, most of the past studies consider only static loads as the load models in the dynamic equivalent model of ADNC [54-56, 61, 62, 65]. Only a few papers take into account dynamic loads in their modelling [63]. A high proportion of induction motors is usually the most significant aspect of dynamic characteristics of system load, as motors consume 60 to 70% of the total energy supplied by a power system [68]. Furthermore, it was suggested by [49] that for transient stability analysis in weak interconnected power systems and high frequency and voltage deviations (like ADNC), the load model needs to be represented by a static part and a dynamic part accounting for dynamics of induction motors. Thus it can be concluded that dynamic load models should be considered in ADNC modelling, together with static load models. In [48] it was concluded that the third-order model of IM is sufficient to represent the dynamic characteristics of power systems.

Since ADNC is no longer a passive network, the DGs have to be treated as active sources because of their high penetration level. Detailed network models are not appropriate, because of the huge dimensions of the system and computational time
constraints. A good balance between detail and simplification must therefore be found. Furthermore, DGs connected to the distribution network through power electronic interfaces are not characterised by angle and angular speeds [67]. Thus conventional dynamic equivalent techniques, i.e., the modal analysis method and coherency-based identification, are not suitable for deriving ADNC equivalents. Moreover, linearisation and model reduction of a distribution network with DG are only appropriate and reliable under certain conditions [54-56]. The linearisation process involved in model reduction methods limits the obtained simulation results from being generalised for large disturbance studies [54-56, 63]. Hence, suitable dynamic equivalent techniques need to be applied in order to obtain the desired ADNC model. System identification techniques seem capable of handling the model derivation problems, as they involve building mathematical models based on observed data from the system to be modelled [57-59, 64, 66, 67].

3.6 Summary

This chapter presented an overview of the development of dynamic equivalent models of power systems. The conventional approaches, i.e., modal analysis and coherency-based methods, applied to develop dynamic equivalent for large power systems were explained along with the main theoretical concepts and practical issues. The measurement- and simulation-based approach was also presented in this chapter.

As a general conclusion, in order to build the equivalent model of ADNC the static load model and dynamic load model should be included. Moreover, the conventional dynamic equivalent techniques are not practical for ADNC applications.
Adoption of the system identification-based technique in developing the ADNC equivalent model seems to be applicable and promising.

Accurate modelling of power systems with DG is becoming essential for both steady state and dynamic stability studies. However, any realistic dynamic DG model that gives reasonable approximation of the DG dynamics and its impacts on the higher voltage networks will contribute to significant simplification of large power system dynamic studies. Therefore, most DG technologies are modelled in generic and simplified manner to represent their dynamic behaviour and characteristics in power system analysis. The next chapter presents the modelling of major types of DG and system loads. The development of dynamic equivalent model for ADNC based on system identification theory is described as well.
Chapter 4  Dynamic Equivalent Model of ADNC

4 Dynamic Equivalent Model of ADNC

4.1 Introduction

The global increase in the penetration level of renewable energy resources and the changed nature (greater use of power electronic components) of connected system loads are resulting in progressive change in the dynamic behaviour of power systems, both transmission and distribution. In particular, the impact of such change requires ADNC equivalent dynamic models, so that power system operators can estimate the ADNC’s impact on the overall power system’s dynamic behaviour, without modelling individual elements of ADNC, i.e., elements connected at lower voltage levels. The equivalent model should be able to describe ADNC dynamics as seen by the external system through ADNC interconnection. The main goal of the dynamic equivalent is therefore to eliminate part of distribution network and to replace it by a simple equivalent model which has similar dynamic characteristics. Detailed modelling of the
whole ADNC is not practical due to the size of the system and the computational time constraints associated with dynamic simulations of large power networks.

### 4.2 System Identification Theory

System identification deals with the problem of building mathematical models based on observed behaviour (measured input and output responses) of the dynamic system to be modelled (refer to Figure 4-1). The task of dynamic equivalent model development is, in fact, a system identification procedure. As discussed in chapter 3, the recorded data are used to fit the model parameters to the selected model structure.

A basic system identification loop is shown in Figure 4-2. The start of all system identification is the observed or measured data. Then, a data set is recorded during a specifically designed identification experiment. With a given observed data set, the system identification procedure’s main tasks are to select an appropriate model and to identify the model’s parameters in the sense of an identification criterion. However, an important question is whether the model is good enough for its intended purpose. Testing to establish whether developed model is good representation of the modelled system/process is known as model validation.

![System Identification Loop](image-url)

**Figure 4-1: System identification process**
Depending on the assumed level of prior knowledge and physical insight about the system, three types of model can be considered: the black-box model, white-box model and grey-box model.

### 4.2.1 Black-box Identification

In black-box modelling, the structure of the model is not necessarily known \textit{a priori}. The only concern is to map the input data set to the output data set in such a way that the output of the model and the output of the modelled system are the same. Black-box identification is useful when the primary interest is in fitting the data, regardless of the particular mathematical structure of the model. There are several linear and
nonlinear black-box model structures available to choose from, e.g., auto-regressive
exogenous (ARX), auto-regressive moving average exogenous (ARMAX) and output
error (OE), which have traditionally been useful for representing dynamic systems
[103]. The model structures vary in complexity depending on the flexibility needed to
accommodate the dynamics and noise in the system. Black-box identification is usually
a trial-and-error process, where the parameters of various structures are estimated and
the results compared. Typically, it starts with a simple linear model structure and
progresses to more complex structures.

4.2.2 White-box Identification

White-box modelling refers to identification of the parameters of a known
structure based on first principles, by taking into account the connection between the
components of the system [132]. This approach involves exact mathematical modelling
of all physical components of the system by writing down all known relationships
between relevant variables and using software support to organize them. In many cases
such models will be very complex and possibly even impossible to construct in a
reasonable time, because of the complex nature of many actual systems and processes.

4.2.3 Grey-box Identification

The grey-box model is typically developed using a known structure of the
system (but not the exact composition of physical components) with unknown
parameters. The parameters are then estimated in a similar way to those in the black-box
model. The grey-box model is, thus, a combination of white-box and black-box models,
allowing more flexibility in parameter estimation than the white-box model and more physical understanding of the developed model than the black-box model. Usually, grey-box model identification involves an optimization process to minimize the difference between the estimated output and the measured real output.

4.3 Load Modelling

The major source of inaccuracy in dynamic power simulations arises from the model used to represent loads, due to their stochastic nature. Most existing software for the simulation of power systems uses a simple load model, such as the constant power load model, the constant impedance load model or the static polynomial load model, to represent real load characteristics. In general, there are two load model approaches: component-based modelling and measurement-based modelling. The following section will describe in detail the available load models and also load modelling techniques.

4.3.1 Load Models

There are two main types of load model, the static load model and the dynamic load model. Traditionally, the load is modelled as a combination of the constant impedance, the constant current and the constant power; this is the static load model. With the increased complexity of power systems dynamics, it is necessary to model the load more accurately. Consequently, the dynamic load model has been developed. Currently, the composite load model, consisting of a static part and a dynamic part, is widely used in power system analysis and control [39-46]. Two methods have been suggested for deriving the load model: the component-based approach and the
measurement-based approach. The following sub-sections will discuss in detail the load models and modelling approaches.

4.3.1.1 Static Load Model

The static load model expresses the active and reactive powers at any moment of time as functions of the bus voltage magnitude and frequency at that same instant [37]. The simplest load model assumes one of the following models: constant impedance (Z), constant current (I) or constant power (P). This model is often used in load flow calculations, but is generally unsatisfactory for other types of analysis, e.g., transient stability analysis in the presence of large voltage variations.

To obtain a more general voltage characteristic, the benefits of each of these characteristics can be combined by using the so-called polynomial or ZIP model composed of the constant impedance (Z), constant current (I) and constant power (P) models.

\[
P = P_0 \left[ a_1 \left(\frac{V}{V_0}\right)^2 + a_2 \left(\frac{V}{V_0}\right) + a_3 \right]
\]

\[
Q = Q_0 \left[ a_4 \left(\frac{V}{V_0}\right)^2 + a_5 \left(\frac{V}{V_0}\right) + a_6 \right]
\]

where \(V_0\), \(P_0\) and \(Q_0\) are the values at the initial operating condition. The parameters of this polynomial model are the coefficients \((a_1 \text{ to } a_6)\). In the absence of any detailed information on the load composition, the real power is usually represented by the constant current model, while the reactive power is represented by a constant impedance [96].

Another common model for voltage dependency of load is the exponential load model. Here, power is related to voltage by
\[ P = P_0 \left( \frac{V}{V_0} \right)^{n_p} \quad \text{and} \quad Q = Q_0 \left( \frac{V}{V_0} \right)^{n_q} \]  

(4-2)

where \( n_p \) and \( n_q \) are the parameters of the model. Note that by setting the parameters to 0, 1, 2, the load can be represented by constant power, constant current or constant impedance respectively. The slope of the characteristics given by (4-2) depends on the parameters \( n_p \) and \( n_q \).

The frequency dependency of load characteristics is usually represented by multiplying either a polynomial or an exponential load model by a factor as follows:

\[ P = P_0 \left( \frac{V}{V_0} \right)^{n_p} \left( 1 + K_{pf} \Delta f \right) \]  

(4-3)

\[ Q = Q_0 \left( \frac{V}{V_0} \right)^{n_q} \left( 1 + K_{qf} \Delta f \right) \]

(4-4)

where \( \Delta f \) is the frequency deviation \((f - f_0)\) and \( K_{pf} \) and \( K_{qf} \) are the frequency sensitivity parameters.

In power system stability studies, only the voltage dependence characteristics of the load are usually considered, because the frequency of the power grid typically changes very little and mostly during large network disturbances so the frequency dependency of the load cannot be assessed properly through staged field tests [96, 133].

### 4.3.1.2 Dynamic Load Model

The dynamic load models can be divided into two categories: input-output load model and physical load model. The input-output load model is actually like a black box model, regarding the mathematical representation of the relationship between the inputs...
and outputs [133]. Its inputs are voltage and frequency, while its outputs are active and reactive powers. In general, the input-output load models are represented as transfer function models, sets of differential equations and neural network models [134-141].

The most popular dynamic load model is the induction motor model. In fact, induction motors can consume 60-70% of the total energy supply of a power grid [68], so they can be seen as the most significant component, to a large extent determining the system’s dynamic load characteristics. Therefore, it is necessary and also reasonable to represent the system load dynamic by using a properly defined induction motor (IM) model. Three models are available:

i) pure mechanical model (the first-order IM model)

ii) single-cage rotor model (the third-order IM model)

iii) double-cage rotor model (the fifth-order IM model).

The first-order IM model describes only the mechanical dynamics of the motor and neglects the flux dynamics. The third-order model considers not only the motor mechanical dynamics, but also the rotor flux dynamics. The fifth-order model additionally includes the stator flux dynamics.

The third-order model is generally recommended for large-scale simulations [142]. The transient response of the stator winding is faster than the transient response of the rotor winding, and it is much faster than the transient state of the power system [133], so it will not have much influence on the system transient characteristics if the stator transient state is intentionally neglected. In practice, the third-order induction motor model generally fulfils the accuracy requirements of the simulation.

The following equations describe the third-order model of IM:
\[ T'_o \frac{dE'}{dt} = -\frac{X}{X'} E' + \frac{X - X'}{X'} V \cos \delta \]

\[ \frac{d\delta}{dt} = \omega - \omega_s - \frac{X - X'}{X'} \frac{V \sin \delta}{T'_o E'} \]

\[ M \frac{d\omega}{dt} = \frac{VE' \sin \delta}{X'} - T_m \]  

(4-5)

where  

\( T'_o \): transient open-circuit time constant  

\( E', \delta \): voltage magnitude and angle behind transient reactance  

\( X, X' \): reactance and transient reactance  

\( V \): terminal voltage  

\( M \): motor inertia  

\( T_m \): mechanical torque constant  

\( \omega, \omega_s \): angular velocity of rotor and stator (rad/s)

### 4.3.1.3 Composite Load Model

The composite load model is widely used nowadays in operation centres and research institutes for power system stability analysis [39-46]. The structure of the composite load model comprises a dynamic load equivalent and a static load equivalent in parallel (refer to Figure 4-3). An equivalent induction motor is used to represent the dynamic load. The induction motor may be represented at different levels of complexity. The third-order model is used for power system stability analysis. At the steady state, its power depends on the slip, s. The constant impedance, constant current
and constant power (ZIP) model are combined to represent the static load characteristics.

![Equivalent circuit of the composite load model in steady state](image)

Figure 4-3: Equivalent circuit of the composite load model in steady state. Adopted from [142]

### 4.3.2 Component-based Load Modelling

Component-based load modelling represents the load by a combination of components with some physical meaning. The approach needs reliable data which are very difficult to acquire. These data are: average characteristics of individual appliances, the composition rate of component loads, and the composition rate of the load classes (refer to Figure 4-4) [37]. It is also difficult to derive the equivalent of the load in total, even when the dynamic characteristics of each individual load component are well known.

The component-based load model cannot represent accurately the steady state reactive power versus voltage response, or the transient response of active and reactive power, because of the complex nonlinear characteristics of load components [68].
4.3.3 Measurement-based Load Modelling

In recent years, the importance of load modelling based on measurement has increased significantly due to its advantages. First, the measurement-based load model can portray the real system load dynamics and represent the load characteristics more accurately [68]. Second, it can be mathematically equivalent to solving the parameter identification problem by using system identification theory. Last, the identified load parameters can easily be altered or updated, as new measurement data becomes available. For these reasons, the measurement-based approach is chosen for this research.

Figure 4-5 shows the general process of measurement-based load modelling [133]. Initially, the field data should be acquired before and after disturbances. The corresponding variation of signals (voltage, frequency, active and reactive power) are measured either in response to intentional by mode disturbances, or to naturally occurring events. Next, the load model used to represent the load characteristics should
be chosen. Finally, the identification algorithm to optimize the load model parameters is applied.

![Figure 4-5: General process of measurement-based load modelling. Adopted from [133]](image)

### 4.4 Modelling of Major Types of DG

As a result of increasing the DG penetration in power systems, the modelling of the DG for system studies is becoming of major concern. With large numbers of DGs connected to the transmission level or embedded in the distribution network, it has become impossible to model each DG in detail due to the dimensions of huge systems and computational time constraints. Therefore, most DG types are modelled using simple equivalent models according to the nature of the study and its application. The models still adequately represent dynamic behaviour, but without significantly increasing computational effort. This section will describe in detail the modelling of major types of DG, i.e. the wind turbine generator, microturbine, photovoltaic and fuel cell.
4.4.1 Wind Turbine Generator (WTG)

A wind turbine generator (WTG) consists of wind turbine, drive train and generation system, as shown in Figure 4-6 [96]. The first two components are similar for different WTGs and can be represented by a unified model. A number of generator drive arrangements can be used in the WTG generation system, but usually induction generators are used. The main parts of a WTG are the tower, the turbine and the nacelle. The transmission mechanisms (gearbox) and the generator are located in the nacelle. The turbine may have two or more blades. The kinetic energy of wind, which is captured by the blades, is converted to electric power by the generator. The gearbox transforms the slower rotational speeds of the wind turbine to higher rotational speeds on the generator side.

![Figure 4-6: Typical arrangement for a WTG: G/B (gearbox), Gen (generator), T (transformer).](image)

Output voltage and frequency are maintained within a specific range, by using supervisory metering, control and protection systems. Besides the generation system, other subsystems are required that will turn the turbine into the wind, the yaw system,
which provide braking. The transformer is placed at the bottom of the tower or in a separate building close to the turbine. It is only in offshore wind turbines that the transformer is located in the nacelle. Wind turbines may have a horizontal or a vertical axis configuration. The average commercial turbine size of WTG was 300 kW until the mid-1990s, but recently machines of larger capacity, up to 5 MW, have been developed and installed [70]

The output power of a wind turbine is defined by the wind velocity, size and shape of turbine. According to aerodynamic theory, the power extracted from the wind is given by:

$$ P = \frac{1}{2} C_p \rho V^3 A $$

(4-6)

where $P$ is power (W), $C_p$ denotes the power coefficient, $\rho$ is air density (kg/m$^3$), $V$ is wind velocity (m/s) and $A$ denotes the swept area of rotor blades (m$^2$).

Power coefficient $C_p$ gives a measure of the amount of energy extracted by the turbine rotor. Its value varies with the rotor design and the tip speed ratio (TSR). TSR is the relative speed of the rotor and the wind given by:

$$ TSR = \frac{\omega r}{V} $$

(4-7)

where $\omega$ is the turbine rotational speed and $r$ is the turbine radius. The maximum practical value of TSR is about 0.4.

The drive train of WTGs is represented by the two masses model:
\[
2H_r \frac{d\omega_r}{dt} = T_{wt} - T_{mec} - D_r \omega_r \\
2H_G \frac{d\omega_G}{dt} = T_{mec} - T_e - D_G \omega_G \\
T_{mec} = D_{mec} (\omega_r - \omega_G) + K_{mec} \int (\omega_r - \omega_G) dt
\]

where \(H_r\) is the inertia constant of the wind turbine(s), \(H_G\) the inertia constant of the generator(s), \(\omega_r\) the rotation speed of the wind turbine (m/s), \(\omega_G\) the rotation speed of the generator (m/s), \(D_r\) the damping coefficient of the wind turbine, \(D_G\) the damping coefficient of the generator, \(D_{mec}\) the damping coefficient of the mechanical coupling, \(K_{mec}\) the stiffness of the mechanical coupling, \(T_{wt}\) the mechanical torque from the wind turbine rotor shaft, \(T_e\) the generator electrical torque, and \(T_{mec}\) the mechanical torque from the generator shaft.

Depending on the control scheme used during the operation, WTGs are classified as fixed-speed wind turbines (FSWT) or variable speed wind turbines (VSWT). The former operate at almost constant speed as predetermined by the generator design and gearbox ratio. Usually a synchronous generator and squirrel-cage induction generator are used for the generation system of the FSWT [96]. The capacitor bank is usually used to condition the power output in case of induction motor.

VSWTs produce energy at slightly higher efficiencies over a wider operational range of wind speeds than FSWTs. The generator options for the VSWT are a wound rotor induction generator, a squirrel-cage induction generator with fully rated converter, a doubly fed induction generator, a permanent magnet generator with fully rated converter, or a wound field generator with fully rated converter [96]. The power electronics necessary in VSWTs to produce grid-quality electricity consume slightly more energy than the capacitors used to condition the power from FSWTs. VSWTs also
enable the turbine to supply reactive power to the grid and dynamically control the reactive power supply (power factor).

The effect of FSWTs on the grid results in the consumption of reactive power. This reactive power must be supplied from other transmission system resources. FSWTs generally have fewer moving parts and are less complex than VSWTs, resulting in lower manufacturing costs. VSWTs are able to optimize blade pitch and adjust it for changes in air density or blade contamination. For these and other reasons, the energy output from VSWTs is somewhat higher than from FSWTs, thus offsetting the higher system costs.

At the moment, WTGs are modelled using different aggregation approaches according to the nature of the study:

1. The simplest is the aggregation of an entire wind farm into an equivalent WTG. This approach is suitable for the assumed similar wind conditions at all the wind turbines [143-146].

2. Aggregating the WTGs into groups is one of the other available approaches. Wind turbines with similar wind speed can be grouped together and represented by an equivalent WTG. Grouping can be also applied if several generation technologies are present, in which case each technology can be represented by an equivalent WTG. The same aggregation approach is applied to group wind turbines on the same feeder when feeder parameters differ within a wind farm [143, 147-149].

3. For different wind speed conditions within a wind farm, separate model for the mechanical system (WTG rotor, drive train, pitch control) and the electrical system (generator, converters, converter controls) for each wind turbine can be
applied. This approach is called the semi-aggregated model [143, 145, 150, 151].

4. For certain types of study, it might be sufficient simply to emulate certain behaviour at the wind farm connection point, e.g., fault ride through capability in accordance with grid code requirements. These models can be used either to assess the share of wind power that can be safely integrated into a particular power system, or when developing grid code requirements for WF and WTGs [152, 153].

4.4.2 Microturbine

Microturbines are small and simple-cycle gas turbines with outputs ranging from around 25 to 300 kW. They are one part of a general evolution in gas turbine technology. There are two main types of microturbine generator system, based on the position of the compressor turbine and generator, i.e. single-shaft microturbine (Figure 4-7) and split-shaft microturbine (Figure 4-8) [70]. The high-speed single-shaft design has a compressor and a turbine mounted on the same shaft as the generator. The generator produces power at a very high frequency, ranging from 1500 to 4000 Hz. The high frequency voltage is first rectified then inverted to normal AC power at 50 or 60 Hz. In another design, the turbine on the first shaft directly drives the compressor, while a power turbine on the second shaft drives the gearbox and conventional electrical generator. The power turbine rotates at 3000 rpm. However, in split-shaft design, these are not required due to the presence of the gearbox.
Figure 4-7: Single-shaft microturbine. Adopted from [70].

Figure 4-8: Split-shaft microturbine. Adopted from [70].

Most microturbines use Permanent Magnet Synchronous Generator (PMSG) or an asynchronous generator for power generation. Ample research has been conducted on PMSG-coupled microtubines [70, 154-161]. In most work, the PMSG is modelled as a fifth-order model in the d-q reference frame [160]. The three equations of the electrical part assume sinusoidal flux:
\[
\frac{di_d}{dt} = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega i_q \\
\frac{di_q}{dt} = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega i_d - \frac{1}{L_q} \lambda p\omega \\
T_e = \frac{3}{2} p \left[ \lambda i_q + \left( L_d - L_q \right) i_d i_q \right]
\]

The other two equations of the model are the mechanical equations of the rotating single shaft with the damping (friction factor) neglected:

\[
\frac{d\omega_r}{dt} = \frac{1}{J} \left( T_m - T_e \right) \\
\frac{d\theta}{dt} = \omega_r
\]

where \(i_d, i_q\) : d and q-axis currents

\(J\) : combined inertia of rotor and load

\(L_d, L_q\) : d and q-axis inductances

\(p\) : number of pole pairs

\(R\) : resistance of stator windings

\(T_e\) : electromagnetic torque

\(v_d, v_q\) : d and q-axis voltages

\(\theta\) : rotor angle position

\(\lambda\) : flux induced by the permanent magnets in the stator windings
\( \omega_r \): angular velocity of the rotor

\( F \): combined viscous friction of rotor and load

### 4.4.3 Photovoltaics (PV)

A solar cell is basically a p-n junction fabricated in a thin wafer or layer of semiconductor. The electromagnetic radiation of solar energy can be directly converted into electricity through photovoltaic effect. A PV system naturally exhibits nonlinear voltage-current (I-V) and power-voltage (P-V) characteristics, which vary with the radiant intensity and cell temperature. A general mathematical description of I-V output characteristics for a PV cell has been developed over the past four decades. An equivalent circuit-based model is mainly used for the Maximum Power Point Tracking (MPPT) technologies. The equivalent circuit of a PV cell consists of a photo current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, as shown in Figure 4-9.

![Figure 4-9: The electrical equivalent circuit of a PV cell. Adopted from [162].](image)

The I-V characteristic equation of a solar cell is given as,

\[
I = I_{ph} - I_s \left[ e^{\frac{q(V+IR_s)}{kT_A}} - 1 \right] - \frac{(V + IR_s)}{R_{sh}}
\]  

(4-14)
where $I_{PH}$: light-generated current or photocurrent

$I_s$: cell saturation of dark current

$q$: electron charge (1.6 x $10^{-19}$ C)

$k$: Boltzmann’s constant (1.38 x $10^{-23}$ J/K)

$T_C$: working temperature

$A$: ideal factor

$R_{sh}$: shunt resistance

$R_s$: series resistance

The photocurrent mainly depends on the solar irradiance and cell’s working temperature, described as:

$$I_{PH} = I_{SC} + K_I (T_C - T_{ref}) \lambda$$

(4-15)

where $I_{SC}$: short circuit current at 25°C and 1 kW/m$^2$

$K_I$: short circuit current temperature coefficient

$T_{ref}$: reference temperature

$\lambda$: solar insolation (kW/m$^2$)

On the other hand, the cell’s saturation current varies with the cell temperature, described as:

$$I_s = I_{RS} \left( \frac{T_C}{T_{ref}} \right)^3 e^{\frac{qE_a}{kA} \left( \frac{1}{T_C} - \frac{1}{T_{ref}} \right)}$$

(4-16)
where $I_{RS}$: reverse saturation current at a reference temperature and a solar radiation

$E_G$: band-gap energy of the semiconductor used.

### 4.4.4 Fuel Cell

Fuel Cells (FCs) are electro-chemical devices which convert the chemical energy of a gaseous fuel directly into electricity. In FCs, a chemical reaction takes place by combining hydrogen and oxygen to form water and releasing electrons in the process [70]. The FC consists of two electrodes, known as the anode and cathode, separated by an electrolyte, as shown in Figure 4-10. Oxygen is applied to the cathode and hydrogen fed to the anode. Hydrogen ions and electrons are formed together at the anode and move to the cathode through the electrolyte. Electrons then flow to the electrode through an external circuit. FCs produce DC power which is converted via an inverter to AC power. A single FC produces output voltage less than 1 V [70]. Therefore, individual FCs are combined in various series and parallel configurations forming an FC system to produce higher voltage. There are several major types of FC, designated by the type of electrolytes used, including phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC) and proton exchange membrane (PEMFC).

The modelling of FCs varies according to the type. The SOFC is chosen as an example to illustrate the FC model. It is the most common model used because it is suitable for large stationary power generation, offers greater efficiency, is relatively simple and is capable of the combined heat and power co-generation of a hybrid system [70, 163]. The SOFC model is derived by considering the total stack voltage of the fuel cell stack, as given by [164]:

\[
V = nF \sum_{i=1}^{n} R_{i} \ln \left( \frac{P_{in,i}}{P_{out,i}} \right)
\]
where,

\[ V = N_r \left( E_0 + \frac{RT}{2F} \ln \frac{R_N}{H_2O} \right) - rI \]  \hspace{1cm} (4-17)

- \( V \): total stack voltage (V)
- \( E_0 \): standard reversible cell potential (V)
- \( r \): internal resistance of stack (Ω)
- \( I \): stack current (A)
- \( N \): number of cells in stack
- \( R \): universal gas constant (J/mol K)
- \( T \): stack temperature (K)
- \( F \): Faraday’s constant (C/mol)
- \( rI \): ohmic loss of the stack

Figure 4-10: Fuel Cell operation diagram. Adopted from [163].
For the dynamics of the SOFC, consider the partial pressure of hydrogen, oxygen and water given by (4-18) to (4-20), respectively. The slow dynamics of the FC current are represented by (4-21).

$$p_{H_2} = \left( \frac{3}{KH_2} \right) \left( qH_2 - 2K,I \right)$$  \hspace{1cm} (4-18)

$$p_{O_2} = \left( \frac{3}{KO_2} \right) \left( qO_2 - 2K,I \right)$$  \hspace{1cm} (4-19)

$$p_{H_2O} = \left( \frac{3}{KH_2O} \right) \left( 2K,I \right)$$  \hspace{1cm} (4-20)

$$I = \left( \frac{I_{ref}}{1+\tau s} \right)$$  \hspace{1cm} (4-21)

$I_{ref}$ is the reference current, given in (4-22). The fuel and oxygen flows are given by (4-23) and (4-24).

$$I_{ref} = \left( \frac{P_{ref}}{V_{fc}} \right)$$  \hspace{1cm} (4-22)

$$qH_2 = 2K,I$$  \hspace{1cm} (4-23)

$$qO_2 = \frac{qH_2}{rHO}$$  \hspace{1cm} (4-24)
Chapter 4

Dynamic Equivalent Model of ADNC

The power output of the SOFC is the product of stack current and voltage.

Figure 4-11 shows the SOFC dynamic model in terms of a block diagram.

![Block diagram of the SOFC dynamic model. Adopted from [164].](image)

**4.5 Modelling of ADNC**

**4.5.1 Preliminary Model of ADNC**

This section describes the preliminary model developed as an initial attempt to model the ADNC based on system identification theory. The preliminary model is developed based on the black-box approach using a combination of Prony analysis and the nonlinear least square optimisation. This model has been developed based on the general nature of responses of ADNC under small disturbances. The responses observed have combination of an initial step and damped sinusoidal waveform. This lead to the formulation of (4-27). The initial model will be used for small disturbance studies of ADNC in large distribution and transmission networks. This section describes the development of the initial model and the relevant results.
4.5.1.1 Model development

Prony analysis has been shown to be a feasible technique to model a linear sum of complex exponentials of signals that are uniformly sampled [165]. For a signal, $f(t)$, consisting of $N$ evenly spaced samples, Prony's method fits a function, $\hat{f}(t)$, as following [165]:

$$\hat{f}(t) = \sum_{i=1}^{N} A_i e^{\sigma_i t} \cos(2\pi f_i t + \phi_i)$$

(4-25)

to the observed function $f(t)$. The prony analysis directly computes the damping coefficient apart from the frequency, amplitude and phase.

After some manipulation of (4-25) utilising Euler's formula the following equation, (4-26), is obtained [165]:

$$\hat{f}(t) = \sum_{i=1}^{N} A_i e^{\sigma_i t} \cos(2\pi f_i t + \phi_i) = \sum_{i=1}^{N} \frac{1}{2} A_i e^{\lambda_i} e^{\lambda_i j}$$

(4-26)

where $\lambda_i = (-\sigma_i \pm j\omega_i) t$ is the eigenvalue of the system, $\sigma_i$ is the damping, $\phi_i$ is the phase angle, $f_i$ are the frequency, $A_i$ is the amplitude of the series and $j = \sqrt{-1}$ [165].

The purpose of this initial model is to represent the response $y(t)$ as the sum of an initial step, $K$, and a damped sinusoid response. Therefore, the ADNC responses are represented as follows:

$$y(t) = [K + A e^{\alpha t} \sin(\omega t + \phi)] u(t)$$

(4-27)

where $y(t)$ is active power response, $K$ is the initial step, $A$ is amplitude, $\alpha$ is damping factor, $\omega$ is frequency (in radians) and $\phi$ is phase angle (in radians). Equation (4-27) is represented in MATLAB/Simulink as shown in Figure 4-12.
4.5.1.2 Parameter estimation procedure

Prony analysis is used for initial estimates; these are further optimised by an iterative nonlinear least square optimisation procedure. Nonlinear least square is a general curve-fitting technique. It fits data to any equation that defines \( Y \) as a function of \( X \) and one or more parameters. It finds the values of those parameters that generate the curve that come closest to the data (minimises the sum of the squares of the vertical distances between data points and curve) [166]. This technique requires a model of the analysed signal. In this study, the signal model is defined by (4-27). The nonlinear least square optimisation is generally used where the goal is to minimise the difference between the physical observation and the prediction from the mathematical model. More precisely, the goal is to determine the best values of the unknown parameters: amplitude (\( A \)), damping factor (\( \alpha \)), frequency (\( \omega \)) and phase (\( \phi \)), in order to minimise the squared errors between the measured values of the signal and the simulated/computed ones.

All of the estimation methods used for the initial model are implemented using MATLAB software. First, the DIgSILENT PowerFactory software is used to simulate the dynamic response of the detailed network, and the appropriate active power responses are recorded. These responses are then imported into MATLAB software to
determine the transfer function of the network. A Prony analysis algorithm is written in
MATLAB software and the active power responses are imported into MATLAB in
order to obtain the parameters of (4-27). Once the parameters have been derived, they
are used as the initial values for the nonlinear least square optimisation algorithm. The
estimation of parameters is performed using MATLAB (7.4)/Simulink Parameter
Estimation. The Simulink model shown in Figure 4-12 is then used to obtain model
responses with estimated parameters and to compare these with actual ADNC responses
(simulated using DIgSILENT). Once the parameters of the model have been tuned, the
model is converted into transfer function form using the Laplace transformation. By
applying trigonometric identities to (4-27), it becomes:

\[
\frac{y(t)}{u(t)} = K + Ae^{at} \sin \omega t \cos \phi + Ae^{at} \sin \phi \cos \omega t
\]

\[
= K + \left[A \cos \phi \right] e^{at} \sin \omega t + \left[A \sin \phi \right] e^{at} \cos \omega t
\]

\[
= K + Be^{at} \sin \omega t + Ce^{at} \cos \omega t
\]

where \( B = A \cos \phi \) and \( C = A \sin \phi \). After transformation of (4-28) into s-domain by
using Laplace transformation, the transfer function form of the model is obtained as
follows:

\[
H(s) = \frac{Y(s)}{U(s)} = K + B \left( \frac{\omega}{(s - \alpha)^2 + \omega^2} \right) + C \left( \frac{s - \alpha}{(s - \alpha)^2 + \omega^2} \right)
\]

(4-29)

\[
= K + \frac{B \omega + C(s - \alpha)}{(s - \alpha)^2 + \omega^2}
\]

The accuracy of the estimation procedure is evaluated by calculating the Root
Mean Square Error (RMSE) values. RMSE is a frequently used measure of the
differences between values predicted by a model or an estimator, and the values actually
observed from the subject being modelled or estimated. These individual differences are
known as residuals and RMSE serves to aggregate them into a single measure of predictive power. In this study, RMSE is used to measure the differences between the estimated responses and the actual responses obtained from measurement.

Let the estimated response be \( \theta_1 = \begin{bmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{1,n} \end{bmatrix} \) and the actual response \( \theta_2 = \begin{bmatrix} x_{2,1} \\ x_{2,2} \\ \vdots \\ x_{2,n} \end{bmatrix} \). RMSE is then calculated as:

\[
RMSE(\theta_1, \theta_2) = \sqrt{\text{MSE}(\theta_1, \theta_2)} = \sqrt{E\left(\left(\theta_1 - \theta_2\right)^2\right)}
\]

\[
= \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}
\]

where \( MSE \) is the Mean Square Error and \( E \) is the error. The MATLAB modelling codes and Simulink files of the initial model are given in Appendix A.

### 4.5.1.3 Case studies

The ADNC study system shown in Figure 4-13 was built in order to evaluate the model’s performance. The ADNC system is broadly based on the UK’s 11kV distribution network. It is connected to a 33kV external grid, represented by an equivalent synchronous generator source. The grid supplies three 11kV feeder systems through a 33/11.5kV, 12/24 MVA transformer with 21% impedance, Dy11 connection and voltage regulation at the low voltage side. The tap range is \( \pm 10\% \) of the nominal voltage, with 1.25% step change. The 11kV feeders are connected to the point of common coupling (bus 2) via fixed tap 11/0.433kV transformers, with rating varying between 0.5-2.5MVA and impedances between 4-6% depending on the load size. The converter connected (CCG) and fixed speed induction generators (FSIG) are connected
on feeder 1. Two synchronous generators (SG) connected to bus 2 are driven by gas turbine units modelled as IEEE GAST type. Further details of ADNC modelling, in DIgSILENT PowerFactory software, can be found in [167, 168]. Detailed parameters for this test network are given in Appendix C.

![Diagram of the single line network of the case study](image)

**Figure 4-13:** Single line network of case study. Adopted from [167, 168].

In the case studies, the total installed local generation, i.e. generation connected at bus 1 (see Figure 4-13), is considered equal to the total active load in ADNC. Thus, there is no exchange of active power with the rest of the distribution network through bus 1. The generation mix consists of 85% synchronous generators and 15% renewable generation. The renewable generation includes fixed speed wind turbines (modelled as conventional induction generators) and converter-connected photovoltaic generation. The load mix consists of 50% static load (modelled as a constant power load) and 50% dynamic load (modelled as a mix of conventional small and large induction motors).
The responses of active power to various small disturbances are measured at the point of connection (bus 1) as tabulated in Table 4-1. Only two types of disturbance are considered at this stage, namely a small increase in ADNC load and torque reduction of the synchronous generators. The disturbances are first simulated and the active power responses at the point of connection recorded. All the responses are simulated for 10 seconds after the initial disturbance. The sampling rate is 0.01s.

Table 4-1: Disturbance variations setting

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Variation of disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase of ADNC loads</td>
<td></td>
</tr>
<tr>
<td>Load 31</td>
<td>Increase by 5%</td>
</tr>
<tr>
<td>Load 43</td>
<td>Increase by 10%</td>
</tr>
<tr>
<td>Load 54</td>
<td>Increase by 30%</td>
</tr>
<tr>
<td>All loads</td>
<td>Increase by 2%</td>
</tr>
<tr>
<td></td>
<td>Increase by 5%</td>
</tr>
<tr>
<td>Generator torque reduction</td>
<td></td>
</tr>
<tr>
<td>Synchronous generator 1 (SG1)</td>
<td>Reduction of 0.08 p.u.</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.1 p.u</td>
</tr>
<tr>
<td>Synchronous generator 2 (SG2)</td>
<td>Reduction of 0.1 p.u</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.15p.u.</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.25p.u.</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.3 p.u</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.35 p.u</td>
</tr>
<tr>
<td></td>
<td>Reduction of 0.4p.u</td>
</tr>
<tr>
<td>Synchronous generator 1 (SG1) and Synchronous generator 2 (SG2)</td>
<td>Reduction of 0.05p.u.</td>
</tr>
</tbody>
</table>

4.5.1.4 Parameter estimation results

Table 4-2 shows the estimated model parameters and corresponding RMSE in all case studies. Figures 4-14 to 4-18 show the comparison between the simulated ADNC responses (obtained using DlgSILENT) and responses obtained with the equivalent model using estimated parameters. From Figures 4-14 to 4-18, it can be seen
that the equivalent model responses match very closely the actual ADNC responses even for large disturbances. The estimation method works particularly well if the response is purely sinusoidal, for example, as shown in Figure 4-17. In the case of non-sinusoidal system responses, e.g. Figures 4-14 to 4-16, the model responses are slightly different from the simulated ones during the first swing and then (about 0.5s after the disturbance, when the higher order frequency mode gets damped) very quickly resume the same form as the original system response.

Table 4-2: Estimation parameters obtained by the proposed estimation procedure

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>K</th>
<th>A</th>
<th>α</th>
<th>ω</th>
<th>φ</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load43 increase 5%</td>
<td>13.5037</td>
<td>0.0787</td>
<td>-1.7891</td>
<td>11.003</td>
<td>6.5066</td>
<td>0.0011</td>
</tr>
<tr>
<td>Load54 increase 5%</td>
<td>13.5038</td>
<td>0.0888</td>
<td>-1.8538</td>
<td>11.0115</td>
<td>6.4958</td>
<td>0.0011</td>
</tr>
<tr>
<td>Load31 increase 5%</td>
<td>13.5043</td>
<td>0.0733</td>
<td>-1.745</td>
<td>10.999</td>
<td>6.5083</td>
<td>0.0019</td>
</tr>
<tr>
<td>Load43 increase 15%</td>
<td>13.6136</td>
<td>0.2518</td>
<td>-1.821</td>
<td>10.9983</td>
<td>6.5076</td>
<td>0.0033</td>
</tr>
<tr>
<td>Load54 increase 15%</td>
<td>13.6137</td>
<td>0.2647</td>
<td>-1.8474</td>
<td>10.9961</td>
<td>6.5178</td>
<td>0.0034</td>
</tr>
<tr>
<td>Load31 increase 15%</td>
<td>13.6154</td>
<td>0.2585</td>
<td>-1.8284</td>
<td>10.9989</td>
<td>6.5003</td>
<td>0.0035</td>
</tr>
<tr>
<td>All load increase 2%</td>
<td>13.6911</td>
<td>0.3781</td>
<td>-1.8308</td>
<td>10.9923</td>
<td>6.5159</td>
<td>0.0050</td>
</tr>
<tr>
<td>Load43 increase 30%</td>
<td>13.7792</td>
<td>0.4972</td>
<td>-1.8111</td>
<td>10.9886</td>
<td>6.5172</td>
<td>0.0067</td>
</tr>
<tr>
<td>Load54 increase 30%</td>
<td>13.7794</td>
<td>0.5248</td>
<td>-1.8395</td>
<td>10.9850</td>
<td>6.5299</td>
<td>0.0068</td>
</tr>
<tr>
<td>Load31 increase 30%</td>
<td>13.7827</td>
<td>0.5128</td>
<td>-1.8212</td>
<td>10.9822</td>
<td>6.5221</td>
<td>0.0071</td>
</tr>
<tr>
<td>All load increase 5%</td>
<td>14.0554</td>
<td>0.9281</td>
<td>-1.8176</td>
<td>10.9692</td>
<td>6.542</td>
<td>0.0141</td>
</tr>
<tr>
<td>SG1 torque reduction 0.1pu</td>
<td>14.0524</td>
<td>3.7412</td>
<td>-1.6866</td>
<td>10.9301</td>
<td>6.3847</td>
<td>0.0061</td>
</tr>
<tr>
<td>SG2 torque reduction 0.1pu</td>
<td>13.5933</td>
<td>0.3862</td>
<td>-2.0844</td>
<td>11.9165</td>
<td>4.8038</td>
<td>0.0076</td>
</tr>
<tr>
<td>SG1 and SG2 torque reduction 0.05pu</td>
<td>13.8223</td>
<td>2.156</td>
<td>-1.7419</td>
<td>10.9045</td>
<td>6.4602</td>
<td>0.0032</td>
</tr>
<tr>
<td>SG2 torque reduction 0.4pu</td>
<td>14.0377</td>
<td>0.5086</td>
<td>-1.4576</td>
<td>11.3136</td>
<td>5.8819</td>
<td>0.0315</td>
</tr>
<tr>
<td>SG2 torque reduction 0.25pu</td>
<td>13.8138</td>
<td>0.6607</td>
<td>-1.8531</td>
<td>11.7337</td>
<td>5.1067</td>
<td>0.0207</td>
</tr>
<tr>
<td>SG2 torque reduction 0.15pu</td>
<td>13.6663</td>
<td>0.299</td>
<td>-1.7143</td>
<td>11.723</td>
<td>5.1237</td>
<td>0.0112</td>
</tr>
<tr>
<td>SG2 torque reduction 0.35pu</td>
<td>13.9628</td>
<td>0.9593</td>
<td>-1.8612</td>
<td>11.6828</td>
<td>5.189</td>
<td>0.0284</td>
</tr>
<tr>
<td>SG2 torque reduction 0.3pu</td>
<td>13.8882</td>
<td>0.8079</td>
<td>-1.857</td>
<td>11.7042</td>
<td>5.1563</td>
<td>0.0245</td>
</tr>
<tr>
<td>SG1 torque reduction 0.08pu</td>
<td>13.9315</td>
<td>3.116</td>
<td>-1.7127</td>
<td>10.9424</td>
<td>6.3733</td>
<td>0.0082</td>
</tr>
</tbody>
</table>

| Average parameter            | 13.7605 | 0.8246 | -1.7987 | 11.1887 | 6.1072 |      |
Figure 4-14: Response following 5% of all load increase

Figure 4-15: Response following 5% increase in Load31

Figure 4-16: Response following 30% increase in Load54
Figure 4-17: Response following 10% reduction in torque of SG1

Figure 4-18: Response following 25% reduction in torque of SG2

Figure 4-19 shows the equivalent model response (thick dashed line) with average values of parameters obtained from all individual responses along with all the individual responses themselves. It can be seen that even with the average values of parameters the model captures qualitatively the response of the ADNC, and that by adjusting parameters a whole range of responses can be easily obtained.
Figure 4-19: Model response with averaged parameters (thick dashed line) and responses with individual sets of parameters

4.5.1.5 Conclusions

The initial stages of model development of ADNC using Prony analysis and nonlinear least square optimisation were described. The model is intended primarily for use in small disturbance stability studies of large distribution and transmission networks, and this study was concerned with the estimation method to establish the deterministic model of reasonably complex ADNC in a simple transfer function form. The results obtained gave significant confidence in the applicability of the method for determining the dynamic equivalent of the ADNC. Since the model is of a simple second-order transfer function form, it could fully capture only one oscillatory mode of the system, and as such it is particularly useful for modelling ADNC where one oscillatory mode clearly dominates its dynamic response. Thus, a higher order dynamic equivalent model might be needed to represent the ADNC in both steady state and dynamic system studies. For this preliminary model, the reactive power responses were not considered.
4.5.2 Proposed Model of ADNC

Following the development of the preliminary model, the equivalent model of ADNC for both steady state and dynamic system studies is further refined to enhance its ability to capture ADNC dynamics particularly in case of multi modal oscillations. The development of ADNC equivalent model proceeded by adopting the grey-box modelling approach. The grey-box approach to the development of an equivalent model of ADNC assumes a known structure of the cell and estimates the parameters of the model from online or offline measurements. The adopted model structure represents the dominant behaviour of the ADNC system and leaves the mismatch part of the system to be approximated by an optimization method. Thus, it is important to carefully select and use an appropriate model structure which will allow better estimation of the model of ADNC. This idea stems from the fact that the grey-box approach has greater potential to significantly improve the accuracy of the ADNC model than the black-box approach, as the structure of the system is known. The assumed equivalent model structure of ADNC comprises a converter-connected generator in parallel with a composite load model.

4.5.2.1 Model Assumptions

The dynamic equivalent model of ADNC is composed of a converter-connected generator and a composite load model connected in parallel. The equivalent model diagram is shown in Figure 4-20. The following assumptions are made in developing the equivalent model:

i) The converter-connected generator model includes a third-order synchronous generator model and a full converter.

ii) The composite load model is represented by the constant impedance, constant power and constant current load model (ZIP load model), accounting for the static
load part; connected in parallel with an induction motor model accounting for the dynamic load part. The composite load model is referred to as the ZIP-IM load model [39, 42-44].

iii) The mechanical torques of both generator and induction motor are assumed to be constant.

![Figure 4-20: The equivalent model diagram](image)

The proposed converter-connected generator model can be used to represent microturbines and wind turbines, especially the direct-drive synchronous generator type [169-172]. The third-order synchronous generator was chosen since this model is adequate to represent the dynamic behaviour of the synchronous generator [171, 173]. Furthermore, the main goal of this work is to develop a simple and low-order equivalent model of ADNC; a higher order model of synchronous generator would increase the order of the equivalent model. In addition, the full converter model used in the converter-connected generator is a simple model that is sufficient to represent the converter without neglecting its main principle, i.e. that the active power flowing through the converter is balanced. In developing the proposed equivalent model, the main interest regarding the converter is preservation of its dynamic characteristics while using a relatively simple model. Thus, a good balance between detail and simplification
has to be found. The chosen converter model preserves the dynamic characteristics represented by the DC-link equation (the capacitor linking between inverter and rectifier) [169, 170].

A general overview of load representation for dynamic performance analysis of a power system is given in [37]. In [38], the standard load model for power flow and dynamic simulation programs were recommended. [23] also included a recommendation regarding the structure of multiple load types connected to a load bus for transient stability, longer-term dynamics and small-disturbance stability programs. However, the standard load model structures of ADNC for dynamic study are still unavailable. Among the load models proposed, the composite load model is widely used, because of its physical meaning and high proportion of induction motor in the total load [39-46]. Furthermore, it has been suggested that for transient stability analysis in weak interconnected power systems (like ADNC), the load model should be represented by a static part and a dynamic part from induction motors [49]. Therefore, the composite load model has been chosen to represent the loads of ADNC. The third order IM model has been selected to represent the dynamic part in the composite load model. The third-order model is usually adequate for aggregated motors in bulk system dynamics simulations [38, 49, 133, 174].

4.5.2.2 Model Development

The nonlinear state space model can be summarized as follows:

\[ \dot{x} = Ax + Bu + f(x) \]
\[ y = Cx + Du + g(x) \]  

(4-31)
where $A$, $B$, $C$ and $D$ are the coefficient matrices, $x$ is the state vector, $u$ is the input vector, $y$ is the output vector and $f(x)$ and $g(x)$ are functions that represent the nonlinear parts of the model.

The schematic of the composite equivalent circuit for the ZIP-IM load model is shown in Figure 4-21. The dynamic part of this model is represented by internal voltage relationships of the third-order induction motor [39, 40].

The composite load model used in the ADNC model is described by the following equations:

$$
\frac{dE_m'}{dt} = \frac{1}{T'_{dm}} \left( -\frac{X_m}{X'_m} E_m' + \left( \frac{X_m - X'_m}{X'_m} \right) V \cos \delta_m \right) 
$$

$$
\frac{d\delta_m}{dt} = \omega_m - \omega_s - \left( \frac{X_m - X'_m}{X'_m} \right) \frac{V}{T'_{dm} E_m'} \sin \delta_m
$$

$$
\frac{d\omega_m}{dt} = -\frac{1}{H_m} \left( \frac{E_m' V}{X'_m} \sin \delta_m + T_m \right)
$$
The output equations of the composite load model are expressed in the following way:

\[
P_L = P_{ZIP0} \left[ P_Z \left( \frac{V}{V_o} \right)^2 + P_I \left( \frac{V}{V_o} \right)^l \right] - \frac{V}{X_m} E'_m \sin \delta_m
\]

\[
Q_L = Q_{ZIP0} \left[ Q_Z \left( \frac{V}{V_o} \right)^2 + Q_I \left( \frac{V}{V_o} \right)^l \right] + \frac{V^2}{X'_m X_m} \frac{V}{X_m} E'_m \cos \delta_m
\]

(4-35)

where \( P_L \) and \( Q_L \) are the active and reactive power of the ZIP-IM model, respectively; \( P_{ZIP0} \) and \( Q_{ZIP0} \) are the active and reactive power of the static ZIP model at steady state.; \( P_Z \) and \( Q_Z \) are the constant impedance part of the ZIP model; \( P_I \) and \( Q_I \) are the constant current part; and \( P_P \) and \( Q_Q \) are the constant power part.

The converter-connected generator is composed of a third-order synchronous generator model and a back-to-back full converter model [169, 170, 173]. The synchronous generator interfaces with the grid via a back-to-back full converter as shown in Figure 4-22 [169, 170]. The active power flow through the converter is balanced via the DC-link (the capacitor linking inverter and rectifier). This model is generator independent, with ideal rectifier and inverter, without modelling the control circuit.

![Figure 4-22: The back-to-back full converter model. Adopted from [169, 170]](image-url)
The dynamic parts of the converter-connected generator can be described by (4-36) to (4-39).

\[
\frac{dE_g'}{dt} = \frac{1}{T_{dg}} \left( E_{FD} - E_g' - \left( X_g - X_g' \right) I_d \right)
\]
\[
= \frac{1}{T_{dg}} \left( E_{FD} - E_g' \left( \frac{X_g}{X_g'} \right) + \left( \frac{X_g - X_g'}{X_g} \right) V \cos \delta_g \right) \quad (4-36)
\]

\[
\frac{d\omega_g}{dt} = \frac{1}{H_g} \left( T_m - T_e - D \omega_g \right)
\]
\[
= \frac{1}{H_g} \left( T_m - \frac{VE_g'}{X_g'} \sin \delta_g - D \omega_g \right) \quad (4-37)
\]

\[
\frac{d\delta_g}{dt} = \omega_g \quad (4-38)
\]

\[
\frac{dV_{DC}}{dt} = \frac{1}{CV_{DC}} \left( V_{ds} I_{ds} + V_{qs} I_{qs} - V_{DG} I_{DG} - V_{QG} I_{QG} \right) \quad (4-39)
\]

The output active and reactive power of the converter-connected generator are computed as follows:

\[
P_G = \frac{V}{X_g'} E_g' \sin \delta_g + V_{DC} I_{DC}
\]
\[
Q_G = \left( \frac{V}{X_g'} E_g' \cos \delta_g - \frac{V^2}{X_g'} \right) + K_q V_{DC} I_{DC} \quad (4-40)
\]

where \( P_G \) and \( Q_G \) are the active and reactive power of the converter-connected generator part and \( K_q \) is scaling factor.

Based on (4-32) to (4-40), the system states, inputs and outputs are defined as follows:
Chapter 4  Dynamic Equivalent Model of ADNC

\[
\begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5 \\
    x_6 \\
    x_7
\end{bmatrix} =
\begin{bmatrix}
    E'_m \\
    \delta_m \\
    \omega_m \\
    \omega_g \\
    \delta_g \\
    V_{DC}
\end{bmatrix}
\]

,  \quad u =
\begin{bmatrix}
    u_1 \\
    u_2
\end{bmatrix} = \begin{bmatrix}
    V
\end{bmatrix},  \quad y = \begin{bmatrix}
    P \\
    Q
\end{bmatrix}

The output equations (P and Q) of the equivalent model can be obtained from the following equation:

\[
P = P_G - P_L
\]

\[
Q = Q_G - Q_L
\]

\text{(4-41)}

Therefore, the nonlinear state space model of ADNC in its final form can be described as follows:

\[
\dot{x} =
\begin{bmatrix}
    \frac{-X_m}{T_{m_e}X_m'} & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 1 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & -\frac{V}{H_mX_m'} \sin \delta_n & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & -\frac{V}{H_mX_m'} \sin \delta_n & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & \frac{1}{H_m} & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{H_m} \\
    0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{H_m} \\
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5 \\
    x_6 \\
    x_7
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
    \frac{X_m - X_m'}{T_{m_e}X_m'} \cos \delta_n & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    u_1 \\
    u_2
\end{bmatrix}
\]

\text{(4-42)}

\[
y =
\begin{bmatrix}
    \frac{V \sin \delta_n}{X_m} & 0 & 0 & \frac{V \sin \delta_n}{X_m} & 0 & 0 & I_{dc}
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_2 \\
    x_3 \\
    x_4 \\
    x_5 \\
    x_6
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
    -P_{zaw} \left( \frac{\rho}{V_{dc}} \right) \frac{V}{V_{dc}} P_{dc} \frac{V}{V_{dc}} & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    u_1 \\
    u_2
\end{bmatrix}
\]

\text{(4-43)}

where \( K_q = (V_{dc}I_{dc} + V_{dq}I_{dq} - V_{dq}I_{dc} - V_{dq}I_{dq}) \) and \( K_q \) is scaling factor.
To avoid complexity in this equivalent model, the unknown parameters are represented as \( P_1, P_2, P_3, \ldots, P_{20} \). Finally, the nonlinear state space model of ADNC can be summarized by matrix equation (4-44).

Obviously the dynamic equivalent model of ADNC as shown in (4-44) is a nonlinear model and has twenty unknown parameters. These twenty parameters have to be identified using a suitable parameter estimation procedure, custom-made or commercially available. Parameters \( P_{10}, P_{19} \) and \( P_{20} \) featuring in (4-44) are the nonlinear parts of the equivalent ADNC model.

\[
\begin{align*}
\dot{x} &= \begin{bmatrix} P_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ P_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & P_3 & 0 & 0 & 0 \\ 0 & 0 & P_4 & P_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & P_6 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} P_7 & 0 \\ P_8 & -1 \\ 0 & 0 \\ 0 & 0 \\ P_9 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \\
y &= \begin{bmatrix} P_{11} & 0 & 0 & P_{12} & 0 & 0 & P_{13} \\ P_{14} & 0 & 0 & P_{15} & 0 & 0 & P_{14} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} + \begin{bmatrix} P_{17} & 0 \\ P_{18} & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} P_{19} \\ P_{20} \end{bmatrix}
\end{align*}
\]

(4-44)

The MATLAB code for developed grey-box model (4-44) is given in Appendix B.

### 4.6 Parameter Identification Methodology

#### 4.6.1 Parameter Estimation Procedure

The parameter estimation procedure is shown in Figure 4-23. Initially, the pre-processing procedure is performed on the input and output signals (voltage, \( v(t) \),...
frequency, $f(t)$, active power $P(t)$, and reactive power $Q(t)$). The pre-processing procedure, also known as data conditioning, filters out the noise contained in the signals. After the data conditioning process, the filtered input signals, voltage and frequency ($V, f$) are imported into the nonlinear grey-box model together with the initial values of model parameters to be estimated. The System Identification Toolbox in MATLAB is used to develop the grey-box model and to produce the output responses of active and reactive power ($\hat{P}, \hat{Q}$). The simulated output responses ($\hat{P}, \hat{Q}$) are obtained from the model using estimated model parameters based on nonlinear least square optimization, according to the specified identification criterion. The parameter estimation procedure is performed in MATLAB software.

![Diagram](attachment:image.png)

Figure 4-23: The parameter estimation procedure

### 4.6.1.1 Sampling Rate

To estimate parameters from measurements requires the specification of models, and each model will exhibit different degrees of sensitivity to the parameters sought. The precision of the estimated parameters is a function of the sensitivity and the statistical characteristics of the data. The precision is affected by any correlation in the
data and by the choice of the model used to estimate the parameters. The sampling rate of the measurement data is one of the key issues in the parameter estimation method. An optimal choice of sampling rate will allow an accurate estimation of results or parameters [103].

A common rule of thumb is to sample signals at a range ten times the guessed bandwidth of the system or the bandwidth of interest for the model [103]. In practice, it is useful to first record a step response from the system and then select the sampling rate so that it gives 4 to 6 samples during the rise time. If uncertainty exists in the system bandwidth and a fast data acquisition environment is available, sampling should be as fast as possible. Following this, digital filtering and decimation should be applied to reduce the sampling rate to the desired value (decimation is a form of downsampling the data set [103]).

New measurement technologies using time-synchronised wide area measurements allow various types of measurement to be recorded. There are diverse devices that can be used to measure the desired data, such as power quality monitors, digital fault recorders, digital relays and Phasor Measurement Units (PMUs). At present, PMUs are the most common measurement technology used in power grid monitoring. Deployment of PMUs in the grid offers a wide range of available data measurements with a high sampling rate, and these data can be used in the proposed parameter estimation procedure.

The perturbations and disturbances used for data acquisition may be from natural or artificial causes. More importantly, they can affect the system’s operating conditions and this change in the network parameters can be measured. The IEEE C37.118 standard [158] allows for a variety of sampling rates in data acquisition
ranging from 10 to 120 per second. Most PMUs can sample at 30 measurements per second, while some are capable of even higher sampling rates. In order to obtain suitable and exact results, a sampling rate of 0.01 sec or 10 samples per second is proposed, and the measurement period should be 5 sec before and 10 sec after each perturbation/disturbance to capture the dynamic performance accurately [133]. The rate of 10 samples per second was chosen in this research to extract the data from simulated responses in the DigSILENT PowerFactory software; it worked well during the parameter estimation process. A high sampling rate can actually cause errors and problems in the identification process, and a rate that is very fast relative to the system dynamics can also cause inaccuracies [103].

4.6.1.2 Filtering Method

First, the pre-processing, or data conditioning, procedure is applied to the input and output signals. The measurement data is frequently contaminated with harmonic components, a problem inherent in any measurement. The filtering method concentrates identification on the frequency range of interest and reduces the effect of high-frequency measurement noise. The high-frequency component needs to be filtered out before the identification process, because the resulting estimate is sensitive to the presence of harmonics in the input and output signals which may cause the resulting estimated parameters to be biased [40]. For the proposed estimation procedure, low-pass filters are sufficient to dampen out the high-frequency harmonics [103], and a simple low-pass filter such as a moving average (available in MATLAB), can be used [40, 175].

4.6.1.3 Best Fit Value

The performance of the developed equivalent model is evaluated by computing the best fit value. The best fit value is the percentage value that shows how well the
simulated model output matches the measured output. The value is computed using (4-45) as below [176]:

$$\text{Best fit} = \left(1 - \frac{|y - \hat{y}|}{|y - \bar{y}|}\right) \times 100$$  

(4-45)

where \(y\) is the measured output, \(\hat{y}\) is the simulated model output and \(\bar{y}\) is the mean of \(y\). 100% corresponds to a perfect fit while 0% indicates that the fit is no better than guessing the output to be a constant (\(\hat{y} = \bar{y}\)). The mean of \(y\) is calculated internally in MATLAB software since best fit value is a built-in function.

### 4.6.2 Nonlinear Least Square Optimization

As mentioned in Section 4.5.1.2, nonlinear least square is an optimisation-based technique used to search for the best model parameters by fitting a curve through data. It finds the values of the model parameters generating the curve that come closest to the data and the goal is to minimise the difference between the physical observation and the prediction from the mathematical model. In this research, the mathematical model is defined by the grey-box model structure. Nonlinear least square optimisation is used to determine the best values of the unknown nonlinear parameters (\(P_1\) to \(P_20\)) in order to minimise the squared errors (\(\varepsilon\)) between the measured values of the signal and the computed ones. The squared error functions for measured and simulated output are defined as follows:

$$\min_{\theta} \varepsilon_p(\theta) = \min_{\theta} \frac{1}{n} \sum_{k=1}^{n} \varepsilon_{kp}^2(\theta) = \min_{\theta} \frac{1}{n} \sum_{k=1}^{n} \left[ P_{km}(\theta) - P_{ks}(\theta) \right]^2$$

$$\min_{\theta} \varepsilon_Q(\theta) = \min_{\theta} \frac{1}{n} \sum_{k=1}^{n} \varepsilon_{kQ}^2(\theta) = \min_{\theta} \frac{1}{n} \sum_{k=1}^{n} \left[ Q_{km}(\theta) - Q_{ks}(\theta) \right]^2$$  

(4-46)
where $P_m$ and $Q_m$ are measured active and reactive power (either actual measurement or simulated from DiGSILENT), $P_s$ and $Q_s$ are simulated active and reactive power from the grey-box model.

The parameter estimation process is performed through iterations. In successive iterations, the sum of squared errors between the simulated and measured output signals is calculated. Based on this, the parameters are updated through the optimisation algorithm. The iterative process and parameter tuning continues until the squared errors ($\varepsilon$) are within a predefined threshold ($10^{-6}$). Three algorithms are available in MATLAB software for solving nonlinear least square problems: trust-region, Levenberg-Marquardt and Gauss-Newton [176]. Trust-region is used for bound constrained problems. Gauss-Newton is a line search method that chooses a search direction based on the solution to a linear least-squares problem. Levenberg-Marquardt is a line search algorithm whose search direction is a cross between the Gauss-Newton and the steepest-descent directions. The Levenberg-Marquardt algorithm was used for estimating grey-box model parameters in this research. The method is both fast and effective [174].

4.7 Summary

This chapter presents the fundamental theoretical concepts behind the nonlinear dynamic system identification techniques. Moreover, the development of a dynamic equivalent model for ADNC was described. First, common system identification techniques and procedures were presented. Afterwards, the modelling of system loads and major types of DG was outlined. The detail of model development process was explained guided by the available prior knowledge of ADNC system. Assumptions and
model selection were justified. Then, the problem of dynamic equivalent of ADNC was formulated under a system identification framework.
5 Validation of Dynamic Equivalent Model of ADNC

5.1 Introduction

In order to demonstrate the developed equivalent model, case study examples were designed and simulated. Various static load models, dynamic load compositions, fault locations and a diverse range of generation scenarios were considered. Extensive results of estimated parameters are presented in this chapter and the researcher attempts to establish a generic range of dynamic equivalent parameters for the ADNC. Numerous simulation results that demonstrate the adequacy of the developed equivalent ADNC model are provided. At the end of the chapter, a set of look-up tables is presented, based on the case study, in order to represent the developed equivalent model of ADNC for different network configurations and fault locations.
5.2 ADNC Network Description

5.2.1 Network Setting

The ADNC study system, shown in Figure 5-1, is broadly based on the UK 11 kV distribution network. The ADNC is connected to a 33 kV external grid, represented by an equivalent synchronous generator source. The study system is very similar to the one shown in Figure 4.13. The only difference is that the new system used here has doubly fed induction generators (DFIG) connected to Feeder 3. The model is built in DigSILENT PowerFactory software, and further details of the ADNC modelling can be found in [167, 168]. The detailed parameters for this test network are given in Appendix C.

| Figure 5-1: Single line diagram of the ADNC network study. Adopted from [167, 168]. |

5.2.2 Case Studies Description

In the case studies, the total installed local generation, i.e. generation connected at Bus 1 (refer to Figure 5-1), is equal to the total load in ADNC, so there is no
exchange of active power with the rest of the distribution network through Bus 1.

Different cases have been considered in order to identify the possible range of responses of the ADNC. The following figures, tables and associated discussion illustrate some of the results from a set of 34 different case studies. The case studies were based on four static load models, two dynamic load compositions, five fault locations and seven DG composition scenarios, as listed in Tables 5-1 and 5-2.

Table 5-1: Configuration parameters of the distributed generation.

<table>
<thead>
<tr>
<th>DG Composition</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG (MW)</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>5.0</td>
<td>2.5</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>FSIG (MW)</td>
<td>3.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DFIG (MW)</td>
<td>3.0</td>
<td>3.0</td>
<td>0</td>
<td>6.0</td>
<td>4.5</td>
<td>0</td>
<td>9.0</td>
</tr>
<tr>
<td>CCG (MW)</td>
<td>0.5</td>
<td>3.5</td>
<td>6.5</td>
<td>0</td>
<td>4.0</td>
<td>8.5</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Static load model</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Constant impedance (Z)</td>
</tr>
<tr>
<td>• Constant current (I)</td>
</tr>
<tr>
<td>• Constant power (P)</td>
</tr>
<tr>
<td>• Composite load (ZIP)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dynamic load composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• (1/3 small + 1/3 medium + 1/3 large) motors (M1)</td>
</tr>
<tr>
<td>• (2/3 small + 1/6 medium + 1/6 large) motors (M2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fault location</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Fault at Bus 1 (F1)</td>
</tr>
<tr>
<td>• Fault at Bus 2 (F2)</td>
</tr>
<tr>
<td>• Fault at Bus 3 (F3)</td>
</tr>
<tr>
<td>• Fault at Bus 4 (F4)</td>
</tr>
<tr>
<td>• Fault at Bus 5 (F5)</td>
</tr>
</tbody>
</table>

Table 5-2: 34 test disturbance scenarios

<table>
<thead>
<tr>
<th>Composition</th>
<th>Fault Location</th>
<th>Static Load</th>
<th>Dynamic Load</th>
<th>Number of case studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F1, F2, F3, F4, F5</td>
<td>I, P, Z, ZIP</td>
<td>M1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>F1, F4</td>
<td>ZIP</td>
<td>M2</td>
<td>2</td>
</tr>
</tbody>
</table>
The input and output responses of various ADNC structure compositions obtained from non-linear simulations using DIgSILENT PowerFactory are measured at bus 1 (grid connection point). All the responses are then used in the parameter estimation procedure to obtain the dynamic equivalent model. Only one type of large disturbance (three phase short circuit fault) is considered in this study. The initial parameter values for the estimation procedure are set using either typical values or parameters from published literature [39, 68, 169, 170, 173]. Example of initial values of parameters is given as follow: P1 = 32, P2 = 0.025, P3 = -3.5, P4 = -0.08, P5 = -0.98, P6 = -10.56, P7 = -3.2, P8 = -10.138, P9 = -9.6, P10 = 9.7, P11 = 30.8, P12 = -45.2, P13 = 0.392, P14 = -10.3, P15 = 9.6, P16 = 0.392, P17 = -291, P18 = -371, P19 = 271 and P20 = 370.

The disturbances are first simulated in DIgSILENT PowerFactory and the active and reactive power responses at the point of connection recorded. All the responses are simulated for 9 seconds after the initial disturbance. The disturbance occurred at 1 second and cleared after 500 ms. The sampling rate was 0.01 s. However, for the purpose of clear viewing, some of the responses in the following figures are shown with shorter duration times. All recorded responses were free from noise, therefore, there was no need for pre-filtering of the responses.

5.3 Parameter Estimation Results

5.3.1 Different Fault Location

Table 5-3 presents the range of best-fit values of the estimated model for each case according to the fault locations. Table 5-4 illustrates the range of estimated model parameter values corresponding to the fault locations. In Table 5-5, three sets of average and median values of parameters for three groups based on fault location are presented.
The groups are G1 for fault at bus 1, G2 for fault at buses 2, 3, 4 and 5, and G3 for fault at all buses.

Table 5-3: The range of best-fit values according to the fault locations

<table>
<thead>
<tr>
<th>CASES</th>
<th>BEST FIT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P RESPONSE</td>
</tr>
<tr>
<td>Fault at Bus 1 (F1)</td>
<td>86.84 - 89.25</td>
</tr>
<tr>
<td>Fault at Bus 2 (F2)</td>
<td>80.44 - 82.46</td>
</tr>
<tr>
<td>Fault at Bus 3 (F3)</td>
<td>80.92 - 83.01</td>
</tr>
<tr>
<td>Fault at Bus 4 (F4)</td>
<td>80.13 - 81.09</td>
</tr>
<tr>
<td>Fault at Bus 5 (F5)</td>
<td>81.05 - 84.35</td>
</tr>
</tbody>
</table>

Table 5-4: Estimated parameters of grey-box model obtained by the proposed estimation procedure based on fault locations

<table>
<thead>
<tr>
<th>CASES</th>
<th>PARAMETERS (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
</tr>
<tr>
<td>Fault at Bus 1 (F1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-39.826</td>
</tr>
<tr>
<td></td>
<td>to</td>
</tr>
<tr>
<td></td>
<td>to</td>
</tr>
<tr>
<td></td>
<td>to</td>
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<td></td>
<td>to</td>
</tr>
<tr>
<td></td>
<td>to</td>
</tr>
</tbody>
</table>
Figures 5-2 and 5-3 show the comparison between the actual ADNC responses (obtained using non-linear simulations in D IgSILENT) and responses obtained with the equivalent grey-box model of ADNC for the case of DG composition T5, and fault at bus 1 (T5 F1) and the case of constant power (P) model of ADNC and fault at bus 5 (P F5). The dashed line represents the responses of the developed grey-box model, and the actual ADNC responses are represented by the solid line.

![Graph showing comparison between actual ADNC responses and responses obtained with the grey-box model]
Figure 5-3 shows that the grey-box equivalent model responses match very closely the actual ADNC responses in both cases. This can be seen from the best-fit value shown in Table 5-3, where the percentages are between 80-93%. That is, the higher accuracy of responses by the developed grey-box model reflects the ability of the model to represent the ADNC under various conditions. The active power response in case of Figure 5-3 with constant power load model of ADNC, however, is not as good as when grey-box model was used instead of constant power model.

Figures 5-4 to 5-9 show the simulated equivalent model response using the median value of parameters (thick solid line) and average value of parameters (thick dashed line) for group G1, G2 and G3 respectively. It can be seen clearly from all plots that the use of median value of parameters results in better fit of the ADNC responses than the average parameter value.
Figure 5-4: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group G1

Figure 5-5: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group G1

Figure 5-6: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group G2
Figure 5-7: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group G2

Figure 5-8: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group G3

Figure 5-9: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group G3
In Figures 5-8 and 5-9, there were differences in the amplitude between 1.0 – 1.5 second, i.e., during the fault. The upper group of responses in both figures comprises the responses of the group G1, external fault, and the lower part comprises the responses of group G2, internal fault. The hypothesis here was that the observed differences during the fault are due the effects of the transformer impedance during the measurement of the responses. Further investigation of the influence of transformer impedance is described in Section 5.3.4. On the other hand, the amplitudes of responses (between 1.0 – 1.5 second) for average and median parameter values of group G3 were in the middle between those of group’s G1 and G2 as one might expect as the model parameters (average and median) were obtained by combining identified parameters for all groups of responses.

5.3.2 Different DG Compositions

Based on Table 5-3, the estimated parameters were also formed into three groups according to the composition of DG in the network, as shown in Table 5-6. The first group is group DG-C1 for the network which contains all the DG types, i.e. SG, FSIG, DFIG and CCG. The second group is group DG-C2 for the network which contains only SG and CCG. Finally, the third group (DG-C3) is for the network which included SG, DFIG and with or without CCG. For each group, the average and median value of parameters were also computed and are tabulated in Table 5-7.

Figures 5-10 to 5-15 show the simulated equivalent model responses using median and average values of parameters for groups DG-C1, DG-C2 and DG-C3 respectively. The simulated equivalent model response using the median value of parameters is represented by a thick solid line and the average value of parameters by a
thick dashed line. The median value of parameters shows a distinctly better performance compared to the average value of parameters in all figures.

Table 5-6: Estimated parameters of grey-box model obtained by the proposed estimation procedure based on network composition

<table>
<thead>
<tr>
<th>CASES</th>
<th>PARAMETERS (p.u)</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>NETWORK COMPOSITION 1 (DG-C1)</td>
<td>-40.544 to -19.046</td>
<td>-4.913 to -3.220</td>
<td>-0.800 to -0.726</td>
<td>-10.560 to 30.279</td>
<td>-7.527 to -208.288</td>
<td>-10.138 to -184.829</td>
<td>-17.990 to 313.474</td>
<td>2.011 to 372.241</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-7: Average and median value of parameters for groups DG-C1, DG-C2 and DG-C3

<table>
<thead>
<tr>
<th>CASES</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE DG-C1</td>
<td>-32.540</td>
<td>0.025</td>
<td>-3.993</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-2.393</td>
<td>-10.138</td>
<td>-11.353</td>
<td>10.936</td>
</tr>
<tr>
<td>MEDIAN DG-C1</td>
<td>-34.623</td>
<td>0.025</td>
<td>-3.898</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-2.854</td>
<td>-10.138</td>
<td>-12.529</td>
<td>12.327</td>
</tr>
<tr>
<td>AVERAGE DG-C2</td>
<td>-34.774</td>
<td>0.025</td>
<td>-7.104</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-9.518</td>
<td>-10.138</td>
<td>-12.875</td>
<td>11.360</td>
</tr>
<tr>
<td>MEDIAN DG-C2</td>
<td>-36.009</td>
<td>0.025</td>
<td>-7.241</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-9.012</td>
<td>-10.138</td>
<td>-13.137</td>
<td>11.435</td>
</tr>
<tr>
<td>AVERAGE DG-C3</td>
<td>-33.013</td>
<td>0.025</td>
<td>-5.888</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-5.775</td>
<td>-10.138</td>
<td>-10.798</td>
<td>9.885</td>
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<tr>
<td>MEDIAN DG-C3</td>
<td>-33.057</td>
<td>0.025</td>
<td>-6.083</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-5.813</td>
<td>-10.138</td>
<td>-9.983</td>
<td>8.884</td>
</tr>
<tr>
<td>MEDIAN DG-C1</td>
<td>30.936</td>
<td>-42.778</td>
<td>0.392</td>
<td>-5.856</td>
<td>11.323</td>
<td>0.392</td>
<td>-259.619</td>
<td>-358.293</td>
<td>259.835</td>
<td>363.082</td>
</tr>
<tr>
<td>AVERAGE DG-C2</td>
<td>30.544</td>
<td>-38.643</td>
<td>0.392</td>
<td>-12.785</td>
<td>18.002</td>
<td>0.392</td>
<td>-253.800</td>
<td>-276.096</td>
<td>254.945</td>
<td>281.100</td>
</tr>
<tr>
<td>MEDIAN DG-C2</td>
<td>30.574</td>
<td>-38.463</td>
<td>0.392</td>
<td>-12.571</td>
<td>18.915</td>
<td>0.392</td>
<td>-249.592</td>
<td>-273.534</td>
<td>251.039</td>
<td>278.735</td>
</tr>
<tr>
<td>AVERAGE DG-C3</td>
<td>29.872</td>
<td>-36.902</td>
<td>0.392</td>
<td>-12.014</td>
<td>18.083</td>
<td>0.392</td>
<td>-251.465</td>
<td>-276.822</td>
<td>251.896</td>
<td>281.935</td>
</tr>
<tr>
<td>MEDIAN DG-C3</td>
<td>29.974</td>
<td>-36.194</td>
<td>0.392</td>
<td>-12.930</td>
<td>18.840</td>
<td>0.392</td>
<td>-249.278</td>
<td>-274.648</td>
<td>249.091</td>
<td>279.793</td>
</tr>
</tbody>
</table>
Chapter 5 Validation of Dynamic Equivalent Model of ADNC

Figure 5-10: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C1

Figure 5-11: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C1

Figure 5-12: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C2
Figure 5-13: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C2

Figure 5-14: Active power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C3

Figure 5-15: Reactive power responses of all cases and simulated equivalent model response using average and median values of parameters for group DG-C3
Similar discrepancy in responses during the interval 1.0-1.5 second, i.e., during the fault, was observed here as in previous set of simulations, see Figures 5-7 to 5-12. The possible reasons for this will be discussed in Section 5.3.4. From the case studies presented here, it can be seen that the model with median parameters determined from 34 case studies captures very well ADNC responses after the fault, i.e., from 1.5 second onwards in previous figures. This match is particularly important for power system dynamic studies as the interest there is in capturing system dynamics between 1.0 and 15 second after the disturbance. The reason for not so good match in responses during the fault in case of combined internal and external fault are nevertheless further explored in Section 5.3.4.

5.3.3 Estimation of model parameters using clustering procedure

Based on the case study, the proposed estimation parameters procedure have to be performed for each of the case, in order to get the dynamic equivalent models (average or median parameter values). The identification of dynamic equivalents, therefore, can be a time consuming online (or offline) task. In the best case, the process of determining the dynamic equivalent model should be quick and accurate, in order to help reduce overall computational time. Therefore, a partitioning procedure that utilises the k-means clustering algorithm to approximate the input and output dynamic responses of the network is also tested. The k-means clustering procedure was used because it is conceptually simple, widely implemented and is probably the most popular clustering procedure used by researchers [177].

By grouping together similar dynamic responses, the clustering procedure is presumed to significantly reduce the computation time required to approximate the
dynamic response of ADNC. The accuracy of the procedure is quantified by analysing the deviation of the DiGSILENT response from the approximated cluster centres shown in the following sub-section. The computational efficiency of the approach is compared against parameter estimation without clustering, and the resulting approximation errors and computational improvements highlighted later.

5.3.3.1 k-means clustering algorithm

The k-means algorithm is a clustering method which aims to partition a data set into different groups called clusters. These clusters may be consistent in terms of similarity of its members. For \( n \) observations of dataset, the k-means algorithm will partition them into \( k \) clusters which are fixed \textit{a priori} [178]. As an example, for a set of observations \( \{x_1, x_2, \ldots, x_n\} \) (where each observation is a \( d \) dimensional vector) the aim of k-means is to assign each observation to a cluster, so as minimising the within cluster sum of squares, as shown in (5-1).

\[
\arg \min_{\mathcal{K}} \sum_{i=1}^{k} \sum_{x_j \in \mathcal{K}_i} \|x_j - \mu_i\|
\]

(5-1)

where \( \mathcal{K} \) is the set of \( d \) dimensional cluster centres, and \( \mu_i \) is the mean of the points in the \( i \) th cluster centre. The algorithmic implementation for k-means used in this work is available in the MATLAB programming environment.

5.3.3.2 Clustering power traces

From the case study in Section 5.2, the active power and reactive power responses of ADNC at Bus 1 were used as inputs to the k-means clustering algorithm. The active power and reactive power values at Bus 1 were re-sampled across the 10 second trace window into 10 ms increments to form two observation vectors with 1000 measurements. Each case study created a set of active power, reactive power, voltage
and frequency traces across the 10 second time interval at Bus 1. Each of these reactive power \((q_i \in P)\) and active power vectors \((p_i \in P)\) were then combined into one single vector \((x_i \in X)\) with 2000 elements.

The k-means algorithm was then applied to the set \(X\) to partition the set into a group of \(k\) clusters, which were selected initially. Each grouping can be labelled with a centroid or mean point [178]. The cluster centroid defines a representative location in \(d\) dimensional space for all the members of that particular cluster. This location can be used as an approximation for all of the values in the cluster.

In the k-means clustering algorithm, the number of cluster, \(k\) has to be set \textit{a priori}. Therefore, selecting the \(k\) is a trade off between the error in the approximation and the speed improvement of the dynamic simulation gained by reducing the number of clusters. A greater number of clusters results in a more accurate classification of the dynamic responses. In this research, 4 clusters were selected to group the 34 scenarios. This number was chosen by analysing the graphical grouping of the clusters (as shown in Figure 5-16) to ensure that obvious differences in the traces were incorporated into each approximation. The distribution of the average absolute difference in both reactive and active power can also be used as a guide (as shown in (5-2)) to select the number of clusters.

\[
e_j(x_i) = \frac{1}{d} \sum_{m=1}^{d} |x_{j,m} - k_{j,m}|
\]

where \(x_{j,m}\) is the \(m\)th element of the \(d\) dimensional vector representing active and reactive power in the \(j\) th cluster, and \(e_j(x_i)\) is a scalar measurement of the accuracy of the \(x_i\) fault scenario.
The distribution of the per unit error \( e_j(x_j) \) across various numbers of clusters is shown in Figure 5-16. Figure 5-16 shows that with one cluster, the median distance across all fault scenarios to a single centroid found with k-means is 0.0023 per unit. The error \( e_j(x_j) \) shown in Figure 5-16 will decline to zero if 34 clusters were selected with k-means, as this would represent an individual centroid for each of the 34 considered scenarios. Figure 5-16 shows that 4 is a reasonable choice for the number of clusters as 3 clusters has a median average error 67% larger, with little change between the median error reduction with 5 clusters (or more clusters). (Note: the red cross symbols in the Figure 5-16 represented the outliers).

Figure 5-17 to 5-20 show the approximated centroids (thick dotted lines) and the active and reactive power responses respectively when they are grouped into four clusters using k-means. Table 5-8 shows how the clustering procedure partitions each of the 34 different fault scenarios.

![Figure 5-16: The distribution of the average per unit error across various numbers of clusters obtained with k-means.](image-url)
Chapter 5: Validation of Dynamic Equivalent Model of ADNC

Figure 5-17: The approximate centroids (centroid 1 and 2) and actual of active power responses achieved when grouping the active power responses into four clusters using k-means.

Figure 5-18: The approximate centroids (centroid 3 and 4) and actual of active power responses achieved when grouping the active power responses into four clusters using k-means.

Figure 5-19: The approximate centroids (centroid 1 and 2) and actual of reactive power responses achieved when grouping the reactive power responses into four clusters using k-means.
Figure 5-20: The approximate centroids (centroid 3 and 4) and actual of reactive power responses achieved when grouping the reactive power responses into four clusters using k-means.

Table 5-8: Cluster groups of the 34 simulated fault scenarios.

<table>
<thead>
<tr>
<th>Fault Location</th>
<th>DG Composition</th>
<th>Static Load Model</th>
<th>Assigned Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>T1</td>
<td>I, P, Z &amp; ZIP</td>
<td>1</td>
</tr>
<tr>
<td>F2</td>
<td>T1</td>
<td>I, P, Z &amp; ZIP</td>
<td>3</td>
</tr>
<tr>
<td>F3</td>
<td>T1</td>
<td>I, P, Z &amp; ZIP</td>
<td>4</td>
</tr>
<tr>
<td>F4</td>
<td>T1</td>
<td>I, P, Z &amp; ZIP</td>
<td>4</td>
</tr>
<tr>
<td>F5</td>
<td>T1</td>
<td>I, P &amp; ZIP</td>
<td>3</td>
</tr>
<tr>
<td>F5</td>
<td>T1</td>
<td>Z</td>
<td>4</td>
</tr>
<tr>
<td>F1</td>
<td>T2, T3, T5 &amp; T6</td>
<td>ZIP</td>
<td>1</td>
</tr>
<tr>
<td>F1</td>
<td>T4 &amp; T7</td>
<td>ZIP</td>
<td>2</td>
</tr>
<tr>
<td>F4</td>
<td>T2, T3, T4, T5, T6 &amp; T7</td>
<td>ZIP</td>
<td>4</td>
</tr>
<tr>
<td>F1 (M1)</td>
<td>T1</td>
<td>ZIP</td>
<td>1</td>
</tr>
<tr>
<td>F4 (M2)</td>
<td>T1</td>
<td>ZIP</td>
<td>4</td>
</tr>
</tbody>
</table>

5.3.3.3 Parameter estimation for 4 cluster centroids

Table 5-9 shows the grey-box model parameter values for each of the 4 cluster centroids. A quick comparison of the parameter values in Table 5-9 with those presented in Table 5-4 shows that the grey box parameter values for the cluster centroids are within the parameter ranges for the individual cluster members. For example, cluster 4 represents faults at bus 3, 4 and 5 (see Table 5-9) and has a P1 value
of -29.9 which is within the range reported in Table 5-4 for F3 (-19.0 to -40.5), F4 (-20.4 to -37.1) and F5 (-21.9 to -36.0).

Table 5-10 presents the best fit values for the estimated model parameters of each cluster compared against the DiGSILENT dynamic response. The best fit percentages range from 81% to 93% as opposed to 80% to 94% when the parameters are estimated for each of the 34 disturbances individually (Table 5-3).

Table 5-9: The estimated parameter values for each of the 20 grey-box model parameters obtained when estimating parameters using the 4 cluster centroids.

<table>
<thead>
<tr>
<th>CASES</th>
<th>PARAMETERS</th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>P4</td>
<td>P5</td>
<td>P6</td>
<td>P7</td>
<td>P8</td>
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<td>P10</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>-37.903</td>
<td>0.025</td>
<td>-5.430</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-7.078</td>
<td>-10.138</td>
<td>-5.882</td>
<td>4.263</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>-38.492</td>
<td>0.025</td>
<td>-6.016</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-7.455</td>
<td>-10.138</td>
<td>-5.551</td>
<td>4.713</td>
</tr>
<tr>
<td></td>
<td>P11</td>
<td>P12</td>
<td>P13</td>
<td>P14</td>
<td>P15</td>
<td>P16</td>
<td>P17</td>
<td>P18</td>
<td>P19</td>
<td>P20</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>30.669</td>
<td>-34.422</td>
<td>0.392</td>
<td>-18.791</td>
<td>25.037</td>
<td>0.392</td>
<td>-231.659</td>
<td>191.627</td>
<td>233.030</td>
<td>196.463</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>27.398</td>
<td>-33.249</td>
<td>0.392</td>
<td>-19.241</td>
<td>24.432</td>
<td>0.392</td>
<td>-231.359</td>
<td>190.640</td>
<td>230.948</td>
<td>195.578</td>
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<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>P4</td>
<td>P5</td>
<td>P6</td>
<td>P7</td>
<td>P8</td>
<td>P9</td>
<td>P10</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>-36.400</td>
<td>0.025</td>
<td>-5.080</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-2.947</td>
<td>-10.138</td>
<td>-12.980</td>
<td>12.754</td>
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<td>Cluster 4</td>
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<td>0.025</td>
<td>-5.683</td>
<td>-0.080</td>
<td>-0.984</td>
<td>-10.560</td>
<td>-1.984</td>
<td>-10.138</td>
<td>-18.999</td>
<td>17.952</td>
</tr>
<tr>
<td></td>
<td>P11</td>
<td>P12</td>
<td>P13</td>
<td>P14</td>
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<td>P16</td>
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<td>P20</td>
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<td>Cluster 3</td>
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<td>-4.764</td>
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<td>-223.544</td>
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<td>0.392</td>
<td>-5.548</td>
<td>9.784</td>
<td>0.392</td>
<td>-294.120</td>
<td>-357.664</td>
<td>294.516</td>
<td>362.709</td>
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</table>

Table 5-10: Best fit value of estimated model for clusters 1 to 4.

<table>
<thead>
<tr>
<th>CLUSTER</th>
<th>BEST FIT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P RESPONSE</td>
</tr>
<tr>
<td>1</td>
<td>88.17</td>
</tr>
<tr>
<td>2</td>
<td>88.28</td>
</tr>
<tr>
<td>3</td>
<td>80.67</td>
</tr>
<tr>
<td>4</td>
<td>81.59</td>
</tr>
</tbody>
</table>
5.3.3.4 Graphical comparison of results

Figure 5-21 to Figure 5-24 shows three comparisons of the active and reactive power dynamic response for four specific disturbances. The graphs compare the DiGSILENT dynamic response of the network (straight line) against an estimated model built for a specific disturbance (dotted line) and an estimated model built using a cluster centroid (dashed line).

Figure 5-21 to 5-24 show that the differences between a disturbance specific grey-box model and a grey-box model based on cluster centroids are very small. Hence, the grey-box models clearly approximate the network’s dynamic response with a high level of accuracy. This supports the results given in Table 5-9 and Table 5-10, which showed little difference in the estimation accuracy of a grey-box model based on both cluster centroid and disturbance specific.

Figure 5-21: The active and reactive power response of a disturbance at fault location 1, composition 1 and ZIP load model compared against an estimated response for this specific disturbance and the estimated response obtained from cluster 1.
Chapter 5

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Figure 5-22: The active and reactive power response of a disturbance at fault location 1, composition 4 and ZIP load model compared against an estimated response for this specific disturbance and the estimated response obtained from cluster 2.

Figure 5-23: The active and reactive power response of a disturbance at fault location 5, composition 1 with constant P load model compared against an estimated response for this specific disturbance and the estimated response obtained from cluster 3.
Figure 5-24: The active and reactive power response of a disturbance at fault location 4, composition 1 and a motor load model compared against an estimated response for this specific disturbance and the estimated response obtained from cluster 4.

5.3.3.5 Computational performance

As mentioned before, by clustering the dynamic responses before performing parameter estimation, it is presumably possible to reduce the computational complexity of the proposed grey-box modelling. Thus, it is crucial to quantify the increase in computational performance that can be achieved with the technique.

Estimating the grey-box model parameter values for a disturbance specific grey-box model took 2 minutes to compute using the MATLAB System Identification Toolbox. Estimating the parameter values for a grey-box model based on a cluster-centroid takes the same length of time. Clustering the dynamic responses takes roughly 10 ms. Performing clustering before parameter value estimation therefore reduced this simulation by 60 minutes (i.e., for disturbance specific model, $34 \times 2 = 68$ minutes compared to $(0.1 \times 4) + (4 \times 2) = 8.4$ minutes for clusters using clustering methods). This represents a reduction in computational time of 88%.
It should be noted that calculations were carried out on a Pentium 4 2.8 GHz workstation, running Matlab 7.7. Both the clustering and parameter value estimation were carried out using Matlab’s internal functions.

5.3.3.6 Analysis of the results

Tables 5-9 to 5-10 and figures 5-21 to 5-24 visually show that the estimated cluster centroids and disturbance specific grey-box models are nearly identical in terms of estimation accuracy. It was hypothesised that the clustering procedure would be as accurate as disturbance specific parameter estimation; the results do seem to support this assertion. The accuracy of the technique is maintained by intelligently grouping together similar dynamic responses, rather than changing the grey-box model estimation procedure. Indeed, Tables 5-9 and 5-10 show that the parameter values obtained using the cluster centroid estimation procedure reside within the same range as those parameters found for a disturbance specific grey box model.

By including the clustering procedure in the parameter estimation process, the overall computational time of the dynamic equivalent identification task has been significantly reduced. Clustering the data before parameter estimation ensures that parameter estimation is run once for four specific cases, rather than 34 times for each specific disturbance. The number of parameter value estimations has been reduced by about 88%.

5.3.4 The Effect of Connecting Transformer impedance on ADNC responses

From Figures 5-8 to 5-15, it can be seen that the amplitude of the responses during the disturbance is different for an external fault, i.e., fault at bus 1 (F1) from that in case
of fault inside the ADNC (F2-F5). The differences are presumed to be caused by the transformer impedance which affected the amplitude of responses during the disturbance. Therefore, a further investigation was performed to study the source of the problem. The investigation was done by performing simulations with different transformer impedance settings for T5 composition and faults at buses 2 to 5 (F2 to F5), as tabulated in Table 5-11.

Table 5-11: The test setting for transformer impedance

<table>
<thead>
<tr>
<th>Test</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test A</strong>&lt;br&gt;Fault impedance ( (Z_F) ) = initial fault impedance ( (Z_{F_{o}}) )</td>
<td>Transformer impedance ( (Z_T) ) = 0.1% of initial transformer impedance ( (Z_{T_{o}}) )&lt;br&gt; Transformer impedance ( (Z_T) ) = 50% of initial transformer impedance ( (Z_{T_{o}}) )</td>
</tr>
<tr>
<td><strong>Test B</strong>&lt;br&gt;Fault impedance ( (Z_F) ) = 25% of initial fault impedance ( (Z_{F_{o}}) )</td>
<td>Transformer impedance ( (Z_T) ) = initial transformer ( (Z_{T_{o}}) )&lt;br&gt; Transformer impedance ( (Z_T) ) = 0.1% of initial transformer ( (Z_{T_{o}}) )</td>
</tr>
</tbody>
</table>

(Note: \( Z_{T_{o}} \) is the transformer impedance in the previous case studies which is 21% impedance and \( Z_{F_{o}} \) is the fault impedance applied in previous case studies which is 2.15+j2.15 p.u. The fault impedance is selected such that the remaining voltage during the fault at the Bus 1 is ~0.5p.u. [167])

Figures 5-25 to 5-28 illustrate the responses of active and reactive power measured at bus 1 for the F4 disturbance and for test A and test B, to demonstrate the transformer impedance effect. Note that the responses for the remaining disturbances appear to be the same as the F4 disturbance.
Figure 5-25: Active power response of T5 composition and F4 disturbance for test A

Figure 5-26: Reactive power response of T5 composition and F4 disturbance for test A

Figure 5-27: Active power response of T5 composition and F4 disturbance for test B
Based on Figures 5-25 and 5-26, it can be observed that the transformer impedance is influencing the amplitude of ADNC responses during the disturbance. The lower transformer impedance leads to a higher fault current level. Consequently, higher active and reactive power was measured during the fault compared to the initial measurement (denoted as T5 F4 in the figures).

For test B (refer to Figures 5-27 and 5-28), the higher total impedance (transformer impedance and fault impedance) during faults caused a higher fault current level. Thus higher active and reactive power was observed during the fault compared to the initial measurement (T5 F4) and measurements in test A (refer to Figures 5-25 and 5-26). The different fault durations observed in Figure 5-25 to 5-28 are due to the different setting of transformer protection used in the simulations.

Based on these results, it can be concluded that the transformer impedance at the point of connection of the ADNC is highly significant for the accuracy of estimated dynamic responses during the fault. The estimation of parameters of the equivalent model of an ADNC, therefore, should be performed based on measurements at the
lower voltage side of the connecting transformer for better representation of ADNC responses to internal faults.

5.3.5 Probability Density Function (PDF) Analysis

The scope of this sub-section is to evaluate the estimated parameter values of the proposed equivalent model by means of PDF analysis. This analysis attempts to categorise the estimated parameter values into PDF distribution types. Based on Table 5-4, a PDF analysis of parameter values was done for each parameter. Each of model parameters are distributed into PDF, based on the range of parameters value. Examples of PDF plots are shown in Figures 5-29 to 5-31 for each group (G1, G2 and G3).

From Figures 5-29(a), 5-30(a) and 5-31(a), it can be clearly seen that the PDF can be formed into a normal distribution type. However, some are hardly able to form any probabilistic distribution type, as shown in Figures 5-29(b), 5-30(b) and 5-31(b). Therefore, only some of the estimated parameter values have normal distribution; other parameters can not be categorised into any distribution type.

Figure 5-29: The PDF of parameter values of P11(a) and P17(b) for group G1
In order to gain a better perspective of the performance of the developed model, a further investigation was undertaken to quantify the model’s responses in small signal studies. Eigenvalue analysis was carried out for that purpose. The eigenvalue plot provides the information of the dynamic behaviour of a power system under different characteristic frequencies or modes.

Figure 5-32 shows the eigenvalue plots of the test network and grey-box model in the s-plane. The circle represents the modes of the test network (T1 composition), the crosses represent the modes of the median parameter and the squares represent the modes of the average parameter. It can be seen from the figure that all the eigenvalues of the developed models (with median and average parameters) are stable. The modes with median model parameters are closer to the actual network modes than the modes with average model parameters.
with average model parameters. It can be concluded, therefore, that both, median and average model parameters are adequate to represent the ADNC in small disturbance stability studies.

![Figure 5-32: The eigenvalue plot of the T1 composition (circle) and median parameter (cross) and average parameter (square) in the s-plane](image)

### 5.4 Parameter Sensitivity Analysis

This section presents the sensitivity analysis of model responses to parameter values in order to provide a perspective of the influence of each model’s parameter on its output signal variation. A sensitivity analysis of the grey-box model parameters was performed to study the effect of each parameter variation (uncertainty) on the system responses. The analysis was done by varying each parameter ±20% of its median G3 value and observing the output responses. The 20% increase and decrease of each parameter was arbitrarily chosen to represent inaccuracies in model parameters and to carry out parameter sensitivity study. The median G3 value is chosen as it represented faults at all buses. The sensitivity analysis was conducted to identify the critical model
parameters to whose identification more attention should be paid if fine tuning of model parameters is required.

From the observed responses, it can be concluded that parameters $P_1$, $P_3$, and $P_{12}$ influenced to a certain extent the amplitude and oscillation of the active power response as shown in Figure 5-33, whilst parameters $P_1$, $P_3$ and $P_{15}$ affected the amplitude and oscillation of the reactive power response (refer to Figure 5-34). Parameter $P_9$ contributed to shifting the responses up and down, as shown in both Figures 5-33 and 5-34 (represented by the dotted line).

![Figure 5-33](image1.png)

**Figure 5-33:** The effects of parameters $P_1$, $P_3$, $P_9$ and $P_{12}$ on the active power response

![Figure 5-34](image2.png)

**Figure 5-34:** The effects of parameters $P_1$, $P_3$, $P_9$ and $P_{15}$ on the reactive power response
The amplitude and oscillation of the active power response was influenced by the change of the parameter P17 and P19 simultaneously (refer Figure 5-35). The amplitude of the active power response increased as the P17 and P19 increased. P18 and P20 had the same influence as above on the reactive power response (Figure 5-36). Parameters P7, P10, P11 and P14 have very small effect on the overall response as shown in Figure 5-37 and 5-38. Parameters P2, P4, P5, P6, P8, P13 and P16 do not contribute to the change of response and can be set to fixed values.

Figure 5-35: The effects of parameters P17 and P20 on the active power response

Figure 5-36: The effects of parameters P18 and P20 on the reactive power response
Figure 5-37: The effects of parameters P7, P10, P11 and P14 on the active power response

Figure 5-38: The effects of parameters P7, P10, P11 and P14 on the reactive power response

Based on the results, it can be observed that parameters P1, P3, P12, P15 and P17 are the most influential on model dynamic response and need to be carefully adjusted during the estimation procedure. These parameters do not represent actual physical values of any single IM or SG even they are basically developed from those components. Their influence on overall dynamic response of the model will increase with the increase in share of dynamic load and distributed generation in ADNC. A detailed analysis of ADNC network performance for a specific case study is required in order to fully explore the influence of these parameters on model dynamic responses.
The analysis presented above is useful for pinpointing which parameters of the model need to be improved and carefully selected during the estimation procedure. Parameter P1, P3, P12, P15, P17 & P19 and P18 & P20 are determined as the important parameters of the developed model and further improvement of the model need to look more carefully into estimating these parameters.

5.5 Typical model parameters for different network configurations

This section attempts to formulate a look-up table for the range of parameter values of the ADNC model parameters for different network topologies and configuration based on the obtained estimated parameters value (refer Table 5-4 and 5-6). Table 5-12 and 5-13 present the typical model parameters for different fault locations, i.e., fault outside and fault inside ADNC respectively. On the other hand, Table 5-14 to 5-16 tabulated the parameters value range of typical model for different ADNC DG types. Table 5-14 presents the typical model parameters for ADNC network that contains all DG types. For ADNC network which only contained SG and CCG, the typical model parameters are tabulated in Table 5-15. Lastly Table 5-16 shows the typical model parameters for ADNC with SG, DFIG and/without CCG.

Table 5-12: Typical model parameters for fault outside of ADNC

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<tbody>
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</tr>
<tr>
<td>-----</td>
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<td>-0.025 to -3.5417</td>
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<td>-0.080</td>
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<td>-0.984</td>
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<tr>
<td>-10.560</td>
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<tr>
<td>-12.8964 to -10.138</td>
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<td>-12.8964</td>
</tr>
<tr>
<td>-10.138</td>
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<th>P16</th>
<th>P17</th>
<th>P18</th>
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Table 5-13: Typical model parameters for fault inside of ADNC

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<th>P4</th>
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<td>-10.560</td>
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<td>to</td>
<td>-19.5068</td>
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<tr>
<td>-19.0462</td>
<td>-3.22031</td>
<td>to</td>
<td>-0.80</td>
<td>to</td>
<td>-10.560</td>
<td>to</td>
<td>-10.138</td>
<td>to</td>
<td>to</td>
<td>-8.57471</td>
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Table 5-14: Typical model parameters for ADNC with all DG types

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<td>-19.0462</td>
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<td>to</td>
<td>to</td>
<td>-0.80</td>
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<td>to</td>
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Table 5-15: Typical model parameters for ADNC with SG and CCG

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<td>-30.171</td>
<td>-6.364</td>
<td>to</td>
<td>to</td>
<td>-0.80</td>
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Table 5-16: Typical model parameters for ADNC contained SG, DFIG with/without CCG

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<th>P2</th>
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<td>-0.984</td>
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<tr>
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</thead>
<tbody>
<tr>
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<tr>
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<td>-227.397</td>
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Based on Tables 5-12 to 5-16, simulations were performed using a sample set of parameters value for each network configuration to evaluate the performance of the proposed typical model parameters. The set of parameters are shown in Table 5-17. Figures 5-39 to 5-43 show the simulated active and reactive power response for a set of typical model parameters for each network composition and composition as shown in Table 5-17. The equivalent model responses are compared with the simulated responses using full ADNC model. From these figures, it can be seen that the model responses obtained using set of parameters (SET 1 to 5) corresponding to respective network configurations are within the range of responses for each group. Thus, it can be concluded that the proposed typical model parameters adequately represent the dynamic characteristics of the ADNC.

Figure 5-39: The active and reactive power response of SET 1 from Table 5-12 compared against all the responses for fault outside of ADNC.
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Figure 5-40: The active and reactive power response of SET 2 from Table 5-17 compared against all the responses for fault inside of ADNC.

Figure 5-41: The active and reactive power response of SET 3 from Table 5-17 compared against all the responses for ADNC composition of all DG types.

Figure 5-42: The active and reactive power response of SET 4 from Table 5-17 compared against all the responses for ADNC composition of SG and CCG.
Figure 5-43: The active and reactive power response of SET 5 from Table 5-17 compared against all the responses for ADNC composition of SG, DFIG with or without CCG.

Table 5-17: Typical model parameters for ADNC contained SG, DFIG with/without CCG

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<th>SET 1 (typical model parameters for fault outside of ADNC)</th>
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</tr>
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<td>-36.5</td>
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<table>
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<td>P11</td>
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<td>29.5</td>
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<table>
<thead>
<tr>
<th>SET 3 (typical model parameters for ADNC with all DG types)</th>
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<td>P1</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>-30.6</td>
</tr>
<tr>
<td>P11</td>
</tr>
<tr>
<td>31.6</td>
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</table>

<table>
<thead>
<tr>
<th>SET 4 (typical model parameters for ADNC with SG and CCG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
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<tr>
<td>-----</td>
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<tr>
<td>-31.8</td>
</tr>
<tr>
<td>P11</td>
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<tr>
<td>29.9</td>
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<table>
<thead>
<tr>
<th>SET 5 (typical model parameters for ADNC contained SG, DFIG with/without CCG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>-29.9</td>
</tr>
<tr>
<td>P11</td>
</tr>
<tr>
<td>28.5</td>
</tr>
</tbody>
</table>
5.6 Conclusions

This chapter revolves around the identification and validation of the dynamic equivalent model of ADNC based on the grey-box approach. The accuracy of the equivalent model was evaluated through calculation of the best-fit value using numerous case studies involving static and dynamic load models, various fault locations and different DG composition in the network. The main interest was in establishing the range of responses of ADNC depending on its structural composition.

A k-means clustering process has been also applied to model parameter estimation in order to improve the computational efficiency of estimation process. The results obtained indiscernible from the original proposed grey-box parameter estimation procedure and closely approximate the dynamic response of the ADNC. The pre-processing of responses, i.e., application of k-means clustering process, though significantly reduces the time needed for parameter estimation.

Based on the sensitivity analysis carried out, it was found that some parameters have little effect on the model responses and can be set to fixed generic values. A few parameters though, have a large influence on the output response, and these parameters need to be carefully tuned in order to get the best fit of the model responses and actual network responses.

Finally, the last part of the chapter presented typical model parameters for different network topologies and configurations. Simulations with these parameters confirmed that the proposed typical parameter values can be used in equivalent model of ADNC to adequately represent responses of ADNC of respective compositions.
As a general conclusion, the system identification theory based on grey-box approach was well suited to model the ADNC for both steady state and dynamic system studies.
6 Application of ADNC Model in Power System Stability Studies

6.1 Introduction

This chapter presents the application of the developed model in a large power system. The main objective here is to validate the effectiveness and accuracy of the developed equivalent ADNC model for large system studies. Validation is the process of determining the degree to which a model is an accurate representation of the active system from the perspective of the intended uses of the model. Various forms of validation can be identified: conceptual model validation, data validation and operational validation [103]. The operational validation is considered in this research to determine if a model’s output behaviour has sufficient accuracy for the model’s intended purpose. The purpose of the equivalent ADNC model is to represent the dynamic behaviour of ADNC in steady state and transient analysis studies of large
power system networks. Therefore, the application in a large power system is essential to evaluate the model performance. As model validation aims at obtaining reasonable models to represent the actual behaviour of a power system, it was essential to validate models against actual measurements or known benchmark behaviour. The process of model validation does not necessarily mean a “perfect” match between the measured and simulated responses, but rather an adequate match that clearly demonstrates capturing the relevant dynamics, and proper representation of the system’s dynamic response.

6.2 Multi-machine Power System

6.2.1 Power System Description

In order to validate the effectiveness and accuracy of the developed model, a validation test was performed using the transmission system test network shown in Figure 6-1. The system is the modified IEEE nine bus transmission system, which includes three generators and three large static equivalent loads connected in a mesh transmission network through transmission lines. A static load (load GB), a 33 kV bus (Bus 1-33 kV) and a transformer (T4) were added to the original IEEE nine bus system [179], as shown in Figure 6-1. The detailed parameters for this test network are given in Appendix D. In the validation test, the load GB was first replaced by the full ADNC network and then by the developed equivalent model.
6.2.2 Power System Simulations with Full ADNC Model

Figure 6-2 shows the input and output responses of the test network recorded at bus 1-33 kV following a three phase self clearing fault at bus 9 with load GB modelled as constant PQ static load. Figure 6-3 shows the input and output responses at the same bus when load GB is replaced by the full ADNC model. The full ADNC model used was the T1 composition which is the SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load model. It can be seen, by comparing corresponding responses from these figures, that there are large differences in the input and output responses obtained with different models of the load/network at bus 1-33 kV.
6.3 Power System with Equivalent ADNC Model

6.3.1 Implementation of Equivalent ADNC Model in DiGSILENT PowerFactory Software

DIgSILENT PowerFactory software provides a feature to integrate the MATLAB files into the DIgSILENT software. The integration provides the opportunity
to model controller or very complex transfer functions and insert them as a block
definition into a frame in DIgSILENT transient simulations [180]. DIgSILENT software
can interact with the MATLAB program during simulation. It will transfer the input
values of a block into MATLAB for every time step, which will then simulate a
specified *.m file in its own environment and give back the results as the outputs of a
block definition, as shown in Figure 6-4. The specified *.m file is an interface to the
Simulink model and is used as a middle layer in communication between DIgSILENT
and MATLAB.

![Diagram](image)

Figure 6-4: Integration of MATLAB files in DIgSILENT PowerFactory software

In this research, the integration is needed to implement the grey-box equivalent
model in the simulation of a large power system. The grey-box equivalent model is
formed in MATLAB/Simulink, as shown in Figure 6-5. Note that ‘fehz’ is the
frequency and ‘u’ is the voltage. Figure 6-6 shows the frame and block definition in
DIgSILENT used for this purpose. ‘Pext’ and ‘Qext’ are the outputs, which are the
active and reactive power from the Simulink model that are applied in the DIgSILENT
environment. All the relevant files for the implementation of equivalent ADNC model
in DIgSILENT PowerFactory environment are given in Appendix E.
6.3.2 Small Disturbance Study

For the purpose of model validation, the test network with the full ADNC network model and developed equivalent model connected at bus 1-33kV was subjected to small disturbances, i.e., the step increase in load and the step decrease in generator torque. The simulations with the full ADNC model were performed with the following ADNC composition: T1 composition of DG from Table 5-1, which is SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load model. The simulation with the equivalent model used corresponding median values of parameters for G3
(refer to Table 5-4). Figure 6-7 to 6-8 show active and reactive power responses at bus 1-33 kV with the full (solid line) and equivalent (dashed line) ADNC model.

In both figures, it can be seen clearly that the responses from the developed equivalent model match very closely, if not excellently, those observed using the full ADNC model under small disturbance studies.

Figure 6-7: Active and reactive power responses for small disturbance (decreased G3 torque)

Figure 6-8: Active and reactive power responses for small disturbance (increased Load C)


6.3.3 Large Disturbance Study

For the model validation in the large disturbance study, the test network with the full ADNC network model and developed equivalent model connected at bus 1-33kV was subjected to large disturbances, i.e., the 500 ms single phase fault, the 500 ms three phase fault and load disconnection. The simulations with the full ADNC model were performed with the following ADNC composition: T1 composition of DG from Table 5-1, which is SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load model. The simulation with the equivalent model used corresponding median values of parameters for G3 (refer to Table 5-4). Figures 6-9 to 6-12 show active and reactive power responses at bus 1-33 kV with the full (solid line) and equivalent (dashed line) ADNC model.

![Graph of active and reactive power responses for large disturbance (single phase fault at bus 9)](image)

Figure 6-9: Active and reactive power responses for large disturbance (single phase fault at bus 9)
Figure 6-10: Active and reactive power responses for large disturbance (three phase fault at bus 9)

Figure 6-11: Active and reactive power responses for large disturbance (three phase fault at bus 13)

Figure 6-12: Active and reactive power responses for large disturbance (disconnection of Load A)
It can be clearly seen from these figures that the large disturbance responses obtained with the equivalent model provided a good match those obtained with the full ADNC model.

### 6.3.4 Fixed Fault Validation

For fix fault validation, the disturbance applied was a three phase self clearing short circuit fault at bus 9. The simulations were performed for different combinations of ADNC compositions and estimated model parameters, as shown in Table 6-1. Figures 6-13 to 6-15 illustrate the results of simulations.

**Table 6-1: Test Setting for Fixed Fault Validation**

<table>
<thead>
<tr>
<th>TEST</th>
<th>Full ADNC model</th>
<th>Greybox model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST 1</td>
<td>T1 composition</td>
<td>T1 estimated parameters</td>
</tr>
<tr>
<td>TEST 2</td>
<td>T1 composition</td>
<td>Median G3 parameters</td>
</tr>
<tr>
<td>TEST 3</td>
<td>T5 composition</td>
<td>Median G3 parameter</td>
</tr>
</tbody>
</table>

![TEST 1](image1)

**Figure 6-13:** Active and reactive power responses for fix fault validation (TEST 1)
It can be seen that the responses with the equivalent model with different parameters match very well the responses obtained with the full ADNC model under different DG compositions. This confirms the robustness of the model and its ability to represent ADNC for various network structures and compositions. From Figure 6-9 to 6-15, it can be observed that there are no transients during the fault (1-1.5 second). This is because the developed model does not account for electromagnetic transients in...
machines while the DiGSILENT simulation results were obtained with full nonlinear
dynamic models of all components of the network without any simplifications.

6.3.5 Generators (G1, G2 and G3) response under same fault

Previous sections presented the validation results for the developed equivalent
model observed at the ADNC point of connection, i.e., bus 1-33kV. This section and the
section afterwards will demonstrate the validation results of the developed equivalent
model recorded at different generators under various faults and fault locations. As for
this section, the results for generators (G1, G2 and G3) response under the same fault
are presented. Figures 6-16 to 6-18 show the active power responses of generators G1,
G2 and G3 following the same fault (three phase self-clearing short circuit at bus 9)
using the full ADNC model (T1 composition) and equivalent grey-box model (median
G3 and average G3 parameters). The T1 composition of DG as shown in Table 5-1,
which is SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load
model. The full ADNC model responses are represented by solid lines and the median
and average parameter responses by dotted and dashed lines respectively.

![Figure 6-16: Active power responses of G1](image-url)
The figures show a negligible differences between the median and average model responses as compared to the response with the full ADNC model. Thus it confirmed that either median or average parameters can represent the ADNC network very well.
6.3.6 Generator G3 response under various faults and different fault locations

A number of simulations were performed to validate the generator G3 response under various faults and different fault locations. For various faults, the generator G3’s response were observed for small and large disturbance. Figures 6-19 to 6-21 show the active power responses of generator G3 following the small disturbance (increase load C) and large disturbance (single-phase fault at bus 9 and disconnection of Load A) using the full ADNC model (T1 composition) and equivalent grey-box model (median G3 and average G3 parameters). As before, the T1 composition of DG is SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load model.

The full ADNC model responses are represented by solid lines and the median and average parameter responses by dotted and dashed lines respectively. From all figures, it can be seen clearly that both median and average model’s response almost perfectly match those obtained with the full ADNC model. The median model responses shown better accuracy than the average model response. The figures confirm that either median or average parameters can represent the ADNC network very well and both models work well in both small and large disturbance studies.
Figure 6-19: Active power responses of G3 for small disturbance

Figure 6-20: Active power responses of G3 for single-phase fault at bus 9

Figure 6-21: Active power responses of G3 for disconnection of Load A
Three simulations were performed to observe the developed equivalent model performance under different fault locations. Figures 6-22 to 6-24 show the active power responses of generator G3 following the various fault location (three phase self-clearing short circuit at bus 10, bus 11 and bus 14) using the full ADNC model (T1 composition) and equivalent grey-box model (median G3 and average G3 parameters). As before, the T1 composition of DG is SG (4.5 MW), FSIG (3.0 MW), DFIG (3.0 MW), CCG (0.5 MW) and ZIP load model. The full ADNC model responses are represented by solid lines and the median and average parameter responses by dotted and dashed lines respectively.

Based on the observed results in all figures, it can clearly seen that the median and average models can captured all the dynamic characteristics for different fault location. Thus both models can represent the ADNC under various fault location studies.

Figure 6-22: Active power responses of G3 for fault at bus 10
6.3.7 Eigenvalue plots

In order to evaluate the developed equivalent model performance under small disturbance stability, eigenvalue plots in s-plane are given. Figures 6-25 and 6-26 show the eigenvalue plots for the network with constant Load PQ, full ADNC model, median...
G3 and average G3 parameters. From the figures, it can be observed that both networks with median and average parameters are stable. The stable oscillatory modes are identified for both median and average model parameters. Modes with average parameters are less damped than those obtained using median parameters. The eigenvalues of the system with median model parameters are closer to eigenvalues of the full ADNC model than the eigenvalues of the system with average model parameters. In both cases however, this representation is much better than the representation with constant PQ load and slightly more conservative compared to full ADNC model representation.

Figure 6-25: Eigenvalue plot for network with constant load PQ (circle), network with full ADNC model (red cross) and network with median parameters (green cross)
Figure 6-26: Eigenvalue plot for network with constant load PQ (circles), network with full ADNC model (red crosses) and network with average parameters (green crosses)

6.4 Conclusions

This chapter described the application of the developed equivalent model in a representative, sufficiently large (for this purpose) power system. Various comparisons between simulations with equivalent ADNC model and simulations using full ADNC model for different events were performed. The observations (monitoring of responses) were carried out at the ADNC point of connection and at different generators within the transmission network, for various fault events (small and large disturbances) and different fault locations. It has been found that the matching of the simulation results obtained with the equivalent ADNC model and the simulation results obtained with the full ADNC model is very good for both small and large disturbance studies. The use of both, median and average model parameter values results in almost perfect match of equivalent ADNC model responses with those obtained using full ADNC model. In most cases, the median values of parameters led to better accuracy than the average model parameters. Such good correspondence between the equivalent model responses
(for a number of different operating conditions) and “recorded” disturbances in the network greatly increases confidence in the adequacy of the developed equivalent model of ADNC.
7 Conclusions and Future Work

7.1 Conclusions

Several original and important contributions are presented in this thesis. The proposed dynamic equivalent model for active distribution network cell (ADNC) takes into account different DG compositions and fault locations, and can be applied in both small and large disturbance system studies. The model was developed using the grey-box approach within system identification theory. The research also proposes parameter estimation procedure that can be applied for identification of the ADNC dynamic equivalent model.

The thesis first, presents an overview of DG technologies and DG penetration level worldwide. Distribution network becomes active when DG units are added in appreciable number to the network. The active distribution network, or rather part of it,
Conclusions and Future Work

called ADNC in this thesis, is then discussed as well as Microgrids (MG), as special case of ADNC. The MGs are considered as an ADNC in this thesis due to the similar concept and structure. Detailed overview of past methodologies for development of equivalent dynamic models of part or whole power network is presented with clear identification of advantages and disadvantages of each of those. This detailed overview represents the first contribution of the research.

The literature review concluded that conventional dynamic equivalent methods cannot be applied to a distribution network with distributed generation as this is no longer a ‘passive’ network. With the increasing penetration of DG at the distribution network level, the network becomes active and the need for a new dynamic equivalent model becomes vital. Therefore, the system identification theory approach seems more practical and can be used for the development of an equivalent model. The approach offers a measurement-based application, from which a dynamic equivalent model can be derived without detailed knowledge of the network. Hence a preliminary model of ADNC has been developed based on a combination of Prony analysis and the nonlinear least square optimisation. The model is in a simple second-order transfer function form and primarily for use in small signal stability studies. The accuracy of the initial model was evaluated by computing the RMSE values. The results obtained gave a significant confidence in the applicability of the model in small signal stability studies. This steady state model of ADNC represents the first original contribution of the research.

This preliminary model is then extended and improved using the grey-box approach. The grey-box approach was chosen as having greater potential to significantly improve the accuracy of the ADNC model than the black-box approach, as the structure of the system is generally known. The adopted model structure represents the dominant composition of the ADNC and leaves the mismatch part of the system to be
approximated by an optimisation method. This model, based on the assumed configuration of ADNC, consists of a converter-connected generator in parallel with a composite load model. The model was developed in MATLAB software in the form of a seventh-order state space model, which makes it readily adaptable to other power system software environments, i.e., it is flexible with respect to future development. This is the second original contribution of the research.

The parameter estimation procedure used to identify model parameters adopts system identification theory and measurement-based techniques incorporating the nonlinear least square optimisation. The estimation procedure was fully developed and operated using the MATLAB System Identification Toolbox.

Next, the investigations using numerous case studies were carried out with different configurations of ADNC and different fault locations to produce a possible range of ADNC responses. The accuracy of the equivalent model was evaluated and validated by comparing equivalent model responses with those obtained using simulations with full non-linear model of ADNC in DlgsILENT PowerFactory. In order to decrease the computational time for the dynamic equivalent identification task, the k-means clustering algorithm was included in this procedure. By clustering the dynamic responses before performing the parameter estimation procedure, the computational time was reduced by 88%. The estimated accuracy between both procedures (with and without the clustering algorithm) is about the same. In other words, the estimated accuracy for the clustering algorithm is as accurate as the disturbance specified parameter estimate. This cross validation of parameter estimation techniques presents the third original contribution of this research.
Further analysis and investigations were carried out on the developed equivalent model. This included development of probabilistic density function of model parameters, sensitivity analysis of the estimated model parameters, the effect of transformer impedance and the eigenvalue analysis of the developed equivalent model. From the obtained probabilistic density functions for estimated parameters, it can be concluded that the estimated parameters hardly form any distribution type. On the other hand, the sensitivity analysis found that some parameters have little effect on the model outputs and therefore can be set to fixed values. A few parameters have a large influence on the variation of output response, and these parameters need to be carefully tuned in order to get the best estimated parameters for the developed equivalent model. The eigenvalues of the developed equivalent model shows that the critical modes of the model are stable and very close to the modes of the full non-linear ADNC model. The investigation into transformer impedance effects verified that dynamic simulations are influenced significantly by transformer impedance. The modelling of ADNC should be therefore performed at the lower side of the transformer for better representation, i.e., the responses during disturbance should be recorded at the lower voltage side of the transformer. These analyses and respective conclusions drawn represent the fourth original contribution of the research.

Based on the findings of case studies and the estimated model parameters, a set of look-up tables containing the typical model parameters for different network topologies and configurations were derived. Simulations with a set of parameter values, based on the typical model parameters, confirmed that the proposed typical model parameters adequately represented the corresponding composition and composition of ADNC. The set of identified typical values represents the fifth original contribution of this research.
An application of the developed equivalent model in a large power system is also presented in the thesis. The aim was to validate the effectiveness and accuracy of the equivalent ADNC model. Its application in a large power system was essential for justifying the overall ADNC's modelling purpose, i.e., to be able to represent the dynamic behaviour of ADNC in steady state and transient analysis studies of large power systems. A modified IEEE nine-bus system was used as the test system for this purpose. The overall model of the system was developed in DIgSILENT PowerFactory environment to facilitate validation and demonstrate applicability of developed equivalent model of ADNC in commercial power system simulation software. Comparisons of the performance of the test system with distribution network model by constant PQ model and the test system with the developed equivalent model were made initially in order to evaluate the effectiveness and accuracy of the equivalent ADNC model. Various simulations were carried out afterwards with the equivalent ADNC model, including small and large disturbance, fixed model validation test, fixed fault validation test and eigenvalue analysis. The simulation results obtained with the equivalent ADNC model matched excellently those obtained using full ADNC model for both small and large disturbance studies. This high level of agreement between the two sets of results greatly increased confidence in the validity of the developed model. The adaptation of the developed equivalent model of ADNC for the use in DIgSILENT PowerFactory environment for large system studies and its validation represents the sixth original contribution of the research. This particular contribution has also a very practical value as DIgSILENT PowerFactory model can be readily used by other researchers working in this area and using DIgSILENT PowerFactory in their studies.

Finally, the major advantages of the developed dynamic equivalent model of ADNC and corresponding parameter estimation procedure are that it is of a low order
and that its parameters are estimated using “measurement-based” approach without the need for detailed information about the distribution network beforehand. Moreover, the developed grey-box equivalent model has more physical meaning than black-box model as it incorporates to a large extent the ADNC structures and compositions and is more easy to develop than white-box model as detailed knowledge of the ADNC is not required. The low order of the model and its demonstrated accuracy greatly facilitate large power system stability studies incorporating active distribution networks of the future.

### 7.2 Suggestion for Future Work

This thesis proposed a dynamic equivalent model for ADNC. As always, there are many interesting aspects that could be further investigated and potentially improved.

One of the key aspects for further model improvement is the parameter estimation procedure. As the nonlinear least square optimisation tended towards the local minimum, other modern optimisation methods, such as the genetic algorithm, particle swarm optimisation, etc., which can identify more accurately a global minimum, can be applied, in order to improve accuracy of estimated parameters and ultimately the accuracy of the model.

As mentioned in previous sections, the sensitivity analysis was carried out; the results showed that some of the model parameters have no influence on the model’s outputs and can be set to fixed values. Even though the developed model is of low order, further analysis and study need to be carried out on these model parameters in order to explore the possibility of the equivalent model order reduction.
The robustness of estimated model parameters and in particular proposed values of parameters for characteristic ADNC composition can also be further explored. This can be done by performing very large number of case studies with many more possible ADNC compositions and with different directions of power flows between ADNC and the grid. These could lead to probabilistic evaluation of some if not all model parameters.

Finally, the modelling approach and parameter estimation procedure presented in the thesis could be also applied to model the plug-in electric vehicles (PEV) since they can be considered as both, ‘moving-load and generation’.
REFERENCES


References


<table>
<thead>
<tr>
<th>Reference</th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal/Citation Details</th>
</tr>
</thead>
</table>


References


References


APPENDIX A : ADNC STEADY STATE MODEL

MATLAB code for ADNC steady state modelling

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%PRONY ANALYSIS FOR INITIAL ESTIMATE OF PARAMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Load response’s file
L=load('sg204.dat');
[o,q]=size(L);
load30=L(1:o,2);
t=L(1:o,1);

% Find the initial point of disturbance
load30sifar=load30(1);
E=(100.05/100)*load30sifar;
for i=1:o
    if load30(i)>=E
        yline=load30(i);
to=t(i);
        break;
    end
end

% Sizing the new range of data
power=load30(i:o);
time=t(i:o);
[aa,bb]=size(time);
powerstable=power(aa)
powerstart=load30(1)
K=powerstable-powerstart
plot(time,power);
hold

inputsignal=power(1:aa);
masa=time(1:aa);
timestart=masa(1)
% plot the actual response
plot(masa,inputsignal,'r')
title('Input Signal')
xlabel('Time')
hold off

% Apply prony
step=masa(2)-masa(1);
fs=1/step;
N=6;
[inumz,idenz]=prony(inputsignal,N,N);

% Compute and plot the impulse response of the Prony approximating system
[iapp,tapp]=impz(inumz,idenz,length(masa),fs);
[r,p,k]=residuez(inumz,idenz);
spoles=log(p(:))*fs;
%values for function form \([K-A*\exp(-B*t)\sin(C*t+D)]\)
amp=(abs(r)); %A value
damp=real(spoles); %B value
phase=1./real(spoles); %D value in rad
omega=(imag(spoles)); %C value in rad

%RESPONSES COMPARISON

%load actual response
A=load('all load 5.dat');
[a,b]=size(A);
power=A(1:a,2);
time=A(1:a,1);

plot(time,power,'b');
hold
plot(tout,ystep,'--r','LineWidth',2); %response from Simulink Parameter Estimation
axis([1 5 13.96 14.16]);
xlabel('time (sec)','FontSize',20);
ylabel('active power (MW)','FontSize',20);

h = legend('actual from DIgSILENT','estimated response',4);
set(h,'Interpreter','none','FontSize',20);
hold off

%COMPUTE RMSE
err=(ystep-power).^2;
rmse=sqrt(mean(err));
APPENDIX B : ADNC GREY-BOX MODEL

MATLAB code for ADNC Grey-box modelling

%load inputs data
gg=load('P_T7_F1.dat');
ZZ=103;
[m,n]=size(gg);
power1=gg(ZZ:m,2);

ee=load('Q_T7_F1.dat');
[o,p]=size(ee);
Q1a=ee(ZZ:o,2);

ff=load('V_T6_F1a.dat');
[q,r]=size(ff);
volt1=ff(ZZ:q,2);

hh=load('F_T6_F1.dat');
[s,t]=size(hh);
freq1=2*pi*hh(ZZ:s,2);
masa1=ff(ZZ:q,1);

%Function file for Grey-box model

Function [dx,y]=gbmodelPQ(t,x,u,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11,P12,
P13,P14,P15,P16,P17,P18,P19,
P20,varargin)

% EQUATION (4.44)
% output equation (y)
y=[P11*x(1)+P12*x(4)+P13*x(7)+P17*u(1)+P19;
P14*x(1)+P15*x(4)+P16*x(7)+P18*u(1)+P20];

% state equation (dx)
dx=[P1*x(1)+P7*u(1);
x(3)+P8*u(1)-u(2);
P2*x(1);
P3*x(4)+P9*u(1)+P10;
P4*x(4)+P5*x(5);
x(5);
P6*x(7)];

% Setting initial parameters
FileName='gbmodelPQ';
Order=[2 2 7];
Parameters=[-37.473;0.025;-4.570;-0.080;-1.984;-10.56;-8.94;-10.138;-4.16;3.253;27.733;-30.8;0.392;-18.994;28.186;0.392;-228.074;
189.585;229.947;195.379];
InitialStates=[0;0;0;0;0;0];
Ts=0;
nlgr=idnlgrey(FileName,Order,Parameters,InitialStates,Ts);

% prepare for iddata
dnetPQ=iddata([power1,Q1a],[volt1,freq1],0.01);
%estimate parameter
PF5=pem(dnetPQ,nlgr);

%plot results
compare(dnetPQ(1:350),PF5);
    h1=subplot(211);axis([0 3.5 -5 95]);xlabel('time (sec)','FontSize',20);ylabel('active power (MW)','FontSize',20);title('');
    h2=subplot(212);axis([0 3.5 -5 95]);xlabel('time (sec)','FontSize',20);ylabel('reactive power (MVar)','FontSize',20);title('');
APPENDIX C : GENERATOR DATA OF ADNC STUDY SYSTEM

DFIG wind turbine data (FSIG data shown in brackets)

Generator parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated stator power</td>
<td>1.27 [1.514] MW</td>
</tr>
<tr>
<td>Rated stator voltage</td>
<td>690 V</td>
</tr>
<tr>
<td>Rated rotor voltage</td>
<td>1945 V</td>
</tr>
<tr>
<td>Machine inertia</td>
<td>84.08 kgm2</td>
</tr>
<tr>
<td>Rated DC-link voltage</td>
<td>1200 V</td>
</tr>
<tr>
<td>Stator/rotor connection</td>
<td>Y/Δ</td>
</tr>
<tr>
<td>Equivalent circuit parameters (in Ω), per-phase, stator-referred</td>
<td></td>
</tr>
<tr>
<td>Stator resistance</td>
<td>0.00562</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>0.00575</td>
</tr>
<tr>
<td>Stator leakage reactance</td>
<td>0.0708</td>
</tr>
<tr>
<td>Rotor leakage reactance</td>
<td>0.0486</td>
</tr>
<tr>
<td>Magnetising reactance</td>
<td>3.188</td>
</tr>
</tbody>
</table>

Turbine parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Total Inertia</td>
<td>3715979 kgm2</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>70 m</td>
</tr>
<tr>
<td>Gearbox ratio</td>
<td>90</td>
</tr>
<tr>
<td>Minimum speed</td>
<td>11.11 rpm</td>
</tr>
<tr>
<td>Maximum (nominal) speed</td>
<td>20 [18] rpm</td>
</tr>
<tr>
<td>Low-speed shaft (LSS) stiffness</td>
<td>274 MNm/rad</td>
</tr>
<tr>
<td>LSS damping</td>
<td>502.4 kNms/rad</td>
</tr>
</tbody>
</table>

PI controller parameter

Power (slower) loop, $K = 1.8$, $T = 0.1$s, Current (faster) loop, $K = 0.3$, $T = 0.01$s.

6MW (SG1) synchronous machine data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$ [pu]</td>
<td>0.00777</td>
</tr>
<tr>
<td>$X_d$ [pu]</td>
<td>2.782</td>
</tr>
<tr>
<td>$X_q$ [pu]</td>
<td>1.37</td>
</tr>
<tr>
<td>$X'_d$ [pu]</td>
<td>0.326</td>
</tr>
<tr>
<td>$X'_q$ [pu]</td>
<td>1.11</td>
</tr>
<tr>
<td>$X''_d$ [pu]</td>
<td>0.227</td>
</tr>
<tr>
<td>$X''_q$ [pu]</td>
<td>0.322</td>
</tr>
<tr>
<td>$T'_{do}$ [s]</td>
<td>3.69</td>
</tr>
<tr>
<td>$T''_{do}$ [s]</td>
<td>0.053</td>
</tr>
<tr>
<td>$T'_{dq}$ [s]</td>
<td>0.85</td>
</tr>
<tr>
<td>$T''_{dq}$ [s]</td>
<td>0.166</td>
</tr>
<tr>
<td>$H$</td>
<td>3</td>
</tr>
</tbody>
</table>

AVR of SG1 – Simplified excitation system (SEXS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_A$</td>
<td>4</td>
</tr>
<tr>
<td>$T_B$</td>
<td>20</td>
</tr>
<tr>
<td>$K$</td>
<td>400</td>
</tr>
<tr>
<td>$T_e$</td>
<td>0.1</td>
</tr>
</tbody>
</table>

1.5MW (SG2), synchronous machine data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a$ [pu]</td>
<td>0.012</td>
</tr>
<tr>
<td>$X_d$ [pu]</td>
<td>1.85</td>
</tr>
<tr>
<td>$X_q$ [pu]</td>
<td>1.11</td>
</tr>
<tr>
<td>$X'_d$ [pu]</td>
<td>0.277</td>
</tr>
<tr>
<td>$X'_q$ [pu]</td>
<td>1.11</td>
</tr>
<tr>
<td>$X''_d$ [pu]</td>
<td>0.161</td>
</tr>
<tr>
<td>$X''_q$ [pu]</td>
<td>0.209</td>
</tr>
<tr>
<td>$T'_{do}$ [s]</td>
<td>1.618</td>
</tr>
<tr>
<td>$T''_{do}$ [s]</td>
<td>0.029</td>
</tr>
<tr>
<td>$T'_{dq}$ [s]</td>
<td>0.85</td>
</tr>
<tr>
<td>$T''_{dq}$ [s]</td>
<td>0.08</td>
</tr>
<tr>
<td>$H$</td>
<td>0.5</td>
</tr>
</tbody>
</table>
AVR of SG2 – Simplified excitation system (SEXS)

<table>
<thead>
<tr>
<th>$T_A$</th>
<th>$T_B$</th>
<th>$K$</th>
<th>$T_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>20</td>
<td>400</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Induction motor parameters:

<table>
<thead>
<tr>
<th>Rating [kW]</th>
<th>Rated voltage [V]</th>
<th>Rated speed [rpm]</th>
<th>$R_{\text{stator}}$ [pu]</th>
<th>$X_{\text{stator}}$ [pu]</th>
<th>$R_{\text{rotor}}$ [pu]</th>
<th>$X_{\text{rotor}}$ [pu]</th>
<th>$X_{\text{mag}}$ [pu]</th>
<th>$H_g$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>415</td>
<td>1470</td>
<td>0.0228</td>
<td>0.0508</td>
<td>0.0204</td>
<td>0.1372</td>
<td>2.76</td>
<td>0.4</td>
</tr>
<tr>
<td>200</td>
<td>415</td>
<td>742</td>
<td>0.0108</td>
<td>0.0704</td>
<td>0.012</td>
<td>0.1602</td>
<td>2.253</td>
<td>0.465</td>
</tr>
</tbody>
</table>
APPENDIX D : MODIFIED IEEE 9 BUS SYSTEM

Original data are taken from [179]. Modifications to network parameters are highlighted in bold. The system base is 100 MVA. Bus 6 is the slack bus.

Generator data

<table>
<thead>
<tr>
<th>Generator</th>
<th>Bus Type</th>
<th>$P$ [MW]</th>
<th>$Q$ [Mvar]</th>
<th>Rated MVA [MVA]</th>
<th>Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>SL</td>
<td>0</td>
<td>0</td>
<td>247.5</td>
<td>1.0</td>
</tr>
<tr>
<td>G2</td>
<td>PV</td>
<td>163</td>
<td>0</td>
<td>192.0</td>
<td>0.85</td>
</tr>
<tr>
<td>G3</td>
<td>PV</td>
<td>85</td>
<td>0</td>
<td>128.0</td>
<td></td>
</tr>
</tbody>
</table>

Generator dynamic data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.1460</td>
<td>0.0969</td>
<td>0.608</td>
<td>0.0969</td>
<td>0.0336</td>
<td>8.96</td>
<td>0.535</td>
</tr>
<tr>
<td>G2</td>
<td>0.8958</td>
<td>0.8465</td>
<td>0.1198</td>
<td>0.1969</td>
<td>0.0521</td>
<td>6.00</td>
<td>0.600</td>
</tr>
<tr>
<td>G3</td>
<td>1.3125</td>
<td>1.2578</td>
<td>0.1813</td>
<td>0.25</td>
<td>0.0742</td>
<td>5.89</td>
<td>0.600</td>
</tr>
</tbody>
</table>

Busbar data

<table>
<thead>
<tr>
<th>Busbar</th>
<th>Nominal Voltage [kV]</th>
<th>Voltage [p.u.]</th>
<th>$P_g$ [MW]</th>
<th>$Q_g$ [MVAR]</th>
<th>$P_l$ [MW]</th>
<th>$Q_l$ [MVAR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 6</td>
<td>16.5</td>
<td>1.025</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 7</td>
<td>18</td>
<td>1.025</td>
<td>163</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 8</td>
<td>13.8</td>
<td>1.025</td>
<td>85</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 9</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 10</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>Bus 11</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>Bus 12</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus 13</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Bus 14</td>
<td>230</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus1-33kV</td>
<td>33</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
### Transformer data

<table>
<thead>
<tr>
<th>Transformer</th>
<th>HV-Side Busbar</th>
<th>LV-Side Busbar</th>
<th>Rated Power [MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Bus 9</td>
<td>Bus 6</td>
<td>250</td>
</tr>
<tr>
<td>T2</td>
<td>Bus 12</td>
<td>Bus 7</td>
<td>200</td>
</tr>
<tr>
<td>T3</td>
<td>Bus 14</td>
<td>Bus 8</td>
<td>150</td>
</tr>
<tr>
<td><strong>T4</strong></td>
<td><strong>Bus 11</strong></td>
<td><strong>Bus1-33kV</strong></td>
<td><strong>250</strong></td>
</tr>
</tbody>
</table>

### Line data

<table>
<thead>
<tr>
<th>Line</th>
<th>From</th>
<th>To</th>
<th>$R$ [pu]</th>
<th>$X$ [pu]</th>
<th>$B/2$ [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>Bus 10</td>
<td>Bus 9</td>
<td>0.010</td>
<td>0.085</td>
<td>0.088</td>
</tr>
<tr>
<td>Line 2</td>
<td>Bus 12</td>
<td>Bus 10</td>
<td>0.032</td>
<td>0.161</td>
<td>0.153</td>
</tr>
<tr>
<td>Line 3</td>
<td>Bus 12</td>
<td>Bus 13</td>
<td>0.0085</td>
<td>0.072</td>
<td>0.0745</td>
</tr>
<tr>
<td>Line 4</td>
<td>Bus 13</td>
<td>Bus 14</td>
<td>0.0119</td>
<td>0.1008</td>
<td>0.1045</td>
</tr>
<tr>
<td>Line 5</td>
<td>Bus 14</td>
<td>Bus 11</td>
<td>0.039</td>
<td>0.170</td>
<td>0.179</td>
</tr>
<tr>
<td>Line 6</td>
<td>Bus 11</td>
<td>Bus 9</td>
<td>0.017</td>
<td>0.092</td>
<td>0.079</td>
</tr>
<tr>
<td>Line 7</td>
<td>Bus 7</td>
<td>Bus 12</td>
<td>0</td>
<td>0.0625</td>
<td>1</td>
</tr>
<tr>
<td>Line 8</td>
<td>Bus 14</td>
<td>Bus 8</td>
<td>0</td>
<td>0.0586</td>
<td>1</td>
</tr>
</tbody>
</table>
APPENDIX E : IMPLEMENTATION OF GREY-BOX MODEL IN DIgSILENT POWERFACTORY SOFTWARE

*.m file for interface between MATLAB and DIgSILENT PowerFactory

%*.m file for interface with Simulink model (GB.mdl)

function [t,x,Out1]=GB

global u fehz Out1

FileName='gbmodelPQ';
Order=[2 2 7];
Parameters=[-37.473;0.025;-5.570;-0.080;-1.984;-10.26;-6.94;-10.138;-5.16;4.253;28.733;-29.8;0.392;-17.994;27.186;0.392;-227.074;-187.585;228.947;192.379];
InitialStates=[0;0;0;0;0;0];
Ts=0;
GBmodel=idnlgrey(FileName,Order,Parameters,InitialStates,Ts);

options=simget('GB');
[t,x,Out1]=sim('GB',[],options);

DIgSILENT PowerFactory window interfaces for setting the block definition

1. Window interface for Matlab Interface block definition
2. Window interface for Load GB block definition

![Image of Load GB block definition interface]

3. Window interface for setting the Simulink model in DlgSILENT

![Image of Simulink model interface]

APPENDIX F : AUTHOR’S THESIS BASED PUBLICATIONS

Submitted international journal papers:


International Conference papers:


Technical reports: