DEVELOPMENT OF NUMERICAL ALGORITHMS FOR FERRORESONANCE MONITORING

A thesis submitted to The University of Manchester for the degree of
Doctor of Philosophy
In the Faculty of Engineering and Physical Science

2015

ZAIPATIMAH ALI

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING, THE UNIVERSITY OF MANCHESTER
## Table of Contents

Table of Contents................................................................. 2  
List of Figures................................................................. 4  
List of Tables................................................................. 9  
Abstract............................................................... 10  
Declaration............................................................ 11  
Copyright Statement.................................................... 12  
Acknowledgement....................................................... 13  

1 Introduction.................................................................. 16  
   1.1 Phenomenon of Ferroresonance.......................... 16  
      1.1.1 Difference between Linear Resonance and Ferroresonance 20  
      1.1.2 Types of Ferroresonance.......................... 31  
      1.1.3 Modes of Ferroresonance.......................... 31  
      1.1.4 The Effect of Ferroresonance.................. 34  
      1.1.5 Power System Configurations Prone to Ferroresonance 35  
   1.2 Signal Processing as a Tool For Assessing Ferroresonance 35  
   1.3 Motivation....................................................... 36  
   1.4 Research Objectives............................................ 37  
   1.5 Methodology.................................................... 38  
   1.6 Contributions.................................................... 40  
   1.7 Thesis Outline.................................................... 40  

2 Literature Survey Ferroresonance................................ 42  
   2.1 Introduction....................................................... 42  
   2.2 Critical assessment of ferroresonance generation from power transformer and voltage transformer 44  
      2.2.1 Power Transformer Cases............................. 44  
      2.2.2 Voltage Transformer Cases............................. 49  
   2.3 Assessment of ferroresonance mitigation actions for power transformer and voltage transformer 52
2.3.1 Preventive ........................................................................................................ 52
2.3.2 Mitigation of Ferroresonance ......................................................................... 54
2.4 Assessment of signal processing technique used in ferroresonance monitoring and feature extraction ................................................................. 57
2.5 Chapter Summary ............................................................................................... 60
3 Ferroresonance Modelling and Simulations .......................................................... 62
3.1 Introduction .......................................................................................................... 62
3.2 Single Phase Models ............................................................................................ 64
  3.2.1 Transformer Losses ..................................................................................... 67
  3.2.2 The EMTP Model ....................................................................................... 70
3.3 The Time Step in Simulation .............................................................................. 72
3.4 Simulation of Different Modes of Ferroresonance Signals ................................... 73
3.5 The Impact of Parameter Variations .................................................................. 77
  3.5.1 The Effect of Grading Capacitance Variation ............................................. 77
  3.5.2 The Effect of Source Voltage Variation .................................................... 79
  3.5.3 The Effect of Switching Instant Variation .................................................. 81
3.6 Chapter Summary ............................................................................................... 83
4 Signal Analysis ..................................................................................................... 85
  4.1 Fourier Transform ............................................................................................ 86
    4.1.1 Choosing the number of samples ............................................................ 88
    4.1.2 Magnitude Spectrum ............................................................................... 89
  4.2 Wavelet Domain Analysis ................................................................................ 95
    4.2.1 Wavelet Transform ............................................................................... 95
    4.2.2 Mother Wavelet (Wavelet Function) ....................................................... 96
    4.2.3 Continuous Wavelet Transform ............................................................ 101
    4.2.4 Discrete Wavelet Transform ............................................................... 104
    4.2.5 Detection of a Transient ....................................................................... 112
    4.2.6 Feature Extraction ............................................................................... 121
  4.3 Chapter Summary ............................................................................................. 143
5 Real Data Analysis ............................................................................................... 146
  5.1 Field Test Data ............................................................................................... 146
  5.2 Fourier Transform ......................................................................................... 148
  5.3 Wavelet Analysis ............................................................................................ 150
List of Figures

Figure 1.1 : Signal partitioning: Periods 1, Period 2 and Period 3.................................18
Figure 1.2 : A diagram of a simple resonance circuit....................................................21
Figure 1.3 : Graphical interpretation of a voltage across the inductor.........................22
Figure 1.4 : Resonance slope ..................................................................................23
Figure 1.5 : Simple Ferroresonance Circuit.................................................................24
Figure 1.6 : Non-linear inductance voltage and current curve.......................................25
Figure 1.7 : Ferroresonance phenomenon due to capacitance variation.......................25
Figure 1.8 : The diagram of stability points...............................................................27
Figure 1.9 : The diagram of the oscillation points .......................................................28
Figure 1.10 : An approximation of the saturation region [31]........................................30
Figure 1.11 : Current linkage with varying exponent [32].............................................30
Figure 1.12 : Fundamental mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4].......................................................32
Figure 1.13 : Subharmonic mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4].......................................................33
Figure 1.14 : Quasi-periodic mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4].......................................................33
Figure 1.15 : Chaotic mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4].......................................................34
Figure 1.16 : Research methodology..........................................................................39
Figure 2.1 : Grounded transformer is coupled through phase–to-phase capacitance [68] ...................................................................................................................45
Figure 2.2 : The energization of power transformer through coupling capacitance [41] ....47
Figure 2.3 : The 525kV transmission system between Big Eddy and John Day [71]......48
Figure 2.4 : Single line diagram of the Brinsworth /Thorpe Marsh circuit [11]..............48
Figure 2.5 : A typical ferroresonance configuration involves transformer voltage [34]......49
Figure 2.6 : A section of a typical double busbar 275kV substation [9]..........................50
Figure 2.7 : Voltage transformer connected to an isolated neutral system [74].............51
Figure 2.8 : Voltage transformer with a damping reactor [49].......................................56
Figure 2.9: Application of wavelets transform in power system [96].............................59
Figure 3.1 : Bus configuration for the Dorsey HVDC converter station [12]...................63
Figure 3.2: Voltage transformer, V13F, at the Dorsey HVDC converter station during ferroresonance [100] ................................................................. 64
Figure 3.3: System configuration for the Dorsey HVDC converter station [12] .......... 65
Figure 3.4: Bus Model [12] ............................................................................. 66
Figure 3.5: The magnetization curve of the voltage transformer ......................... 67
Figure 3.6: The hysteresis loop ........................................................................ 69
Figure 3.7: EMTP Model for Voltage Transformer [12] ....................................... 70
Figure 3.8: The EMTP model for ferroresonance circuit ....................................... 71
Figure 3.9: Ferroresonance signals (a) field recording [100] (b) simulation .......... 72
Figure 3.10: Plots of a different time step ............................................................. 73
Figure 3.11: Voltage signal for fundamental mode ferroresonance ...................... 74
Figure 3.12: Current signal for fundamental mode ferroresonance ....................... 74
Figure 3.13: Voltage signal for subharmonic mode ferroresonance ..................... 75
Figure 3.14: Current signal for subharmonic mode ferroresonance ..................... 75
Figure 3.15: Voltage signal for chaotic mode ferroresonance ......................... 76
Figure 3.16: Current signal for chaotic mode ferroresonance ....................... 76
Figure 3.17: Voltage signal for grading capacitance variation ....................... 78
Figure 3.18: Ferroresonance mode for different grading capacitance values ......... 79
Figure 3.19: Voltage signal for voltage source variation ..................................... 80
Figure 3.20: Ferroresonance mode with respect to source voltage .................... 80
Figure 3.21: Changing the system voltage ............................................................. 81
Figure 3.22: Voltage signal for various switching time .......................................... 82
Figure 3.23: Ferroresonance mode with respect to switching time, showing that the circuit is in a fundamental mode throughout the simulation .......... 83
Figure 4.1: Sustained fundamental mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum ............................................................. 90
Figure 4.2: Sustained fundamental mode ferroresonance (a) current signal (b) current magnitude spectrum ............................................................. 90
Figure 4.3: Sustained subharmonic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum ............................................................. 91
Figure 4.4: Sustained subharmonic mode ferroresonance (a) current signal (b) current magnitude spectrum ............................................................. 91
Figure 4.5: Sustained chaotic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum ............................................................. 92
Figure 4.6: Sustained chaotic mode ferroresonance (a) current signal (b) current magnitude spectrum.

Figure 4.7: Transient fundamental mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum.

Figure 4.8: Transient fundamental mode ferroresonance (a) current signal (b) current magnitude spectrum.

Figure 4.9: Transient subharmonic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum.

Figure 4.10: Transient subharmonic mode ferroresonance (a) current signal (b) current magnitude spectrum.

Figure 4.11: Transient chaotic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum.

Figure 4.12: Transient chaotic mode ferroresonance (a) current signal (b) current magnitude spectrum.

Figure 4.13: (a) Voltage signal that contains the three period (b) voltage magnitude spectrum.

Figure 4.14: Daubechies mother wavelet (a) $db2$, (b) $db3$, (c) $db4$, (d) $db5$, (e) $db6$, (f) $db10$.

Figure 4.15: Example of mother wavelets [109].

Figure 4.16: Dilated and translated mother wavelets [109].

Figure 4.17: The CWT of fundamental mode ferroresonance signal (a) voltage signal, (b) $db5$ mother wavelet, (c) time-frequency representation of the CWT, (d) 3D time–frequency plot.

Figure 4.18: Relationship between frequency and level of decompositions.

Figure 4.19: DWT of fundamental mode ferroresonance signal.

Figure 4.20: DWT Three Levels of Decomposition.

Figure 4.21: Sample signal and seven levels of $Detail$ coefficient waveforms.

Figure 4.22: Energy distribution of $Detail$ for each decomposition level.

Figure 4.23: Signal use for detection of the transient.

Figure 4.24: The detection process.

Figure 4.25: Voltage signal (black) superimposed with $Detail$ coefficients waveform (blue).

Figure 4.26: Flow chart of pre-processing to choose a mother wavelet.

Figure 4.27: Flow chart of detection process.
Figure 4.28: Feature extraction process ................................................................. 121
Figure 4.29: The Process of choosing the mother wavelet .................................. 123
Figure 4.30: Samples of analysed signals (a) fundamental (b) subharmonic (c) chaotic
1 (d) chaotic 2 (e) no ferroresonance 1 (f) no ferroresonance 2 .......................... 124
Figure 4.31: Sample signals for sustained period of ferroresonance (a) fundamental
(b) subharmonic (c) chaotic (d) no ferroresonance .............................................. 125
Figure 4.32: Flowchart of choosing the mother wavelet ....................................... 126
Figure 4.33: Percent energy plots of Detail coefficients for 21 different mother
wavelets .................................................................................................................. 129
Figure 4.34: Detail coefficients energy plots for rbior1.5, db5 and sym5 .................. 130
Figure 4.35: Flow chart of feature extraction ....................................................... 132
Figure 4.36: Voltage signal for grading capacitance variation .............................. 133
Figure 4.37: Detail coefficients energy plots using db5 mother wavelet for 72 voltage
signals .................................................................................................................... 133
Figure 4.38: Summary of sustained ferroresonance mode of Figure 3.17 by
observation ............................................................................................................. 134
Figure 4.39: The Detail coefficients energy plots for each mode: (a) fundamental, (b)
subharmonic, (c) chaotic and (d) no ferroresonance ............................................ 135
Figure 4.40: Sample signals for transient period of ferroresonance mode: (a)
fundamental, (b) subharmonic, (c) chaotic (d) no ferroresonance ......................... 137
Figure 4.41: Energy distribution for transient period of different ferroresonance mode:
(a) fundamental, (b) subharmonic, (c) chaotic, (d) no ferroresonance .................. 138
Figure 4.42: Sample voltage signals for (a) sustained period of fundamental mode and
(b) transient signal of fundamental mode ............................................................. 139
Figure 4.43: Samples of correlation waveforms of sustained fundamental mode with:
(a) transient fundamental, (b) transient subharmonic, (c) transient chaotic, (d)
 transient no ferroresonance ............................................................................. 140
Figure 4.44: Detail coefficients energy distribution for four different correlated
signals ..................................................................................................................... 140
Figure 4.45: Energy plots of Detail coefficients for correlated signals between
sustained fundamental and 72 voltage signals in Figure 3.17 using db5 mother
wavelet .................................................................................................................. 141
Figure 4.46: Energy plots of Detail coefficients for correlated signal for (a) fundamental mode (b) subharmonic mode (c) chaotic mode (d) no ferroresonance mode ..................................................................................................................................................... 142

Figure 4.47: A sample of correlated signal between a sustained subharmonic signal and a transient signal and (b) the Detail coefficient energy distribution for four different correlated signals............................................................................................................................................. 142

Figure 4.48: Energy plots of Detail coefficients for correlated signals between sustained subharmonic and 72 voltage signals in Figure 3.17 using db5 mother wavelet.................................................................................................................................................................... 143

Figure 5.1: Single line diagram of the line bay involved in ferroresonance [43] ................ 146

Figure 5.2: Field recordings of ferroresonance waveforms; phase ‘a’ (red), phase ‘b’ (green), phase ‘c’ (blue)..................................................................................................................................................................................... 147

Figure 5.3: Real recording of fundamental mode ferroresonance (a) voltage signal (b) its FFT................................................................................................................................................................................................. 148

Figure 5.4: Real recording of sustained fundamental mode ferroresonance (a) voltage signal (b) FFT................................................................................................................................................................................................. 149

Figure 5.5: Real recording of transient fundamental mode ferroresonance (a) voltage signal (b) FFT................................................................................................................................................................................................. 149

Figure 5.6: Relationship between frequency and level of decompositions ................... 151

Figure 5.7: The sustained voltage signal and the corresponding Detail coefficient waveforms for each level of decomposition........................................................................................................................................................ 151

Figure 5.8: The Detail coefficients energy plots of the sustained signals for phase a and c................................................................................................................................................................................................. 152

Figure 5.9: The transient voltage signal of phase a and the corresponding Detail coefficient waveforms for each level of decomposition........................................................................................................................................................ 153

Figure 5.10: The transient voltage signal of phase c and the corresponding Detail coefficient waveforms for each level of decomposition........................................................................................................................................................ 154

Figure 5.11: The Detail coefficients energy plots of the transient signals for phase a and c................................................................................................................................................................................................. 155

Figure 5.12: Field recording of (a) sustained signal (b) transient signal of fundamental ferroresonance mode ............................................................................................................................................................................................................................ 155

Figure 5.13: Correlated signal between sustained fundamental signal and transient fundamental signal of ferroresonance’s real recording signal .................................................................................................................................................................................................. 155

Figure 5.14: Field recordings of ferroresonance waveforms ............................................................................................................................................................................................................................................. 156
Figure 5.15: The *Detail* coefficients energy plots of the correlated signals for phase $a$ and $c$.................................................................................................................................................................................................................................................. 157

Figure 8.1: Fundamental Mode for Ferroresonance Voltage Signal.............................................. 169

Figure 8.2: First Harmonic for (a) 32, (b) 64 and (c) 128 samples per 16 ms window.......... 169

Figure 8.3: THD for (a) 32, (b) 64 and (c) 128 samples per 16 frame................................. 170
List of Tables

Table 2.1 : Ferroresonance Cases According to the System Configuration ......................44
Table 3.1 : Parameters to simulation fundamental mode ferroresonance .......................73
Table 3.2 : Parameters to simulation subharmonic mode ferroresonance .......................75
Table 3.3 : Parameters to simulation chaotic mode ferroresonance ...............................76
Table 3.4 : The range of parameters for simulations ....................................................77
Table 3.5 : Parameters for simulation 1 ........................................................................77
Table 3.6 : Parameter for simulation 2 ........................................................................79
Table 3.7 : Parameter for simulation 3 ........................................................................82
Table 4-1 : Number of samples, sampling frequencies and sampling time ....................88
Table 4.2 : Mother wavelet families and their attributes .............................................98
Table 4.3 : Results of detection time $t_1$ and coefficient values in choosing the threshold voltage ........................................................................................................117
Table 4.4 : Results of detection of 72 samples of the voltage signal .............................120
Table 4-5 : Maximum level of decomposition ................................................................127
Table 4-6 : Results of Energy Distribution ...................................................................129
Table 4.7 : Different features of ferroresonance signals .............................................131
Table 4.8 : Parameters to simulation 72 ferroresonance signals ..................................132
Table 4-9 : Simulation number for each ferroresonance mode .................................134
Table 4-10 : Features of the sustained ferroresonance signals ....................................136
Table 4-11 : Type of waveform for transient feature extraction .................................136
Table 4.12 : Parameters for simulation of the transient ferroresonance ....................137
Table 4-13 : Two types of correlated waveforms for feature extraction process ..........139
Abstract

The University of Manchester
Faculty of Engineering and Physical Science

PhD Thesis
Development of Numerical Algorithms for Ferroresonance Monitoring

Zaipatimah Ali
January, 2015

Ferroresonance is a nonlinear phenomenon that could cause damage in the power systems equipment due to a high voltage and current during its sustained period. If the system is under sustained ferroresonance for a long time, it can cause thermal damage to the equipment. Therefore, it is important to eliminate or mitigate ferroresonance. It is shown that different mode of ferroresonance gives different impact to power systems. Thus, being able to detect and classify ferroresonance according to its mode during the transient period could avoid the system from going into the sustained period by initiating appropriate mitigation or elimination procedures.

The objective of this research is to develop numerical algorithms for ferroresonance monitoring by analysing its voltage and current signals using Fourier transform and wavelet transform. The aim of this research is to provide features that can be used in the development of a real time monitoring system that may be incorporated in mitigation or elimination procedures in the future.

Ferroresonance voltage and current signals are obtained from the modelling of the ferroresonance circuit in the transient program. The sensitivity studies are performed to obtain different modes of ferroresonance and to observe the sensitivity of ferroresonance towards its initial condition and parameter variation. The signals are then being analysed using Fourier transforms and wavelet transforms to obtain features that can be used in the classification process. Both the sustained and transient periods of the ferroresonance signals are analysed. The results show that the ferroresonance voltage signals during sustained period are able to be classified according to their modes, however, the ferroresonance signals of the transient period require further analysis. The algorithms are tested on the real data and produce the similar results that validate the algorithms.
Declaration

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

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://www.campus.manchester.ac.uk/medialibrary/policies/intellectualproperty.pdf), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on presentation of Theses.
Acknowledgements

Alhamdulillah, I am grateful to Allah SWT for the opportunity that is given to me. All the hardship is paid off.

I would like to express my indebted gratitude to my supervisor, Prof. Vladimir Terzija for his outstanding support and guidance throughout my PhD studies.

Special thanks to my colleagues, especially Mr. Syed Mohammad Sadegh Mir Ghafourian, Steve Ang Swee Peng, Jairo Tortos, Happy Novanda and Ozgur Karacasu for all helps and supports that they have given me, technically and emotionally, throughout my PhD.

I would like to express my special thanks to the Universiti Tenaga Nasional, Malaysia for providing the scholarship to pursue my PhD at the University of Manchester, UK.

Last but not least, my special thanks to my beloved husband Mazlan Noor and my children Luqman Hakim, Saiful Hakim and Nadiyya Sofea. I would not have completed this thesis without their inspirations and prayers. Lastly, my countless thanks to my mother who have prayed for my success all my life until I have achieved this far. May Allah bless all of them.
Chapter 1

1 Introduction

This chapter gives an overview of this project. Problem statements, motivation and research objectives are explained. The research approach and methodology are discussed in detail. The end of the chapter tables out the outline of this thesis.

1.1 Phenomenon of Ferroresonance

Ferroresonance is a nonlinear and complex electrical phenomenon that is due to the interaction between the nonlinear characteristics of the transformer core and system’s capacitance. The system capacitance can be caused by circuit-to-circuit capacitance of parallel lines, conductor-to-earth capacitance, circuit breaker grading capacitance, busbar capacitance, bushing capacitance, etc. According to ANSI/IEEE C37.100 Standard, ferroresonance is defined as “an electrical resonance condition associated with the saturation of a ferromagnetic device, such as a transformer through capacitance” [1]. Another standard, ANSI/IEEE Std 100-1984 defines ferroresonance as “a phenomenon usually characterized by overvoltages and irregular wave shapes and associated with the excitation of one or more saturable inductors through a capacitance in series with the inductor” [2].

Ferroresonance is considered as a complex electrical phenomenon due to its unpredictable behaviour of jumping from one state to another on the same network parameters. Ferroresonance is also considered as a low-frequency transient phenomenon because when it happens, its frequency spectrum is below 2 kHz [3].

Ferroresonance is usually initiated by the changes in the network topology caused by events such as switching operations or faults occurrence or clearance. Some examples
of electrical power system configurations that are prone to ferroresonance are a voltage transformer energized through grading capacitance of one or more open circuit breakers, a voltage transformer connected to an isolated neutral system, and a transformer accidentally energized in only one or two phases. More examples and detailed discussion on other configurations are available in [4-8].

Ferroresonance may cause overvoltage and overcurrent in an electrical power system. If the system is under sustained ferroresonance for a long time, it can cause thermal damage of the equipment. This will result in overheating at some parts of the transformer as it is being repeatedly driven into magnetic saturation. Other consequences include the appearance of a continuous and excessive loud sound and structural damage of transformer windings.

In the literature, ferroresonance has been classified into different modes according to its steady state or sustained signals. Ferracci has classified ferroresonance into four modes, namely fundamental mode, subharmonic mode, quasi-periodic mode and chaotic mode[4]. However, a lot of researchers are dealing with three modes only, which are fundamental, subharmonic and chaotic mode.

The occurrence of ferroresonance and initiation of different modes are very sensitive towards parameters changes and initial conditions such as the remnant magnetic flux in a core of a power transformer [9, 10]. In addition, the nonlinearity of inductance property in the transformer gives rise to the jump phenomenon of ferroresonance from one stable state into another steady state.

Since it is a complex phenomenon, ferroresonance is becoming widely researched. The research areas related to ferroresonance range from modelling of the actual ferroresonance circuit in transient programs [11] [12], modelling the components (transformer modelling) inside the ferroresonance circuit [13, 14], understanding the behaviour of ferroresonance from chaos theory and nonlinear dynamics [15, 16], identification, detection and classification of ferroresonance signals among other transient disturbances [17-20] and finding mitigation and suppression methods to mitigate or eliminate ferroresonance[21-23].
For analysis purposes, the output signal from the simulation is partitioned into three periods; normal period, transient period and sustained period, as depicted in Figure 1.1.

**Figure 1.1 : Signal partitioning: Periods 1, Period 2 and Period 3**

Period 1, the period between 0 and $t_1$ is the time when normal operation is taking place. Period 2 is the transient period and Period 3 is the sustained period. Time $t_1$ is the time when the event causing ferroresonance phenomena happens. In this thesis, it represents the time when the circuit breaker switching operation occurred. Time $t_2$ is defined as the time when the system enters the sustained ferroresonance period. The signals in each period is described as follows: Period 1 is a normal steady state signal for $t<t_1$, Period 2 is a transient signal for $t_1<t_2$ and Period 3 is a sustained signal for $t>t_2$.

During simulation, time $t_1$ is detected using wavelet analysis, and time $t_2$ is assumed 0.5s after time $t_1$. Time $t_2$ is impossible to be determined precisely because each mode and each case produces different values of $t_2$.

The study of ferroresonance in transformers started more than 80 years ago [5]. The word ferroresonance was first used in 1907 by Bethenod when he analysed transformer resonance [3, 5]. Only in 1920 Boucherot published a work on the complex resonance oscillation in a series RLC circuit with nonlinear inductance [5]. Due to the severe impacts of ferroresonance in power systems and the increase in awareness of ferroresonance phenomena by power engineers and researchers, a working group was established by IEEE Power and Energy Society (IEEE PES)
around 2001. The working group concentrates on the practical aspect of ferroresonance in order to tackle the ferroresonance issues. The objectives of this working group are listed below [24]:

1. To give a comprehensive survey of the literature on ferroresonance
2. To provide a special publication on the subject
3. To become the point of reference for engineers and researchers regarding the issue of ferroresonance
4. To document system configurations that are prone to ferroresonance and non-ferroresonance

The initiation of ferroresonance could be due to any changes in the network topology such as transient overvoltage and temporary fault, or switching events such as fault clearing, single phase switching, energising or deenergising transformer of load or inductive elements.

The evolution in power systems has increased the complexity of ferroresonance phenomenon. For example, the increasing use of insulated ungrounded cables with high capacitance, single phase connection and disconnection, the used of MOV surge arrestors and improved low loss transformers with different magnetic response have increased the tendency for ferroresonance to occur [25].

The main characteristic of ferroresonance that concerns electrical utilities the most is the possibility of having more than one stable ferroresonance steady states for the same set of network parameters [4]. During ferroresonance, even under normal operating conditions, the response can suddenly jump from one normal steady state response to another ferroresonance steady state response. This behaviour is possible due to the nonlinear inductance inside the transformer core. Due to this nonlinearity, the response of the system is highly sensitive to the changes in system parameters and initial conditions. Even a small variation in the initial conditions such as remnant flux in the magnetic cores, switching time, losses and capacitance value can lead to a drastic change in the response of the system [26, 27].
In order for ferroresonance to occur, the system must contain at least the following elements [3, 4]:

i. A nonlinear inductance that is saturable, such as in a voltage transformer and power transformer ferromagnetic core or a reactor.

ii. A capacitance such as circuit breaker grading capacitance, conductor to earth and cable capacitance, busbar capacitance and coupling between a double circuit line, capacitor banks, bushing capacitance or capacitive voltage transformer.

iii. A voltage source which is sinusoidal.

iv. Low losses such as lightly loaded transformers and unloaded transformers. A voltage transformer is very susceptible to ferroresonance because it is lightly loaded since it only feeding voltage metering devices.

Besides the above elements, the initial conditions of the capacitor and inductor, such as initial charge on capacitance components and the level of residue flux in the magnetic core, respectively, can also influence the ferroresonance phenomena. The point in the cycle when the voltage is applied (point of wave), can also contribute to ferroresonance phenomena as discussed in [25, 28].

### 1.1.1 Difference between Linear Resonance and Ferroresonance

#### 1.1.1.1 Linear Resonance

Ferroresonance is a nonlinear resonance phenomenon that should not be confused with linear resonance. Even though both linear resonance and ferroresonance occur when capacitance and inductance in the circuit are equal, their behaviours are different. The details are discussed below.

Consider a resonance circuit that consists of a voltage source, a capacitor and an inductor as depicted in Figure 1.2. For simplicity, resistance is omitted.
Using Ohm’s Law, the voltage in the circuit is given by:

\[ V_S = V_L + V_C \]  \hspace{1cm} (1.1)

where \( V_S \) is the voltage source, \( V_L \) is the voltage across the inductor and \( V_C \) is the voltage across the capacitor.

The inductive and capacitive reactance are assumed in full absolute constant. For linear resonance, the inductance voltage is proportional to current, inductance and frequency and is written as:

\[ V_L = \omega LI \]  \hspace{1cm} (1.2)

where \( \omega \) is the frequency in radians, \( L \) is the inductance and \( I \) is the current.

The voltage across the capacitance is proportional to current and inversely proportional to frequency and capacitance. The voltage is in phase opposition to the voltage at the inductance [29], thus

\[ V_C = -\frac{I}{\omega C} \]  \hspace{1cm} (1.3)

Substituting (1.2) and (1.3) into (1.1) leads to the voltage across the inductor

\[ V_L = \omega LI = V_S + \frac{I}{\omega C} \]  \hspace{1cm} (1.4)
Equation (1.4) is a straight line equation where the slope of the line is given by

\[ \tan \varphi = \frac{1}{\omega C} \]  

Figure 1.3 shows the graphical interpretation between the voltages in the circuit. The voltage relation in equation Figure 1.4 is satisfied only by the intersection between the capacitance and inductance lines, point ‘a’ in Figure 1.3. The projection of the point on the x-axis gives the current in the circuit and the projection on the y-axis gives the voltage across the inductor.

Figure 1.3 : Graphical interpretation of a voltage across the inductor

As the capacitance decreases, the slope of the line \( V_C \) becomes steeper. As shown in Figure 1.4, the intersection of line \( V_C \) with line \( V_L \) will increase (point ‘a’ to point ‘b’) and at one point the slope of line \( V_C \) will be equal to the slope of line \( V_L \) as shown by line \( V_{C3} \).
Resonance occurs where

\[ \tan \varphi_2 = \tan \theta \]  

(1.6)

Substituting (1.5) into the left hand side of (1.6) and replacing \( \tan \theta \) leads to

\[ \frac{1}{\omega C} = \frac{\omega LI}{I} = \omega L \]  

(1.7)

Resonance occurs when capacitance reactance is equal to the inductive reactance, \( X_L = X_C \). The resonance frequency is given by

\[ \omega_{\text{resonance}} = \frac{1}{\sqrt{LC}} \]  

(1.8)

In this linear case, the resonance frequency is determined by the values of inductance and capacitance in the circuit. The possibility for the inductive reactance and capacitive reactance to match each other is very rare in a linear inductance. However, in a nonlinear inductance, as in the iron core of a transformer, the possibility for them to match is high. The resonance frequency of nonlinear resonance is not easy to determine due to the existence of more than one stable states and the jump from one state to another. The existence of an oscillation state is discussed in the next section.
1.1.1.2 Non-linear Resonance or Ferroresonance

Consider the simple LC circuit in Figure 1.2 where a linear inductance is replaced by a non-linear inductance as shown in Figure 1.5. The nonlinear inductance in the transformer that involves in ferroresonance is saturable. The iron core that is used in the transformer is a ferromagnetic material. The ferromagnetic material has the ability to retain some of its magnetic properties even though there is no more magnetic force is applied to the material.

Equation (1.1) can still be applied where supply voltage, \( V_S \) must balance the voltage across the capacitance and inductance. However, the voltage across the inductance in this case is not proportional to the current but depends on the magnetic characteristics of the iron core [29]. The inductance is written as a function of current, \( I \). Thus the voltage across the inductance is written as

\[
V_L = \omega f(I)
\]  

(1.9)

The voltage characteristic of the inductance is plotted in Figure 1.6. Due to the saturable property of the iron core, the voltage characteristics can be divided into two parts, linear and saturation. In the linear region, the voltage across the inductor is proportional to the current as for linear inductance. In the saturation region, the flux is saturated thus the voltage is not proportional to the current. In this region, the
magnetic flux in the iron core is fully aligned, where changes in current will only affect a small increase in the inductance voltage.

![Non-linear inductance voltage and current curve](image)

**Figure 1.6 : Non-linear inductance voltage and current curve**

1.1.1.3 *Impact of Capacitance Variation*

The existence of more than one stable solutions, or more than one intersection between line $V_C$ and line $V_L$ is explained in Figure 1.7.

![Ferroresonance phenomenon due to capacitance variation](image)

**Figure 1.7 : Ferroresonance phenomenon due to capacitance variation**
In this plot, the values of the system voltage $V_S$, and the characteristic of the nonlinear inductor $V_L$, are unchanged. The value of the capacitance is changed by changing the slope of $V_C$. When the capacitance decreases, the slope of the line $V_C$ becomes steeper. When the slope of the line $V_C$ becomes steeper, the voltage across the inductor increases considerably. The value of the voltage across the inductance is determined by the point of intersection between line $V_L$ and line $V_C$. When capacitance is large as represented by the line $V_{C1}$, there is only one intersection with the line $V_L$ at point ‘a’ which indicates one stable solution. When the capacitance decreased, as indicated by the line $V_{C2}$, there are three intersection points which indicated by point $1$, $2$ and $3$.

Reducing the capacitance further will produce line $V_{C3}$. For this line, the intersection only occurs at point ‘z’ in the third quadrant. This changes the direction of the current, and the voltage across the inductor and capacitor will increase greatly leading to excess voltage in the circuit. Consider the line $V_{C2}$ where there are three points of intersections with line $V_L$. In this condition, point $1$ and point $2$ represent stable states of operation while point $3$ is unstable. The stability of point $1$ and $2$ and the instability of point $3$ is explained further in Figure 1.8.

The instability point is defined as the point where the voltage decreases with the increase of current. This is not physically attainable. The plot shows that, as the source voltage is increased by a small amount from $V_{S1}$ to $V_{S2}$, the line $V_C$ is displaced upward from $V_{C1}$ to $V_{C2}$. As the source voltage increases, the current in the circuit is also supposed to increase. Thus, the current at point ‘$I$’ increases to point ‘a’, and the current for point ‘$2$’ increases to point ‘$b$’. However, the current for point ‘$3$’ decreases to point ‘$c$’, which is not physically possible. The intersection of ‘$3$’ and ‘$c$’ are unstable operating points, where the solution will not remain there during the steady state but might pass through this point during transient. Point $1$ and point $2$ are stable and exist in the steady state. Point ‘$2$’ or ‘$b$’ corresponds to a normal operation in the linear region. In this region, the flux and excitation current are within the design limits of a transformer. Point ‘$1$’ or ‘$a$’ corresponds to the ferroresonance condition. In this region, the flux in the transformer is saturated and a large excitation current occurs. The current and voltage are high at point $1$ because during ferroresonance there is no reactance. Thus, the current is only limited by the resistance in the circuit,
which results in a high voltage and/or current [30]. According to Marti [31], the system will settle at point 1 or 2, depending on the initial conditions and on the trajectory towards the final state.

Figure 1.8 : The diagram of stability points

Figure 1.9 shows the ‘jump’ or oscillation phenomena in the circuit. Due to the saturation of the inductor characteristics, there is a jump of voltage across the inductor from a smaller value, at point 2, to a higher value, at point 1. At point 2, the voltage is low and the current is lagging. At point 1, the capacitive reactance is larger than the inductive reactance resulting in a leading current. The voltage across the capacitor is higher than normal voltage, where it is the sum of the voltage across the inductor and the system voltage.
As indicated in the plot, the voltage across the inductor at point 2 is the sum of system voltage and the voltage across capacitor. The voltage across the capacitor is the length of the line between the intersection of line $V_{C2}$ with line $V_S$ and the intersection between the line $V_{C2}$ and line $V_L$, given by:

$$V_L = V_S + V_C$$

(1.10)

However, at point 1, the voltage across the inductor is the difference between the capacitor voltage and the system voltage, given by:

$$V_L = V_C - V_S$$

(1.11)

At this point, the state of oscillation from point 1 and point 2 of the circuit may cause excess voltage and current in the circuit. According to [29], at which state the point will stabilize depends on the phase of the voltage under which the circuit is switched on.
1.1.1.4 The Effect of the Nonlinear Inductance Saturation Curve

The representation of the magnetisation curve of the core in the transformer is the most important part in modelling the ferroresonance circuit [32]. For example, Rezaei-Zare shows the impacts of the core saturation curve on ferroresonance behaviour of the transformer in [10]. The accuracy of the modelling depends on the accurate description of the magnetisation curve.

A two term polynomial has been used by researches to represent the nonlinear characteristic of the iron core as indicated by the following equation

\[ i = a\lambda + b\lambda^n \]  

(1.12)

where ‘a’ and ‘b’ are the coefficients, \( \lambda \) is the total magnetic flux linkage and ‘n’ is the order of the polynomial.

The first term on the right hand side of (1.12) represents the linear region of the magnetisation curve. The second term represents the saturation region. Coefficient ‘a’ corresponds closely to the unsaturated magnetising inductance \( (a \approx 1/L) \). Coefficient ‘b’ and the exponent of the second term ‘n’ are chosen such that they provide the best fit for the saturation region. Beside the two terms polynomial, there is also three terms polynomial used by [33] to represent the nonlinear inductance in the transformer.

According to Mozaffari and Marti [31, 32], a polynomial of order eleven and less is sufficient to represent the magnetisation curve for small-capacity transformers. However, such polynomials are not suitable to represent the magnetisation characteristic of modern high capacity transformers.

Figure 1.10 shows the difference of the saturation regions with respect to the order of the second term, \( n \).
Figure 1.10: An approximation of the saturation region [31]

The dotted lines are the approximated best fit curves for \( n = 7, 9 \) and 11. The solid line is the transformer’s actual saturation curve obtained from the data. From the plot, the \( n = 11 \) line shows the best fit to the solid curve.

Figure 1.11 taken from [32], shows the different curves when the exponent value is varied between 5 and 15. Lines \( a, b, c, d \) and \( e \) represent \( n \) equals to 5, 7, 9, 11 and 15, respectively.

Figure 1.11: Current linkage with varying exponent [32]
1.1.2 Types of Ferroresonance

As for RLC circuits, ferroresonance can be categorised into two categories: a) series ferroresonance and b) parallel ferroresonance. The example of the series ferroresonance is the energization of a voltage transformer through grading capacitors of an open circuit breaker. In this case, the voltage transformer is connected between the phase and the ground.

Parallel ferroresonance can occur when there is a single phase to ground fault in an isolated neutral system. In this case, the inductance and capacitance are in parallel.

Beside series and parallel types, ferroresonance can also be split into sustained ferroresonance and transient ferroresonance. Sustained ferroresonance is similar to the second order step response RLC circuit, where there is a source that supplies the resonating phenomena. The source can come from the system voltage. Sustained ferroresonance will continue forever until the voltage source is cut off. On contrary, transient ferroresonance will decay with time as the source that supplies the resonating phenomena is a limited energy source. Such source can be the capacitance of the cable that is being separated from the network.

1.1.3 Modes of Ferroresonance

Ferroresonance can be classified into four different modes [4]. The classification refers to the steady state or sustained. The mode of ferroresonance can be identified by looking at the spectrum of the current and voltage, or by a stroboscopic image obtained from current and voltage measurements at a given point in the system. The four modes of ferroresonance are the fundamental mode, the subharmonic mode, the quasi-periodic mode and the chaotic mode [4].

Fundamental Mode

The fundamental mode is characterized by the voltage waveforms having the same frequency as the electrical system and multiple of the system frequency. The signal of
the fundamental mode is periodic. The time domain signal for the voltage and current have a period equal to the system period \( T \). The signal can contain various harmonics such as third or fifth harmonics. The spectrum of the signal is a discontinuous spectrum that consists of the fundamental frequency \( f_0 \) of the system and its harmonics \((3f_0, 5f_0, \text{etc})\). The stroboscopic image consists of a point far removed from the point representing the normal state. Figure 1.12 below shows the time domain signal, the spectrum and the stroboscopic image of the fundamental mode [4].

![Figure 1.12: Fundamental mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4]](image)

**Subharmonic Mode**

In the subharmonic mode, the current and voltage waveforms have submultiple frequencies of the power system frequency. The subharmonic mode is also periodic. The time domain signal for the voltage and current has a period of \( nT \) which is a multiple of the system period \( T \). This subharmonic can be classified as subharmonic \( n \) or harmonic \( 1/n \). Usually, the subharmonic ferroresonance are of odd order. The spectrum of the signal is a discontinuous spectrum that consists of the fundamental frequency, which is equal to \( f_0/n \); where \( f_0 \) is the system frequency and \( n \) is an integer. The system frequency \( f_0 \), therefore, becomes one of its harmonics. The stroboscopic image shows the \( n \) points of the subharmonic. Figure 1.13 below shows the time domain signal, the spectrum and the stroboscopic image of the subharmonic mode [4].
Quasi-periodic Mode

The quasi-periodic mode is not truly periodic. The spectrum of the signal is also a discontinuous spectrum. The frequencies of the spectrum consist of the frequencies in the form of \( nf_1 + mf_2 \); where \( m \) and \( n \) are integers and \( f_1/f_2 \) is not a rational real number. Figure 1.14 shows the time domain signal, the spectrum and the stroboscopic image of the quasi-periodic mode [4]. The stroboscopic image on the right shows a closed curve.

Figure 1.14: Quasi-periodic mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4]
Chaotic Mode

The chaotic mode is not periodic. The spectrum of the signal is continuous and has broadband frequencies. The stroboscopic image consists of separate points that occupy an area in the $v$, $i$ plane known as the strange attractor as shown in Figure 1.15 [4].

![Chaotic mode, showing, left: the time domain signal, middle: the spectrum and right: the stroboscopic image [4]](image)

However, most publications only classify ferroresonance into three modes: which are the fundamental, the subharmonic and the chaotic modes [34-36] [37]. This thesis deals only with these three modes.

1.1.4 The Effect of Ferroresonance

The main effect of ferroresonance is the high sustained overvoltage and overcurrent that can cause damage to equipment in a power plant including switchgear and endanger the operation personnel. The transformer voltages can increase up to several times of the normal ratings. During overcurrent, the large current can overheat the transformer windings and cause insulation breakdown. The existence of harmonic components in the voltage and current that maintain the levels of distortion could produce extremely hazardous consequences to the involved devices. All these issues could lead to a catastrophic operation condition, sometimes even to an explosion as a result of the insulation stress on the equipment.
Some of the symptoms of ferroresonance are [25] :

- Loud humming from the transformer
- Arcing over surge arrestors or phase switches on open phase
- Insulation overstress due to high current
- Transformer heating due to a high peak current and high core fluxes.

### 1.1.5 Power System Configurations Prone to Ferroresonance

There are certain configurations in power systems that are prone to ferroresonance. When the nonlinear magnetisation of an iron core in the transformer interacts with a capacitor, an oscillation is produced with an unexpected resonance frequency. Typical configurations comprise of an excited grading capacitance of a circuit breaker in series with an unloaded inductive voltage transformer. Additional power system configurations that are prone to ferroresonance include [38]:

- The energization of voltage transformer through grading capacitors of open circuit breakers
- The energization of power transformer in one or two phases through coupling capacitance with other phases
- A power transformer that is lightly loaded connected to a cable network with low short circuit power
- Traction supply transformer
- Series compensated distribution and subtransmission
- Grounded Wye-Wye Padmounted Transformer[39, 40]

The most common configurations are the first three configurations. Discussion on other configurations can also be found in [41].

### 1.2 Signal Processing as a Tool For Assessing Ferroresonance

Signal processing has become a major contribution in engineering related researches. For example, a Fourier transform has been used to find the frequency components inside a signal while a wavelet transform has been used to extract features for signal
classification. The emergence of wavelet transform applications in power systems has motivated the author to venture in applying signal processing techniques to analyse ferroresonance signals for detection and feature extraction in order to assist mitigation process. The extracted features can then be used in ferroresonance classification. This detailed study of ferroresonance signals would increase the understanding of ferroresonance behaviour from the perspective of signal quality and feature extractions. This knowledge could be used in developing a ferroresonance signal detection and classification tool, which in turn may be incorporated into ferroresonance’s mitigation and elimination process in the future.

1.3 Motivation

There are a few reasons that motivated the author to explore this research topic. The first reason is that the ability to predict the mode of sustained ferroresonance phenomena could assist a power system protection engineer to engage timely and appropriate measures to mitigate ferroresonance. Different modes of ferroresonance, such as fundamental mode and subharmonic mode give different impact to power systems. As mentioned in [42], the damaged cause by sustained fundamental mode is more severe than the subharmonic mode. The fundamental mode can have overvoltage and overcurrent that can reach between 2p.u [43] to 4p.u [44]. Sustained fundamental ferroresonance can cause a transformer to be in the saturation mode for a long time that can cause overheating. As a result, it will accelerate aging to the transformer’s insulation. The subharmonic mode also can caused damage to voltage transformer. Author in [2] reported a real case where a voltage transformer was damaged due to subharmonic mode ferroresonance. Because subharmonic mode ferroresonance has a lower voltage level and current, it did not blow out the fuses of the voltage transformer primary. Thus appropriate mitigation measures should be implemented according to the mode of ferroresonance.

There are a few mitigation or suppression methods than have been proposed in the literature such as by connecting damping resistors [23, 33], shunt reactors [21] and ferroresonance limiter circuits [45]. Among the proposed methods, damping resistor is the most effective and common method of mitigation. However, there are some issues
with connecting the damping resistor to the system. The first issue is that introducing additional resistor will increase the system losses. The second issue is a damping resistor can cause thermal damage of a VT resulted from prolonged earth fault, as described by Piasecki in [33]. In order to avoid or reduce the aforementioned issues, the damping resistors are better not to be connected permanently, but temporarily during ferroresonance period. The damping resistors should only be connected when it is necessary. The time and duration of the connection should vary depending on the severity and mode of sustained ferroresonance phenomenon. The value of the damping resistors also depend on the characteristics of the transformers and the characteristics of the circuit. Stucken in [46] reported the problem of finding the right damping circuit for all ferroresonance mode. Thus, an intelligent ferroresonance detection device would be necessary to overcome this problem.

In terms of signal processing, Wavelet Transform has not been fully utilized in analysing ferroresonance problems. There are a few researchers who have analysed ferroresonance voltage signals in terms of classifying sustained ferroresonance from other overvoltage transients [18, 19, 47, 48]. But, wavelet transform has not been used to classify different modes of ferroresonance.

Based on the reasons described above, analysing ferroresonance using wavelet transform is essential in assisting the mitigation procedure. As mentioned by Piasecki in [33], detection of ferroresonance requires intelligent signal processing. Therefore, development of a monitoring system for ferroresonance based on wavelet transform will contribute to an intelligent signal processing tools for ferroresonance detection and mitigation in the future. This idea supports the idea by Olguín-Becerril in [49].

1.4 Research Objectives

The main objective of this thesis is to provide a tool that can help improve mitigating action and to understand the mitigation process using signal processing tool by analysing the ferroresonance signals based on its mode. The intent of this research is to contribute to the development of a real time monitoring system for ferroresonance mitigation in the future. This objective is achieved by:
1. Modelling a ferroresonance circuit in a transient program to produce ferroresonance sample signals, such as voltage and current.

2. Performing sensitivity studies to produce different modes of ferroresonance due to different impact of initial conditions and parameters.

3. Analysing the voltage and current signals in terms of the frequency components in Fourier Transform and feature extraction in Wavelet transform for both transient and sustained period.

4. Showing the advantage of using wavelet transform over Fourier transform in development of ferroresonance monitoring algorithm.

### 1.5 Methodology

In achieving the research objectives, the project was divided into two main phases:

1. Phase I: modelling and simulation

2. Phase II: signal processing

The first phase involves modelling a ferroresonance circuit in a transient modeling software called Electro-magnetic Transient Program, EMTP [50]. The inputs to the software are the ferroresonance system configuration and system parameters such as the type of a transformer and its magnetization curve, the value of capacitance, source voltage and point of wave. The outputs are voltage and current signals. This research models the configuration of a voltage transformer energized through a grading capacitance. The output voltage signal from the simulation is compared with the actual voltage waveform of the ferroresonance during the disturbance in order to validate the model. The actual waveform is obtained from [12]. Then sensitivity studies are conducted by changing the parameters and initial conditions to obtain different modes of ferroresonance signals.
The second phase of this research involves performing signal processing on the output signals of the model using MATLAB [51]. Signal processing is divided into two parts; Fourier analysis and wavelet analysis. In Fourier analysis, detailed analysis of the different ferroresonance mode signals in frequency domain using the Fourier Transform is performed. Voltage and current signals for each mode of ferroresonance in the transient and sustained periods are analysed in terms of the magnitude spectrum. The aim is to provide a better understanding on the transient and sustained periods for each ferroresonance mode signals in terms of frequency components. The knowledge is important in understanding the features that will be extracted using the wavelet analysis technique in the second part of the analysis.

Wavelet transform is used for the detection of the transient inception at time $t_i$ and for the extraction of features for different modes of the ferroresonance signals. Since the
voltage and current output signals produce the same time $t_1$, only the output voltage signal is used for the detection of the transient inception.

In feature extraction, the analysis is divided into sustained signal and transient signal analysis. The sustained signal analysis uses the voltage signals while the transient signal analysis uses the transient voltage signals and correlated waveforms. The correlated waveforms are generated by correlating sustained and transient signals.

### 1.6 Contributions

The main contributions of this thesis are:

1. Modelling of ferroresonance circuit with assessments of the impact of parameter variations. The assessment of sustained voltage signals provide a graphical analysis of different modes of ferroresonance with respect to the values of the parameters.
2. Detailed understanding of different ferroresonance modes with regards to the transient and sustained ferroresonance period. This is a prerequisite to the future development of new signal processing methods for ferroresonance detection and classification.
3. Detailed understanding of ferroresonance features in the spectrum domain with regards to the spectral density of magnitude spectrums.
4. Detailed understanding of ferroresonance features in the wavelet domain with regards to the transient and sustained periods.
5. Classification of sustained ferroresonance signals according to their modes using features extraction in the wavelet domain.

### 1.7 Thesis Outline

This thesis is organised as follows.

Chapter 1 gives the introduction to the research. The problem statement, motivation, objectives and research methodology are discussed in detail. The outline of the thesis is also presented in this chapter.
Chapter 2 presents the literature review that explains the power system configurations that are prone to ferroresonance. Detailed discussion on four configurations of the generation of ferroresonance phenomenon in power transformers and voltage transformers are presented. Ferroresonance elimination and mitigations methods are also discussed in detail. Lastly, the application of signal processing tools in power system and in ferroresonance are presented.

Chapter 3 describes the modelling of ferroresonance circuit and its EMTP model. The impact of different parameters are investigated by performing various simulations on the ferroresonance model in EMTP. Different mode of ferroresonance signals are produced from these simulations.

Chapter 4 presents the signal analysis of different modes of ferroresonance signals. Frequency domain analysis is performed using Fourier Transform. Detection and feature extraction are performed using wavelet transform. Detailed analysis of transient periods and sustained periods of different modes of ferroresonance signals are presented using spectrum density. Wavelet analysis is applied in detection of the transient inception and extraction of features during transient and sustained periods of different modes of ferroresonance signals.

The analysis of a real signal is presented in Chapter 5 to validate the algorithms presented in Chapter 4. Lastly, Chapter 6 provides the conclusion of the thesis and recommendation for future work.
Chapter 2

2 Literature Survey Ferroresonance

This chapter presents literature reviews on the generation of ferroresonance phenomenon that involve power transformers and voltage transformers. Different power system configurations that are prone to ferroresonance are discussed. Extensive discussion is performed on four different configurations involving power transformers and voltage transformers. The most common mitigation and elimination methods are discussed for both power transformers and voltage transformers. The discussion of the application of signal processing in power system, ferroresonance monitoring, detection and classification are also presented in this chapter.

2.1 Introduction

In 1997, the Slow Transient Task Force of the IEEE Working Group on Modelling and Analysis of Systems Transients Using Digital Programs has published a guideline for the modelling and the analysis of ferroresonance [5]. According to this publication, the research on ferroresonance has been divided into two main areas: improving the transformer models and studying ferroresonance at systems level.

After reviewing the literature with regards to ferroresonance up to 2014, ferroresonance research area can be divided into five areas. The first area is the research on understanding the fundamental behaviour of ferroresonance. This includes the analysis of ferroresonance circuits using nonlinear dynamics and chaos [31, 32, 35, 52-55]. In nonlinear dynamic and chaos theory, the bifurcation diagram, the
Poincare plot, and the phase plane diagram [10, 56-58] are used to study ferroresonance and analyze the stability domain of ferroresonance with respect to system parameters and initial conditions.

The second research area is the modelling of ferroresonance circuits in transient programs [59, 60] which includes transformer core modelling. Extensive studies have been conducted on the accurate modelling of transformers [13, 61]. It is stated by [5, 62] that the accurate modelling of a transformer core is the most important issue in analysing ferroresonance simulations. The impact of hysteresis is also being analysed in [63, 64] to find the most accurate model components to represent real systems.

The third research area is the reported cases or examples of ferroresonance phenomenon including experimental [65] and real life cases [2, 44, 66]. Further assessment on the cases that involve power transformers and voltage transformers are discussed in detail in this chapter.

The fourth research area is the mitigation and elimination methods that have been performed to mitigate or eliminate ferroresonance. The elimination methods can be considered as preventive actions while the mitigation or suppression methods can be considered as remedy actions. Further assessment of ferroresonance mitigation actions due to power transformers and voltage transformers are discussed more detail in this chapter.

The fifth research area is the analysis of the ferroresonance signal using signal processing tools such as wavelet transforms. The wavelet transform method is used to classify power system disturbances in [67]. Wavelet transforms are also used for the detection and the classification of ferroresonance signals by distinguishing ferroresonance from other transient overvoltages.
2.2 Critical assessment of ferroresonance generation from power transformer and voltage transformer

Jacobson in [8] has categorized seven system configurations that are prone to ferroresonance as shown in Table 2.1.

<table>
<thead>
<tr>
<th>System Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1  Transformer supplied accidentally on one or two phases</td>
</tr>
<tr>
<td>Case 2  Transformer energized through the grading capacitance of one or more open circuit breakers</td>
</tr>
<tr>
<td>Case 3  Transformer connected to a series compensated transmission line</td>
</tr>
<tr>
<td>Case 4  Voltage transformer connected to an isolated neutral system</td>
</tr>
<tr>
<td>Case 5  Capacitor voltage transformer</td>
</tr>
<tr>
<td>Case 6  Transformer connected to a de-energized transmission line running in parallel with one or more energized lines</td>
</tr>
<tr>
<td>Case 7  Transformer supplied through a long transmission line or cable with low short-circuit power</td>
</tr>
</tbody>
</table>

Ferroresonance that involved voltage transformer cases are more to be found in the literature when compared to the power transformer cases. This is because voltage transformers are easier to saturate compared to power transformers due to the characteristic of voltage transformers that have lower knee points. Another reason is because voltage transformers, especially inductive voltage transformers, have a typically low thermal capacity and high accuracy due to their measuring functions. In order to obtain a high accuracy, low core losses are necessary. As a result, they also reduce its damping ability and therefore increase the possibility of ferroresonance.

2.2.1 Power Transformer Cases

This section discusses the two most common ferroresonance configurations. They are transformers supplied accidently on one or two phases and transformer connected to a de-energized transmission line running in parallel with one or more energized lines.
2.2.1.1  Transformer supplied accidently on one or two phases

One of the configurations that can cause ferroresonance is when a power transformer is supplied accidently on one or two phases. This occurs under unbalanced switching such as blown fuses or single phase switching (or single phasing) of the transformer. Both grounded and ungrounded transformers are susceptible to ferroresonance in this configuration.

Horak in [41] and Price in [68] provide detail explanations on how the ferroresonance phenomenon can establish in the three phase system. One of the configuration is shown in Figure 2.1. The figure shows how the single phasing can provide a path for ferroresonance to establish in a grounded transformer. During unbalance switching when one phase of the transformer is disconnected from the system, the transformer still can be energized through the coupling capacitance from the other two energized phases. Voltage will be induced in the open phase(s) due to the direct magnetic coupling between phase windings.

![Figure 2.1: Grounded transformer is coupled through phase-to-phase capacitance [68]](image)

This configuration can be found in pad-mounted transformers which are mainly manufactured in a five-legged wound core construction to reduce the weight. Distribution systems use five-legged core grounded wye to grounded wye pad-mounted transformers. The five-legged core transformers are constructed of four separate cores with five legs. The windings are placed around the three inner legs and no windings are placed on the two outer legs. Adjacent cores therefore have a
common winding. When one or two of the three phases are excited, there will be an induced voltage on the unexcited winding because of the common core. Detail model of the transformer can be referred to [62] and the equivalent circuit can be referred to [69]. This type of transformer is more susceptible to ferroresonance even with a shorter cable length, which do not occur in the higher-loss core transformers.

Young in [70] had performed a laboratory investigation on 13kV pad-mounted distribution transformers. In this experiment, three single phase 15kV 100-ampere load break cutouts were used to energize the test transformers from a 13kV grounded source through various cable lengths. Cable were represented by capacitors connected line to ground and the values were varied from 0.007-0.07µF, representing cable lengths from 100 to 1000 feet. High-side voltages and currents were measured with 47kV potential transformers and 69kV current transformers, respectively. Transformers with primary windings connected delta, wye grounded, wye ungrounded, and T were tested. All transformer banks were rated approximately 13kV and either 150 or 300kVA. A series of single-phase energizing and deenergising tests were performed to simulate actual operating conditions. Each switching sequence was performed from 25 to 50 times for cable lengths ranging from 100 to 5000 feet (0.007 to 0.35µF) and for secondary resistance loading from 0 to 4 percent of the transformer nameplate rating. The results showed that the cable length affects the occurrence of the overvoltages in delta-connected, ungrounded-wye and T connected primaries, especially during de-energizing.

2.2.1.2  Transformer connected to a de-energized transmission line running in parallel with one or more energized lines

Another case is the energization of power transformer in one or two phases through coupling capacitance. Consider Figure 2.3 below [41] that shows the mutual coupling between the de-energized and the energized line.
Line A is de-energized and the only load on the line is the magnetizing impedance of the transformer, $T_{xmr}$ A. This line is capacitively and inductively coupled to the energized line, line $B$, through $C_M$ and $L_M$, respectively. Thus, transformer A could be energized through the coupling capacitance $C_M$.

Dolan reported in [71], a ferroresonance incident occurred at the Big Eddy Substation of Bonneville Power Administration (BPA) near The Dalles, Oregon, USA. During the incident, a transformer with a rating of 1000MVA 525/241.5kV 60Hz Y-connected bank of autotransformers had experienced ferroresonance phenomenon. The autotransformer at Big Eddy Substation was connected to 30.5km of transmission line. There was another 525kV John Day-Oregon City line was connected in parallel and on the same right of way. The adjacent phase between the two lines was 30.5m. When the incident happened, the big Eddy line was disconnected for line maintenance. The transformer experienced sustained fundamental ferroresonance of 420kV peak, after being capacitive coupled to the 525kV John Day-Oregon City energized line around 20min. Figure 2.3 shows the transmission system between Big Eddy and John Day.
This configuration was also experimented at 400kV system in the UK by Charalambous [11, 37]. The 400kV system consists of a mesh corner substation, parallel overhead lines of approximately 37km and a feeder that has a 1000 MVA 400/275/13 kV power transformer as shown in Figure 2.4.

During the test, the disconnector X_{303} at Thorpe Marsh 400 kV substation side was open and mesh corner 3 was restored to service while the circuit breaker T10 was open at Brinsworth 275kV substation. All disconnectors and circuit breakers X_{420} at Brinsworth 400kV substation were in service. Ferroresonance was induced by performing the point-on-wave (POW) switching on the Brinsworth/Thorpe Marsh circuit using circuit breaker X_{420}. Subharmonic and fundamental mode
ferroresonance were produced during the test at different time of point of wave switching.

2.2.2 Voltage Transformer Cases

Two common cases that involve voltage transformers are voltage transformers energized through the grading capacitance of one or more open circuit breakers and voltage transformers energised through isolated neutral systems.

2.2.2.1 Transformer energized through the grading capacitance of one or more open circuit breakers

The most common case for ferroresonance that involves voltage transformer is the energization of voltage transformer through grading capacitance of an open circuit breaker. Grading capacitors are installed in parallel with each break to obtain an equal voltage distribution. The typical circuit configuration for ferroresonance in a voltage the configuration is explained Figure 2.5 [34] at one of the London substations. The voltage transformer is disconnected from the section of busbars by opening the disconnector $DS_2$. The transformer is connected to a supply by closing the disconnector $DS_1$. When the transformer is de-energised by opening the circuit breaker, ferroresonance occurs due to the nonlinear transformer core still being connected to the supply through the circuit breaker grading capacitor $C_{CB}$.

![Figure 2.5: A typical ferroresonance configuration involves transformer voltage [34]](image-url)
Another example of a voltage transformer configuration is shown in Figure 2.6 [9]. In this configuration, the disconnector $DS2$ is opened and $DS1$ or $DS3$ is closed. Ferroresonance occurs when the circuit breaker is opened and the voltage transformer is still energised though the grading capacitor $C$.

A lot of cases reported in the literature with regards to this ferroresonance configuration. Jacobson in [12] reported the Dorsey HVDC converter station experienced the ferroresonance phenomenon in one of the voltage transformers. The voltage transformer was damaged due to ferroresonance after switching operation at one of the buses. Fundamental mode ferroresonance was reported. The switching had caused the de-energized bus being energized by adjacent energized bus through grading capacitance of open circuit breakers.

Marta in [38, 43] reported voltage transformers energised through grading capacitance of open circuit breakers during commissioning of a new 400kV substation in Ireland. During the incident, two single phase inductive voltage transformers were driven into ferroresonance. The ferroresonance was initiated due to the opening of a circuit breaker. Sustained fundamental mode ferroresonance was recorded with overvoltage of 2p.u.
Bronzeado in [72] mentioned the ferroresonance of the same configuration occurred producing subharmonic mode of 16.67Hz. Tseng in [73] described the same configuration of ferroresonance in GIS producing fundamental mode ferroresonance of 2.15p.u. Quite recent case was reported in Mexico where ferroresonance occur in 400kV substation producing subharmonic 3rd mode [49].

2.2.2.2 Voltage Transformer connected to an isolated neutral system

An isolated neutral system can be found in power system auxiliaries, distribution networks in factories and distribution networks temporarily isolated. In this system, phase to ground connected voltage transformers are prone to ferroresonance because the neutral point of the systems are not grounded. One example of an isolated neutral system is the no-load energization of the wye side of a wye to delta power transformer. The delta side will “float” with respect to earth, until some load or other source of grounding is connected. Ferroresonance can occur if there is a voltage transformer connected to the delta side of the power transformer. The capacitance in this case comes from stray coupling capacitance that exists between the delta windings and earth. Figure 2.7 shows an example circuit of a voltage transformer being connected to an isolated neutral system.

![Voltage transformer connected to an isolated neutral system](image)

Figure 2.7 : Voltage transformer connected to an isolated neutral system [74]

The system consists of a balanced three-phase voltage supply \((U1, U2, U3)\), the zero sequence capacitance of a feeding cable, \(C_0\) and an inductive voltage transformer \(T\).
Momentary ground faults or switching surges can cause the voltage to be unbalanced and cause the line-to-ground voltages to rise to higher values than normal. These voltage disturbances will cause an oscillation between the grounded potential transformers and the capacitance to ground of the circuit. This can lead to ferroresonance.

Guuinic in [75] performed a full scale laboratory investigation on the three single phase ferroresonance phenomenon. The experiment consists of a power transformer with an ungrounded wye connected secondary winding, a variable grounded wye connected capacitor bank and a bank of three single phase of grounded wye voltage transformers. Ferroresonance was produced after energizing operations were performed. The response of the system was investigated by varying the value of capacitor bank and the voltage source. Fundamental and subharmonic modes ferroresonance were recorded in the investigation.

2.3 Assessment of ferroresonance mitigation actions for power transformer and voltage transformer

Ferroresonance can be managed by performing preventive and/or mitigation action. Preventive actions could eliminate ferroresonance phenomenon from occurring while mitigation actions could suppress the ferroresonance phenomenon from remaining in the sustained period that can caused catastrophic incident.

2.3.1 Preventive

Ferroresonance phenomenon can be prevented or eliminated by performing a proper switching procedure, using a transformer that has a high knee point, choosing the right type of transformer cores and windings and avoiding the configurations that are prone to ferroresonance.
2.3.1.1 Switching

Swee in [76] mentioned that ferroresonance can be prevented by avoiding switching operation that will lead to ferroresonance such as single phase switching. For example, for five-legged cable-fed grounded-wye to grounded-wye distribution transformer, three phase switching and interruption should be used in order to avoid ferroresonance [62, 70, 77].

2.3.1.2 High knee point

Another preventive measure is to use a transformer that has a high knee point. A transformer with a higher knee point of the saturation curve is less susceptible to ferroresonance compared to a transformer with a lower knee point [72]. Mork in [40] described an actual case that happened in Norway where 72 voltage transformers that have a lower knee point were damaged after the system went under temporary ungrounded after clearing a fault. The voltage transformers that have a higher knee point remained in service and experienced no damage. Mork also mentioned that the typical knee point of a voltage transformer is between 1.65p.u and 2.0p.u. The damaged voltage transformers were reported to have knee point around 1.5 p.u which allow the transformers to saturate at a lower voltage level. Thus, preventive action can be taken by choosing a voltage transformer that has a higher knee point to avoid ferroresonance from occurring.

2.3.1.3 Type of transformer core and winding

The type of transformer core design also plays an important role in preventing ferroresonance. In order to meet the specification by the utilities to reduce core loss levels, the design of modern transformers have been optimized. Walling in [39] mentioned that grounded wye-wye three phase distribution transformers with five-legged silicon steel wound core are prone to ferroresonance. In grounded wye five-legged core, there is a magnetic interphase coupling that makes it vulnerable to ferroresonance. As reported in [77], five-legged wound core transformer is more
susceptible to ferroresonance because there will always be a backfeed voltage on the open phase. The induced voltage of un-energised phase of grounded wye–grounded wye of this core type will reach 50% due to magnetic coupling to the adjacent energized phase. Ferroresonance can be prevented if other type of transformer core design is used. For example, other grounded wye transformer such as triplex or transformer banks composed of single-phase units are immune to ferroresonance because they do not have phase to phase capacitance. Mairs in [77] recommended to use only single-phase transformers or triplex core designs in three-phase transformers to create a grounded-wye grounded-wye service connection.

2.3.1.4 Avoid configuration that can lead to ferroresonance

Another preventive method is to avoid any configuration that is prone to ferroresonance. Extra measures should be taken at system design and commissioning stages to avoid the ferroresonance circuit condition such as [78]:

- To increase the phase-to-earth capacitance of the VT ferroresonance circuit by making use of a longer busbar, some cables, CVTs, CTs, and bushings capacitance.
- To connect VTs directly electrically to power transformers so that the VTs will not resonate.
- To avoid the connection of VTs to isolated sections of busbar that represent a low capacitance.

2.3.2 Mitigation of Ferroresonance

Mitigation of sustained ferroresonance is based on the system configurations that the ferroresonance is created. Mitigation methods that are applicable to voltage transformers might not be applicable to power transformers.
2.3.2.1 Power Transformer Mitigation

Tong in [78] mentioned that power transformer ferroresonance can be mitigated by the disconnection of either the transformer from the feeder or the parallel circuit excitation source that provides the energy for sustained ferroresonance. Another way of mitigating power transformer ferroresonance is that if surge arresters are fitted at the power transformer, the circuit may be re-energised from the main system and then de-energised again.

Van Riet in [79] described the mitigation of ferroresonance by mounting corrective capacitors on the low voltage side of a high voltage power transformer. This capacitors can avoid ferroresonance at the low voltage side. The elimination of ferroresonance in this case can be achieved by connecting a capacitor of 2pF to earth on the low voltage side of a power transformer.

2.3.2.2 Voltage Transformer Ferroresonance

The common mitigation methods that involved voltage transformers mentioned in the literature are to use damping resistors, damping reactor in series with resistors and active damping devices.

The most common ferroresonance mitigation method that involved voltage transformer is to use damping resistors to increase losses. One of the conditions for ferroresonance to occur is that when there are low losses. Therefore, by connecting the damping resistors, losses will increase and ferroresonance can be mitigated.

For ferroresonance that involved voltage transformers being energized through grading capacitors of open circuit breakers, one of the effective methods is to permanently connect damping resistors to the open-delta arranged auxiliary windings of a three single-phase voltage transformers. For example, this method successfully mitigate the ferroresonance at 230kV converter station in [12]. The damping resistors were permanently connected at the secondary side of the transformer.
However, not all this configuration of ferroresonance circuits can be mitigated using this method because the value of the resistor that can be inserted depends on the thermal capacity of the transformers. The value of the resistor is obtained by considering a phase-to-earth fault which generates a driving voltage equal to three times the rated voltage in the tertiary. Marta in [38, 43] and Yunge in [80] proved that the damping resistor connected at the open delta winding did not mitigate the ferroresonance in their cases. Instead, connection of damping resistors into the voltage transformer’s wye secondary circuit mitigated ferroresonance in their cases.

### 2.3.2.3 Use damping reactor

Ferroresonance phenomenon also can be mitigated by adding an appropriate damping reactor to the circuit. To prevent ferroresonance occurrence, a damping reactor could be connected to the secondary winding of the IVT. Figure 2.8 shows the connection of a damping reactor at the secondary winding of a voltage transformer. The reactor should have high impedance under normal operating conditions to eliminate power usage and minimize disturbance of the IVT measurements. Upon ferroresonance occurrence, the damping reactor reaches its saturation state earlier than the voltage transformer. Then a resistor is inserted in series to damp the ferroresonance. Parameters of damping reactor depend on the circuit parameters, ferroresonance mode, etc. Calculations of damping reactor parameters is discussed in [49].

![Figure 2.8: Voltage transformer with a damping reactor](image-url)
2.3.2.4 **Active damping device**

One of the disadvantages of using a low value of damping resistor is the risk of thermal damage of the VTs during abnormal network asymmetry resulted from prolonged earth faults. To overcome the problem, improved active damping devices have been developed. One example of the active damping device is discussed in [33]. This device uses the concept of limiting the time for which the burden is present. A positive temperature coefficient (PTC) thermistor is connected in series with the resistor to limit the time of the resistor being connected to the system.

2.4 **Assessment of signal processing technique used in ferroresonance monitoring and feature extraction**

The application of Fourier Transform (FT) in power systems is very broad. It is hard to determine when the application of FT in power system started but [81] has proved that at almost 40 years ago researchers have already applied FT in power systems, and it is still applicable whenever the analysis of the frequency component in a signal is desired. For the last few decades, the modified or improved version of Fourier Transforms such as STFT and windowed Fast Fourier Transform (FFT) [82], have been applied in power systems. Nowadays, with the emergence of wavelet transforms, some researchers have utilized both transforms in power system applications especially in detection and classification of power systems signals [83] [84]. One of the reasons for adopting both techniques is because FFT is more suited for stationary signals while the wavelet method is suited for non-stationary and transient signals. The combination of these transforms has improved the constraints faced by FT alone.

In early 1990s, the emergence of wavelet theory has enticed a lot of researches into analysing the transient and non-stationary signals [3]. This powerful tool of signal processing has been used widely in analysing non-stationary and transient signals. Such applications range from classifying and detecting of moving vehicles on the road [85], classifying snapping shrimp and whale clicks in the ocean [86], to detecting voltage disturbances in power system [87].
Wavelets analysis has been popular for some time under various names such as multiresolution analysis (MRA), and quadrature mirror filters. According to [88], the application of WT in science and technology began in 1990. The emergence of (WT) more than three decades ago in particular has increased the interest of power system engineers and researchers to apply WT in power systems problem analysis, particularly in detecting and analysing power system transient disturbances [89-93]. The main reason for this growing interest is the ability of the WT to provide the frequency resolution and also the time resolution of a signal. WT decomposes a signal into non-linear division of frequency domain, where it focuses on short time intervals for the high frequency components and long time intervals for low frequencies. This has overcome the limitation of Fourier transforms which only provides the frequency component of the signal without giving any information about when the disturbance occurs.

These characteristics of WT are the key elements to measure and present the changes in the spectral components of non-stationary and transient signals in the form of time-frequency maps. This is very much applicable to ferroresonance signals as ferroresonance signals are considered as non-stationary and transient in nature. Besides that, WT is good for transient analysis because it can divide the frequency spectrum according to identifiable frequencies, which could provide feature detection strategy for an automated transient classification system in the future.

In power system applications, WT is widely used, ranging from detection of fault location to characterisation of power system disturbance [94]. Chul Hwan Kim in [95] gives a breakdown of the application areas of the WT in power systems. Figure 2.9 below shows in detail the percentage of application areas of wavelet transforms in power systems. Power quality dominates the application area with almost 50 percent followed by power system protection. Power system transient and partial discharge are almost the same, which is around 10 percent. Condition monitoring is the least application, with only two percent.
Figure 2.9: Application of wavelets transform in power system [96]

Besides being used in detecting voltage disturbances, WT has also been introduced in detecting ferroresonance disturbances. Currently, only a small number of papers have been published on the application of wavelet transforms in ferroresonance. Mostly, the papers are on detection and classification of sustained ferroresonance signals from other transients. For example, Mokryani [17, 18, 20] uses wavelet based Kernel Fisher classifier and WT with Multi Layer Perceptron (MLP) neural network and artificial neural network in identifying ferroresonance and differentiate ferroresonance from other transients. Another author, Zhang Bo [97] has used wavelet decomposition for ferroresonance detection. Valverde in [98] used ANN to characterized fundamental mode ferroresonance and Akinci in [99] present the continuous wavelet transform of fundamental mode ferroresonance. As far as the author is concerned, there is no publication on classifying ferroresonance mode using discrete wavelet transform by feature extraction. Thus, this thesis presents an algorithm of using WT to detect the inception of ferroresonance and classify different modes of ferroresonance using feature extraction.
2.5 Chapter Summary

This chapter discusses the literature review of three key aspects of this thesis: (a) the assessment of ferroresonance occurrence in power transformers and voltage transformers, (b) the assessment of ferroresonance mitigation and elimination methods, (c) the assessment of signal processing techniques in power systems, particularly in ferroresonance monitoring and feature extraction.

A lot of configurations in power systems are prone to ferroresonance because the existence of nonlinear inductance of the power and voltage transformers and capacitances in the system. Even though ferroresonance mode has been classified into four different modes, many real cases reported either fundamental mode or subharmonic mode ferroresonance. The quasi periodic and chaotic mode only occurred at a very short period during transient but the system will settle at either abovementioned two modes of ferroresonance. The mode of ferroresonance is independent of the system configuration. For example, the configuration of voltage transformer being energized though grading capacitance of open circuit breakers, both fundamental and subharmonic modes appear during sustained period in the system.

Ferroresonance can be controlled by performing preventive and/or mitigation actions. Ferroresonance phenomenon can be eliminated by performing a proper switching procedure, using a transformer that has a high knee point, choosing the right type of transformer cores and windings and avoiding the configurations that are prone to ferroresonance. If the ferroresonance cannot be eliminated, then mitigation actions should be implemented when ferroresonance occurs. Mitigation of sustained ferroresonance is based on the system configurations that the ferroresonance is created. Mitigation methods for voltage transformers are different from power transformers. The most common mitigation method for voltage transformers is to permanently connect damping resistors at the secondary or tertiary winding of the voltage transformers. However, this method has some disadvantages and in some cases do not work. So researchers around the world are improvising the current method by developing active damping devices. However, one device cannot be used for all system configurations and it is applicable to specific system configurations. This complicates the mitigation and elimination procedures. Thus, these limitations
and issues open another area of research which to develop an intelligent device or system to mitigate ferroresonance.

The application of signal processing in analysing ferroresonance is still in its early age. This can be seen from the number of publications available related to signal processing and ferroresonance. Wavelet transform has been used to detect and classify ferroresonance from other overvoltage transient but not to classify the mode of ferroresonance. Thus, the intent of this thesis is to develop numerical algorithms for ferroresonance monitoring by analysing ferroresonance signals using signal processing tools so that it could contribute to the future development of the intelligent system.
Chapter 3

3 Ferroresonance Modelling and Simulations

This chapter is about ferroresonance modelling and simulations. The aim of this chapter is to model a ferroresonance circuit in a transient program, ATP-EMTP. A single phase model is presented. Different modes of ferroresonance signals are produced by varying some parameters. The impact of parameter variation with respect to ferroresonance mode is analysed. Three parameters; grading capacitance, voltage source and switching time are varied, and their results are analysed. The ferroresonance operating region is plotted for each case of parameter variation. These signals are used in Chapter 4 for the signal analysis.

3.1 Introduction

In the literature, many system configurations prone to ferroresonance are reported. One of the most reported cases is ferroresonance that occurs when a voltage transformer is energized through grading capacitance of open circuit breakers. This thesis focuses on this system configuration, which is adopted from [12]. According to Jacobson [12], ferroresonance phenomenon has occurred at the Dorsey HVDC converter station in Manitoba Hydro, Canada. The Dorsey 230-kV Converter Station is located north of Winnipeg in the province of Manitoba. Due to the wear and tear and lack of spare parts availability, the planning studies recommended that twenty five breakers and current transformers should be replaced and five breakers should be upgraded in the station.
The specifications of the new breakers are: (a) to have a 63.5-kA interrupting rating at -55°C Celsius and (b) be able to clear short line faults at up to 90% of the short-circuit current rating. The manufacturer proposed to install multi-head breakers with two breaks per phase and 1500 pF of grading capacitance across each break in order to meet these specifications. As a result, the maximum total grading capacitance of all parallel breakers will be 7500 pF, following a *jumbo* bus outage.

Figure 3.1 shows the bus configuration at the Dorsey Station which is constructed in a standard breaker-and-a-third configuration. There are four main buses; *A1, A2, B1* and *B2*. The long bus or *jumbo* bus, bus *A2*, is roughly 500 m long while the short bus, bus *A1*, is 50 m. All nine ac filters, four station service transformers and wound voltage transformers of interest are also shown in the figure.

![Figure 3.1: Bus configuration for the Dorsey HVDC converter station [12]](image)

On May 20, 1995, bus *A2* was scheduled to be removed from service to accommodate the replacement of some of the circuit breakers and current transformers. The manual disconnects of three breakers were previously open and the motor operated disconnect of the station service transformer (SST2) was also open. There are 8 circuit breakers that were open which resulted in total of 5061pF grading capacitors connected to the de-energized bus.
Approximately thirty minutes following the bus de-energization, phase A of wound voltage transformer, V13F failed catastrophically. The ferroresonance occurred due to the failure of the 4 kVA, 138kV grounded wye 115/69V 1200:1 voltage transformer. As a consequence, the equipment was damaged up to 33 meters. Figure 3.2 shows a photograph of voltage transformer, V13F, taken shortly after the explosion.

![Voltage transformer, V13F, at the Dorsey HVDC converter station during ferroresonance](image)

Figure 3.2: Voltage transformer, V13F, at the Dorsey HVDC converter station during ferroresonance [100]

### 3.2 Single Phase Models

ATPDraw is a general purpose program for simulating transient phenomena in power systems [50]. The Alternative Transient Program-Electro–magnetic Transient Program (ATP-EMTP) is used to model the ferroresonance equivalent circuit. Figure 3.3 shows the system configuration for the Dorsey Converter Station.
In the model, a strong equivalent source impedance of 12000MVA was used in the simulation. For single phase modelling, the positive sequence impedance value is used because the system is considered as a balanced system. The impedance is given by:

\[ Z_1 = 0.212 + j4.38 \ \Omega \quad (3.1) \]

For a multi-break circuit breaker, grading capacitances are necessary in order to obtain a proper voltage distribution across each breaker. In Dorsey station, there are 12 circuit breakers that can be connected to bus A2, however, there were only three circuit breakers were connected to the bus during the incident. Nine circuit breakers were open which leads to a total of 5061 pF grading capacitance value. As a result of the switching, the de-energized bus A2 was connected to the energised bus B2 through the grading capacitors of open circuit breakers.

The maximum grading capacitance of all circuit breakers was 6885.5pF. Since the typical tolerance in grading capacitance value is ± 2%, the capacitance operating range was between 325pF to 7500pF depending on how many circuit breakers are open. The bus coupling capacitance between the conductors was calculated using the bus model given in Figure 3.4 below. The equivalent bus capacitance to ground on
each phase is 6450pF however, according to Jacobson [12], it is too low to match field measurements of the steady state coupled voltage under non-ferroresonance conditions. Thus, 4000pF was added to account for stray capacitances due to equipment such as bushing and etc. This lead to capacitance to ground value to be 10450pF.

![Bus Model](image)

**Figure 3.4 : Bus Model [12]**

Transformer core modelling is the most important component in ferroresonance circuit modelling. The important parameters for transformer modelling are the core losses, winding resistance and exciting current. Iron core losses that are due to the cyclic changes in flux are measured during excitation tests. Iron core losses consists of hysteresis and eddy current losses. In this thesis, the hysteresis losses is approximated by the corresponding power loss as part of the core total loss. The core total loss is represented by a constant resistance. According to Jacobson in [12], a more accurate hysteresis model should be used if subharmonic ferroresonance mode want to be studied in detail. Another researcher also has shown the impact of hysteresis on the stability domain and mode of ferroresonance [57]. However, the scope of this ferroresonance modelling is to produce different mode of ferroresonance which has been accomplished by using a constant resistance to represent the core losses. The same approach was taken by Jacobson and Marta [43]. In the preliminary development of the ferroresonance monitoring system, the lumped resistor values would be sufficient. Further analysis should be conducted in the future to consider a more accurate and detail model of hysteresis involved in the ferroresonance circuit.

The average power losses in the iron core losses is considered as in (3.2).

\[ P_{iron\_core} = \frac{V_n^2}{R_m} \]

(3.2)

where \( V_n \) is the nominal voltage and \( R_m \) is the core resistance.
In this simulation, no load loss with a value of 200 watts per nominal voltage (115V) is considered. This corresponds to a resistor value of 95.2MΩ with respect to primary. The calculation is shown in (3.3).

\[ R_m = \frac{V_n^2}{P_{\text{iron,core}}} = \frac{138kV}{200W} = 95.2M\Omega \]  \hspace{1cm} (3.3)

The magnetization characteristic of the iron core in the transformer can be represented by a single-valued function of the applied magnetic field such as linear, piecewise-linear, polynomial and trigonometric functions. In this model, the magnetization curve is represented by the magnetisation characteristic curve in Figure 3.5. The two term polynomial is used, where \( n = 15, a = 0.1, \) and \( b = 0.06 \) [12]. The 75 VA burden for the voltage transformer is assumed as the normal voltage transformer loading.

![Figure 3.5: The magnetization curve of the voltage transformer](image)

### 3.2.1 Transformer Losses

The transformer core has two type of losses, i.e iron core loss and copper loss. Iron core loss consists of hysteresis loss and eddy current loss. Copper loss is also called Ohmic loss because it dissipates as heat in the windings. Both hysteresis and eddy
current losses depend upon magnetic properties of the materials used to construct the core of the transformer and its design.

**Hysteresis loss**

The iron core in a transformer is made of ferromagnetic materials. Ferromagnetic materials such as iron are characterised by a magnetic field that is a thousand times greater than that of air. These kinds of materials are very sensitive to magnetization. Whenever an external magnetic field or magneto motive force (mmf) is applied to the ferromagnetic material, the material becomes strongly magnetized in the direction of the applied field. After removing this external mmf, most of the magnetic moments in the material will move to previous random positions, but some of them still remain in their aligned positions. Because of these unchanged positions, the material becomes slightly magnetized permanently. To neutralize this magnetism some opposite mmf is required to be applied. The opposite mmf will consume extra electrical energy which is known as the hysteresis loss of a transformer.

Figure 3.6 shows a hysteresis loop, which represents the relationship between the induced magnetic flux density, $B$ and the magnetizing force, $H$. It is often referred to as the $B$-$H$ loop. The loop is generated by measuring the magnetic flux of a ferromagnetic material while changing the magnetizing force. Assume that a ferromagnetic material has never been magnetized, so the loop will start at the origin. As the magnetizing force, $H$ is increased, the stronger the magnetic field, $B$ exists in the component. At point ‘$a$’ almost all of the magnetic moments are aligned. At this region, increment in the magnetizing force will produce a very little increase in magnetic flux. The material is said to be saturated.

When the magnetizing force is reduced to zero, the curve will move from point ‘$a$’ to point ‘$b$’. At this point, some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph. The point ‘$b$’ indicates the remanence or level of residual magnetism in the material where some of the magnetic moments remain aligned.
Figure 3.6: The hysteresis loop

As the magnetizing force is reversed, the curve moves to point ‘c’ where the flux density is zero. This is called the point of coercivity on the curve. The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material.

As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the negative region, point ‘d’. Reducing the magnetic force to zero brings the curve to point ‘e’. The flux density will be zero at point ‘f’ when the magnetic force increases back in the positive region. The curve does not return to the origin of the graph because some force is required to remove the residual magnetism. As the magnetic force increases again, the curve will take a different path to the saturation point where it will complete the loop.

**Eddy Current Loss**

When alternating current is supplied in the primary side of the transformer, the alternating current produces an alternating magnetizing flux in the core. Ideally, all the fluxes should link the secondary winding to induce voltage in the secondary winding. However, some of the alternating fluxes of the transformer may also link with other conducting parts such as the steel core or iron body of the transformer. As alternating
flux links with these parts of the transformer, there is a locally induced \textit{emf}. Due to this \textit{emf}, there are currents that will circulate locally at these parts of the transformer. This type of energy loss is called eddy current loss of the transformer.

### 3.2.2 The EMTP Model

The EMTP model for the voltage transformer that does not consider hysteresis is shown in Figure 3.7. The core losses are represented by a constant resistor and the characteristic of iron core is represented by the nonlinear inductance.

![Figure 3.7: EMTP Model for Voltage Transformer][12]

$R_{wp}$ and $R_{ws}$ are the winding resistance for primary winding and secondary winding respectively. $X_{wp}$ and $X_{ws}$ are the leakage inductance for the primary and secondary winding respectively. These values are obtained from short circuit tests of the transformer. The leakage inductance at the primary is assumed to be negligible and is set at 0.001 Ohms.

Figure 3.8 shows the EMTP model for the ferroresonance circuit without considering hysteresis. The model consists of an equivalent source, grading capacitance, bus capacitance, voltage transformer and the voltage transformer burden. The equivalent source is modelled using components $AC1PH$ and a series $RLC$. The circuit breakers with grading capacitance are modelled using a switch $TSWTCH$, parallel with a capacitance $CAP_RS$. A transformer has four major components, winding resistance, leakage inductance, turn ratio and iron core. Transformer winding resistance and leakage inductance are modelled using components $RESISTOR$ and $IND_RP$, respectively. The turn ratio is modelled using component $TRAFO_1$. The iron core is

\[
\begin{align*}
R_{wp} &= 7490 \, \Omega \\
X_{wp} &= 0.001 \, \Omega \\
R_{ws} &= 0.046 \, \Omega \\
X_{ws} &= 0.1642 \, \Omega \\
R_m &= 95.2 \, M\Omega
\end{align*}
\]
modelled using components *RESISTOR* and nonlinear inductance *NLIND93* connected in parallel.

In order to validate the simulation model presented above, the simulated signal is compared with the field recording signal recorded by at the Manitoba Hydro. The field recording sample is copied from a paper published by Jacobson [100] as shown in Figure 3.9.

As can be observed from Figure 3.9, the sustained part of the signal can be simulated as per field recording, which shows the fundamental mode of ferroresonance. However, the transient period cannot be simulated exactly as the field recording. The duration for the transient period in the simulated signal is shorter than the transient period of the field recording and it is impossible to be duplicated. This transient period depends on the initial conditions and exact parameter values such as the breaker opening time, initial values of the voltage and flux in the transformer at the time the incident occurs. Even though the transient period is shorter in the simulated signal, by visual inspection the frequency components inside the transient period might be similar. This can be observed from some parts of the transient. Thus, this has motivated the author to attempt the identification and classification of the transient part. This idea is investigated further in the later chapters.
3.3 The Time Step in Simulation

In any simulation, the time step is very important in order to obtain any meaningful output. According to CIGRE [76], ferroresonance is considered as a low frequency transient with a maximum frequency of 1kHz.

A simple experiment has been conducted to study the impact of the time step in the simulation. Four different values of time step have been considered; 0.1 µs, 1µs, 10µs, 100µs. The result is shown in Figure 3.10. As can be seen, the plots for 10µs, 1µs and 0.1µs are exactly the same. They are superimposed on each other. But the plot for 100µs has a very bad waveform. Thus, for this ferroresonance study, the time step of smaller than 10µs could be used. Therefore, for this simulation the time step of 1µs is used.
3.4 Simulation of Different Modes of Ferroresonance Signals

The ferroresonance signals are obtained by performing a switching of the circuit breaker in the ferroresonance circuit shown in Figure 3.8. The simulation time is set at 2 seconds so that all the three periods; normal period, transient period and sustained period, can be seen in the signal.

Different mode of ferroresonance voltage and current signals are produced by varying parameters such as capacitance value. The sensitivity studies are performed to observe the impact of parameters in the ferroresonance mode. The fundamental mode ferroresonance is obtained by setting the parameters of the simulation according to Table 3.1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>5061pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>187794.2136 V</td>
</tr>
<tr>
<td>Switching Time</td>
<td>0.1s</td>
</tr>
</tbody>
</table>

Figure 3.11 depicts the voltage signal and Figure 3.12 depicts the current signal for the fundamental mode ferroresonance respectively.
The voltage signal for fundamental mode ferroresonance is a periodic signal. The signal consists of the frequency component of fundamental system frequency and the odd multiples of the system frequency. If the system frequency is 50Hz, then fundamental mode ferroresonance will have 150Hz, 300Hz and other multiples of 50Hz frequency components in the voltage signal. The magnitude of the voltage for the sustained period of the fundamental mode ferroresonance is almost 150% of the normal voltage rating. This overvoltage can reach up to 2pu. This sustained overvoltage can cause damage to electrical equipment. When referring to the current signal during the sustained fundamental mode ferroresonance, the current shows a peaky waveform, which indicates that the transformer is in saturation. This sustained peaky current can result in overstressing insulation and can cause over heating to the transformer and to certain extent a possibility to cause an explosion. Many cases reported in the literature are suspected to have been caused by fundamental mode ferroresonance. This adverse effect of fundamental mode ferroresonance is the reason why the fundamental mode is considered to be the most severe mode of ferroresonance. It has a potential to cause severe damage to power systems.

Figure 3.11: Voltage signal for fundamental mode ferroresonance

Figure 3.12: Current signal for fundamental mode ferroresonance

The voltage signal for fundamental mode ferroresonance is a periodic signal. The signal consists of the frequency component of fundamental system frequency and the odd multiples of the system frequency. If the system frequency is 50Hz, then fundamental mode ferroresonance will have 150Hz, 300Hz and other multiples of 50Hz frequency components in the voltage signal. The magnitude of the voltage for the sustained period of the fundamental mode ferroresonance is almost 150% of the normal voltage rating. This overvoltage can reach up to 2pu. This sustained overvoltage can cause damage to electrical equipment. When referring to the current signal during the sustained fundamental mode ferroresonance, the current shows a peaky waveform, which indicates that the transformer is in saturation. This sustained peaky current can result in overstressing insulation and can cause over heating to the transformer and to certain extent a possibility to cause an explosion. Many cases reported in the literature are suspected to have been caused by fundamental mode ferroresonance. This adverse effect of fundamental mode ferroresonance is the reason why the fundamental mode is considered to be the most severe mode of ferroresonance. It has a potential to cause severe damage to power systems.
The subharmonic mode ferroresonance is obtained by setting the parameters of the simulation according to Table 3.2.

Table 3.2: Parameters to simulation subharmonic mode ferroresonance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>625pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>187794.2136 V</td>
</tr>
<tr>
<td>Switching Time</td>
<td>0.1s</td>
</tr>
</tbody>
</table>

The voltage and current signals for the subharmonic mode ferroresonance are depicted in Figure 3.13 and Figure 3.14, respectively.

![Voltage signal for subharmonic mode ferroresonance](image1)

**Figure 3.13: Voltage signal for subharmonic mode ferroresonance**

![Current signal for subharmonic mode ferroresonance](image2)

**Figure 3.14: Current signal for subharmonic mode ferroresonance**

Subharmonic mode ferroresonance is also periodic but the magnitude of the voltage is less than 1pu. The existence of subharmonics is not desirable. The subharmonic mode contains a frequency components that is a subfrequency of the fundamental frequency
\( f_0 \), such as \( 1/3f_0 \) or \( 1/nf_0 \). The current signal also has peaky waveforms, however, the magnitude is only around one fifth of the fundamental mode ferroresonance.

For chaotic mode ferroresonance, the parameters are set according to Table 3.3.

<table>
<thead>
<tr>
<th>Table 3.3 : Parameters to simulation chaotic mode ferroresonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Grading Capacitance</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
</tr>
<tr>
<td>Source Voltage</td>
</tr>
<tr>
<td>Switching Time</td>
</tr>
</tbody>
</table>

The voltage and current signal are shown in Figure 3.15 and Figure 3.16, respectively. Chaotic mode is not periodic. It does not have a sustained period because the transient period prolongs for some time. Thus in this thesis, the sustained transient period is taken after \( t = 1\,\text{s} \) because according to [101], in general, the transient should last not more than 1 second.
3.5 The Impact of Parameter Variations

Three system parameters are varied in the ferroresonance simulations to study their effect on ferroresonance modes. They are the grading capacitance, the supply voltage and the switching instant. The simulation is divided into three simulations which corresponds to each parameter variation. The range of the parameters used in the simulation is shown in Table 3.4.

Table 3.4: The range of parameters for simulations

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Initial Value</th>
<th>Final Value</th>
<th>Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 1: Grading Capacitance</td>
<td>325 pF</td>
<td>7500 pF</td>
<td>100 pF</td>
</tr>
<tr>
<td>Simulation 2: Source Voltage</td>
<td>80%</td>
<td>130%</td>
<td>1%</td>
</tr>
<tr>
<td>Simulation 3: Switching Instant</td>
<td>0.1s</td>
<td>0.132s</td>
<td>0.1ms</td>
</tr>
</tbody>
</table>

3.5.1 The Effect of Grading Capacitance Variation

The first simulation involves varying the grading capacitance value with the increment step of 100 pF. The voltage source was fixed at 132 kV. The switch was closed before $t=0$ and it was opened at 0.1 s. The parameters used in simulation 1 are shown in Table 3.5.

Table 3.5: Parameters for simulation 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>325 pF- 7500 pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>132 kV</td>
</tr>
<tr>
<td>Switching Instant</td>
<td>0.1s</td>
</tr>
</tbody>
</table>

By varying the grading capacitance, the response of the system was observed. The plot of the voltage signal for 72 different grading capacitance values is depicted in Figure 3.17. Ferroresonance does not occur when the grading capacitance is below 525 pF. When the value is above 3125 pF, the system is sustained in the fundamental
mode. When the grading capacitance value is between 525pF and 3125pF, the system jumps chaotically between subharmonic, chaotic and fundamental mode. The mode of ferroresonance with respect to the grading capacitance values is shown Figure 3.18.

These results validate the discussion in Chapter 1. When the value of the capacitance is low, the intersection of line $V_{C1}$ with the magnetization curve is in the linear region. When the capacitance is increased to line $V_{C2}$, there are three points that intersect with the magnetization curve, which lead to the ‘jumping’ phenomenon between the modes of ferroresonance. As the value of capacitance is increased further, the capacitance has increased to line $V_{C3}$, where the point of intersection is at point ‘z’ in the negative saturation region in the third quadrant.

![Figure 3.17: Voltage signal for grading capacitance variation](image)
3.5.2 The Effect of Source Voltage Variation

The second simulation involves varying the source voltage from 80% to 130% of the rated voltage with the increment step of 1% for each simulation. The grading capacitance, \( C_g \) was fixed at 5061pF and the shunt capacitance, \( C_b \) was at 10450pF. The parameters used in simulation 2 are shown in Table 3.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>5061 pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>80% - 130%</td>
</tr>
<tr>
<td>Switching Instant</td>
<td>0.1s</td>
</tr>
</tbody>
</table>

The voltage signals for various source voltages are shown in Figure 3.19, and the modes of ferroresonance with respect to source voltage are shown Figure 3.20.
Referring to the parameters of the simulation, the parameters indicate that the system is already in the ferroresonance operating region. Variation of source voltage only results in the change of ferroresonance modes between chaotic and fundamental. The chaotic mode is observed when the system voltage is between 80% and 86%. Then the system remains in sustained fundamental mode until the voltage is increased to 130% of the system voltage. Except for one simulation when the voltage is at 91%, ferroresonance does not occur.
Consider a plot in Figure 3.21 where the capacitance and inductance lines remain the same, but the system voltage is changed.

If the system voltage is increased from $V_{S1}$ to $V_{S2}$, line $V_{C1}$ moves upward to $V_{C2}$. This $V_{C2}$ line only has an intersection at point ‘a’ in the third quadrant. Due to high current, the line $V_{C2}$ drops again to line $V_{C1}$ and three intersections, point 1, 2 and 3 occur again. The solution then jumps between points 1, 2 and ‘a’, depending on the value of the system voltage. Leonardo energy explains in [102] why a 25kV or a 35kV system is more prone to have ferroresonance compared to a 12kV system.

### 3.5.3 The Effect of Switching Instant Variation

In the third simulation, the switching instant was varied from 0.1s until 0.132s with 0.0005s increments. The grading capacitance, shunt capacitance and source voltage were fixed as shown in Table VI.
Table 3.7: Parameter for simulation 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values From</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>5061 pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>132 kV</td>
</tr>
<tr>
<td>Switching Instant</td>
<td>0.1s to 0.132s</td>
</tr>
</tbody>
</table>

The plot of variation of source voltage values is given in Figure 3.22 and the correlation results depicted in Figure 3.23.

Referring to Figure 3.22, the switching instant does not affect the ferroresonance mode because the other system parameters have influenced the initiation of fundamental ferroresonance modes. The duration of the switching time is 2 cycles. Since the switch is opened at the current equals to zero, the changes within a positive half and negative half of the cycle do not affect the system response.
Figure 3.23: Ferroresonance mode with respect to switching time, showing that the circuit is in a fundamental mode throughout the simulation

According to Valverde in [3], the switching instant plays an important role in ferroresonance analysis. The effect of the switching instant is the same as the inrush current in the transformer. By changing the switching instant at 0°, 30° and 90°, the latter does not produce ferroresonance but the first two does. The system is more susceptible to ferroresonance if it is energised near to 0°.

### 3.6 Chapter Summary

This chapter discusses the modelling of ferroresonance circuit in a transient program. Sensitivity studies are performed with the variation of different system parameters. The voltage signal is plotted with the variation of different parameters. The mode of ferroresonance for each case is also plotted.

The model is able to reproduce the sustained period of ferroresonance signal. This can be seen from the sustained part of the simulated and field recorded signals. However, the transient part cannot be reproduced. The duration of the transient part is shorter in the simulated signal. This simulation has validated the statement by other researchers that the transient part is impossible to be duplicated due to the dependencies of exact parameters in the modelling.

From all three simulations in analysing the impact of system parameters, the results have proved that changing the capacitance, the source voltage and the switching time affect the occurrence of ferroresonance and the modes of which ferroresonance will
fall into. For simulation 1, it is concluded that for a small value of capacitance, ferroresonance will not occur. As the capacitance increases, the system will be susceptible to ferroresonance due to the interception of voltage capacitance characteristics with inductance characteristics.

For simulation 2, it is shown that the value of the source voltage affects ferroresonance. When the voltage is lower than the system voltage, the slope of the characteristics is steep and the variation in source voltage does not affect the system. However, when value of capacitance is increased, the variation of the source voltage takes the system in and out of ferroresonance phenomena and the modes of ferroresonance also vary.

Simulation 3 proves that the switching instant affects ferroresonance. The switching effect depends on whether the switch is opened during the first half cycle or during the second half cycle. It is observed that the switch will open when the current is zero. However, this condition only applies to a system when the capacitance is in a range that is prone to ferroresonance. If the system is not susceptible to ferroresonance, as in case 1, where the capacitance is very low or when the system is already in ferroresonance as per case 3, the switching instant does not have any effect.
Chapter 4

4 Signal Analysis

This chapter discusses the signal analysis using Fourier transform and wavelet transform to analyse ferroresonance signals. The beginning of the chapter provides a brief introduction to the Fourier Transform (FT). Some examples of application of FT in power systems are presented. Different modes of ferroresonance voltages and currents signals are analysed by observing the frequency component of current and voltage signals during transient and sustained periods. Then, the chapter continues with the theory and background of wavelet transforms. It introduces the important concept of Continuous Wavelet Transform (CWT) and how the mother wavelet is dilated and translated to obtain wavelet coefficients. The wavelet coefficients are presented in the time-frequency plane. Discrete Wavelet Transform (DWT) is introduced. Detail explanation is given on how a signal is decomposed into high frequency and low frequency components through mother wavelet and scaling function. The application of DWT in transient detection is presented, followed by the feature extractions. Feature extractions are performed in the transient period and the sustained period of different modes of ferroresonance voltage signals. The chapter is concluded with a discussion of the features that can be used to classify the sustained period with respect to different ferroresonance modes.
4.1 Fourier Transform

Fourier Transform is an important and powerful tool in signal processing. It provides a method for examining the level of distortion in a signal. Among the most common applications of the FT are the analysis of linear time-invariant systems. In power systems for example, a spectrum analyser that is based on FT is used to analyse the quality of the voltage and current signals.

According to Fourier, a signal can be represented in a mathematical form as a linear combination of signals of different frequencies with different amplitudes. For example, if a signal is represented by a function \( f(t) \) has a finite energy (norm) defined as

\[
\int_{0}^{\infty} |f(t)|^2 \, dt < \infty, \quad t \in (0, 2\pi)
\]  

(4.1)

then, the signal can be expanded into a Fourier series

\[
f(t) = \sum_{n} c_n e^{jn\omega}
\]  

(4.2)

where the coefficient \( c_n \) have the form

\[
c_n = (2\pi)^{-1} \int_{0}^{2\pi} f(t) e^{-jnt} \, dt
\]  

(4.3)

A Fourier transform is used to find the frequency content of a particular waveform that exists in a signal. Given a continuous signal, \( x(t) \) the frequency content of the signal is given by the Fourier Transform, \( X(\omega) \):

\[
X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} \, dt
\]  

(4.4)

where \( e^{-j\omega t} \) is the ‘basis’ of the Fourier Transform.

\( X(\omega) \) is a continuous function in the frequency domain and the integration goes from minus infinity to infinity. However, in a digital computer, the calculation must be discrete. Thus, the discrete form of Fourier Transform with a finite length signal, \( x[n] \) is given by:
\[ X[k] = \sum_{n=0}^{N-1} x[n]e^{-2\pi kn/N} \]  \hspace{1cm} (4.5)

where \( X[k] \) is the complex value of the discrete sequence in the frequency domain, \( N \) is the number of samples of the input sequence, \( x[n] \) is the sequence of input samples in the time domain, \( n \) is the index of the input samples in the time domain and \( k \) is the index of the DFT output in the frequency domain that is defined as:

\[ k = 1, 2, 3 \ldots N-1 \]  \hspace{1cm} (4.6)

When applying the Fourier transform, there are two values that need to be chosen very carefully; (a) the sampling frequency \( f_s \), (b) the number of samples \( N \). The sampling frequency will determine the distance between one point to adjacent points and the number of samples will determine how many points will be in one cycle.

These values are important because these determine the analysed frequency. The frequency analysis of the processed signal depends on the sampling frequency \( f_s \) and the number of samples, \( N \). It is given by the following equations [103]

\[ F_a(m) = \frac{m f_s}{N} \]  \hspace{1cm} (4.7)

where \( F_a \) is the frequency that is analysed, \( f_s \) is the sampling frequency of the signal and \( N \) is the number of points.

For this simulation, the frequency analysis, \( F_a \) is 60Hz. Since MATLAB uses the FFT algorithm to calculate the DFT, \( N \) is chosen to be \( 2^n \). In order to obtain an exact 60Hz frequency analysis, the ratio of sampling frequency, \( f_s \) and the number of points, \( N \) must be equal to 60 [103]. If the ratio of \( \frac{f_s}{N} \) is not the same as the analysed frequency, a characteristic known as \textit{leakage} will occur that will cause the FFT results to be only an approximation of the true spectra of the original input signals. Further details on this topic can be found in [103, 104].
4.1.1 Choosing the number of samples

In order to obtain an accurate analysing frequency, \( F_a \) which is 60Hz for this case, some values of sampling frequencies and the number of samples were chosen. These values were used in the next simulations.

The data window size that is used in this analysis is \( 2T_0 \), where \( T_0 \) is defined as:

\[
T_0 = \frac{1}{60\text{Hz}} = 16.667\text{ms} = 1\text{period}
\] (4.8)

The number of samples per \( T_0 \) is 128 samples, so each data window contains 256 samples.

Since the data window size, \( T_0 \), is fixed at 16.67ms, the number of samples and the sampling frequencies are varied according to (4.7). MATLAB uses a FFT where the number of samples must be \( 2^N \). Otherwise, the signal will be zero-padded to obtain the \( 2^N \) samples. To accommodate the FFT rule, the number of samples for this case is varied from \( 2^5 \) until \( 2^7 \). The sampling frequency is varied from 1920Hz to 7860Hz for the 16ms window to obtain the 60Hz analysing frequency.

Table 4-1 shows the number of samples, the sampling frequencies and the corresponding sampling time.

<table>
<thead>
<tr>
<th>Number of Samples</th>
<th>Sampling Frequency, ( F_s )</th>
<th>Sampling Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2^5 ) = 32 samples</td>
<td>1920</td>
<td>0.00052 second</td>
</tr>
<tr>
<td>( 2^6 ) = 64 samples</td>
<td>3840</td>
<td>0.00026 second</td>
</tr>
<tr>
<td>( 2^7 ) = 128 samples</td>
<td>7680</td>
<td>0.00013 second</td>
</tr>
</tbody>
</table>

To investigate the effect of different numbers of samples, an experiment is conducted on the THD waveform algorithm. The objective is to investigate if the number of samples per cycle gives different THD waveforms. Two sample waveforms are compared to find the differences. The results are shown in the Appendix A. It is proven that all of the waveforms for the 32 samples per frame are the same as the
waveforms for the 64 samples and the 128 samples per frame. To comply with the frequency of ferroresonance, a higher sampling frequency is chosen to avoid aliasing [104]. Thus, 128 samples per 16ms window is used for the rest of the simulations.

4.1.2 Magnitude Spectrum

To study the quality of the signal for each ferroresonance mode, the voltage signal and the current signal in both the transient period and the sustained period were analysed. The magnitude of the spectrum was calculated using the (FFT) function in MATLAB. The number of samples when using the FFT function must be equal to $2^N$. Otherwise, the signal will be zero-padded. To accommodate this FFT rule, the number of samples $N$, is chosen to be $2^7$. This corresponds to the sampling frequency of 7692Hz for a 16.67ms window. According to the Nyquist rule, the sampling frequency must be the double of the maximum frequency of the signal in order to avoid aliasing [104]. Since ferroresonance falls under low frequency transients with a maximum frequency of 1kHz [76], then the sampling frequency of 7692kHz is more than sufficient to avoid aliasing.

4.1.2.1 Sustained Period

For analysing the sustained period, a signal of duration of 0.1s is analysed. The voltage signal of fundamental mode ferroresonance obtained from Section 3.4 is shown in Figure 4.1(a). The amplitude of the voltage during the sustained period is around 280kV. This magnitude can also be seen from the magnitude spectrum in Figure 4.1 (b). The value is almost 50% more than the normal voltage. The voltage signal has harmonic distortion. The frequency components of the signal are shown in Figure 4.1(b) where the odd multiple of the fundamental frequencies exist in the signal but fundamental frequency is the dominant frequency. The third harmonic is only around one third of the fundamental frequency.
Figure 4.1: Sustained fundamental mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum

Figure 4.2: Sustained fundamental mode ferroresonance (a) current signal (b) current magnitude spectrum

The current signal shows a spiky waveform in Figure 4.2 (a), which indicates that the transformer is operating in the saturation region. The amplitude of the current is quite high which is about 10A. The frequency components inside the current signal show an interesting spectrum as depicted in Figure 4.2 (b). The frequency components of fundamental mode of the current signal consist of the fundamental frequency and odd harmonics. The magnitude of the current signal spectrum decreases gradually from the preceding harmonics. It can be observed that the magnitude of the next frequency decreases about 20% from the preceding frequency. This characteristic is different from the magnitude of the voltage spectrum where the fundamental frequency is dominant.

Subharmonic mode ferroresonance voltage and current signals and their respective frequency spectra are depicted in Figure 4.3 and Figure 4.4, respectively. The voltage signal has a magnitude which is less than the normal steady state magnitude. The concern of subharmonic ferroresonance is not about the overvoltage but instead the frequency of the signal. The existence of subharmonic frequency may cause problems in electronic equipment. The spectrum of the voltage signal shows that the signal consists of the subharmonic frequency at 20Hz, which is 1/3 of the fundamental frequency. The existence of the fundamental frequency is very low as indicated by the small magnitude of the spectrum in the figure. Other frequencies also present in the
signal. However their magnitude is very small if compared to the subharmonic frequency.

![Figure 4.3: Sustained subharmonic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum](image)

The current signal for the subharmonic also has a spiky shape as in the fundamental mode. However, the amplitude of the current, which is only 0.5A, is much lower than the fundamental mode’s current. The magnitude spectrum of the current signal consists of subharmonic, fundamental, and multiples of subharmonic frequencies as depicted in Figure 4.4(b).

![Figure 4.4: Sustained subharmonic mode ferroresonance (a) current signal (b) current magnitude spectrum](image)

The chaotic mode ferroresonance voltage signal and its respective magnitude spectrum are shown in Figure 4.5. Due to the chaotic nature of the signal, there is no specific voltage magnitude that can be identified from the figure. Its magnitude spectrum consists of a continuous spectrum or broadband frequency as can be seen from Figure 4.5(b). However, the presence of fundamental and subharmonic frequencies can be noted from the spiky waveforms in the magnitude spectrum. The frequency range of the chaotic mode is in the 400Hz range, which is eight times the fundamental frequency. The spectrum can be divided into two regions; the first region
is the region where the frequency is lower than the fundamental frequency, and the second region is the region where the frequency is higher than the fundamental frequency. As can be seen, the magnitude spectrum for the first region is higher compared to the magnitude in the second region.

The current signal and the magnitude spectrum for the sustained chaotic mode are shown in Figure 4.6. The current waveform also has a spiky shape which indicates that the transformer is in the saturation region. However, the magnitude of the spikes varies. As with the voltage signal, the current signal also has the broadband frequency range as can be seen from Figure 4.6(b). The range of the frequency is within 500Hz.

![Figure 4.5: Sustained chaotic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum](image)

![Figure 4.6: Sustained chaotic mode ferroresonance (a) current signal (b) current magnitude spectrum](image)

### 4.1.2.2 Transient Period

In order to have a better understanding of ferroresonance modes, the transient period for each ferroresonance mode signals are also analysed. Figure 4.7 through Figure 4.12 show the voltage signals and current signals with their respective magnitude spectra.
Figure 4.7: Transient fundamental mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum

Figure 4.8: Transient fundamental mode ferroresonance (a) current signal (b) current magnitude spectrum

Figure 4.9: Transient subharmonic mode ferroresonance (a) voltage signal (b) voltage magnitude spectrum

Figure 4.10: Transient subharmonic mode ferroresonance (a) current signal (b) current magnitude spectrum
From all ferroresonance modes, the voltages and the currents of the transient period have broadband the frequency.

### 4.1.2.3 Three Periods

This section presents the magnitude spectrum of ferroresonance signal that contains all three periods: normal period, transient period and sustained period. Figure 4.11(a) shows the spectrum of the signal that contains fundamental, subharmonic and chaotic mode ferroresonance and Figure 4.13(b) shows the FFT of the signal.

It can be observed that all the three mode ferroresonance signal contained the same frequency component with the sustained ferroresonance but with different magnitudes. This result shows the limitation of Fourier transform where it cannot display the time of the frequency component. Therefore, further analysis is conducted using wavelet transform to overcome this limitation.
4.2 Wavelet Domain Analysis

The application of wavelet transforms in power systems is very important especially with regards to the analysis of transient signals as described by many publications in the early 90s [93, 105]. The ability of wavelet transforms to provide frequency resolution and time resolution is the key factor for the increase in the application of the Wavelet Transform (WT) in the detection and classification of the transient in power system. This means that with the wavelet transforms, the frequency components inside the signal and also the time when it is present can be determined. The other key factor is the process of decomposing a signal using WT is equivalent to a multi-resolution analysis. The multi-resolution analysis provided by wavelet transform is very useful in feature extraction. This feature extraction is the prerequisite to signal classification.

4.2.1 Wavelet Transform

Wavelet Transform (WT) refers to a transformation process of a signal from time domain into another representation that is more useful, called wavelet domain. Wavelet domain is also known as a time-frequency domain, time-scale domain, space-scale domain and space-frequency domain. In this thesis, the time-frequency domain term will be used to maintain consistency.

Figure 4.13: (a) Voltage signal that contains the three period (b) voltage magnitude spectrum
Mathematically, WT is a convolution of the wavelet function or ‘mother wavelet’ with an input signal. WT is manipulated into 2 ways, where the mother wavelet is moved or translated throughout the signal and dilated (stretched or squeezed) while moving. During the wavelet transformation process, the mother wavelet is correlated with the input signal in order to produce wavelet coefficients. When the mother wavelet matches or correlates well with the shape of the signal at a specific location, the large wavelet coefficients are obtained. Then, wavelet transforms represents the signal as a sum of wavelets coefficients at different locations and scales.

There are three main wavelet transforms which are continuous Wavelet transform (CWT), discrete wavelet transforms (DWT) and wavelet packet transforms (WPT). This thesis only explains the CWT and DWT. CWT is the fundamental concept of WT and DWT is the fast version of CWT. This project applies DWT to decompose the signal for feature extraction because DWT provides sufficient information to analyse power system problems. Section 4.2.3 and Section 4.2.4 below explain in detail the CWT and DWT, respectively. A more detailed discussion on the wavelet transforms can be found in [106-108]

In all wavelet transforms, understanding the wavelet function or mother wavelet, and choosing the best or the most suitable mother wavelet for the analysis are very important. There are a large number of mother wavelets to choose from but the best one for a particular application depends on the nature of the signal and what is required from the signal.

4.2.2 Mother Wavelet (Wavelet Function)

The word ‘Wavelet’ refers to a ‘short wave’ that is translated from French word ondellets. Unlike in Fourier analysis which uses only one basis function (cosine), wavelet transforms rely on a number of different basis functions that are referred to as mother wavelets. This mother wavelet is also known as a wavelet function or just wavelet in the literature. For clarity and consistency, this thesis will use the term mother wavelet (MW) to refer to the wavelet.
As mentioned above, the mother wavelet is a wave-like oscillation that starts out at zero, increases and decreases back to zero. It is a short wavelet that has zero integration value given by

\[ \int \psi(t) \, dt = 0 \]  

(4.9)

where \( \psi(t) \) is the mother wavelet.

Any function can be a mother wavelet, if it consists of the following characteristics [91]:

1. Oscillatory
2. Must decay quickly to zero
3. Must have average value of zero or integrate to zero

There are four types of mother wavelets, which are a real crude mother wavelet, a complex crude mother wavelets, an orthogonal mother wavelets, a biorthogonal and reverse biorthogonal mother wavelets. Table 4.2 shows the different mother wavelet families and their attributes.
Table 4.2: Mother wavelet families and their attributes

<table>
<thead>
<tr>
<th>Wavelet Family</th>
<th>Wavelet Type</th>
<th>Transform Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexican Hat</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Morlet</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Gaussian</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Meyer</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Shannon</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Complex B-Spline</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Complex Morlet</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Complex Gaussian</td>
<td>Crude</td>
<td>CWT</td>
</tr>
<tr>
<td>Haar</td>
<td>Orthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Daubechies</td>
<td>Orthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Symlets</td>
<td>Orthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Coiflets</td>
<td>Orthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Discrete Meyer</td>
<td>Orthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Biorthogonal</td>
<td>Biorthogonal</td>
<td>CWT and DWT</td>
</tr>
<tr>
<td>Reverse Biorthogonal</td>
<td>Reverse Biorthogonal</td>
<td>CWT and DWT</td>
</tr>
</tbody>
</table>

The crude mother wavelets come from explicit mathematical equations, which means they can be represented by mathematical equations. For example, the Mexican Hat wavelet can be represented by (4.10).

\[
mexh(t) = \left(\frac{2}{\sqrt{3}} \pi^{0.25}\right) e^{-\frac{t^2}{2}} (1 - t^2) \quad (4.10)
\]

Crude mother wavelets have no orthogonality so they can only be used by CWT but not DWT. DWT requires another function called ‘scaling function’, which is derived from mother wavelets that have orthogonality. Complex crude wavelets also have the same characteristic as the crude mother wavelets. The advantage of the complex crude mother wavelets is that they can be used with complex signals.

Orthogonal mother wavelets are mother wavelets that have orthogonality, for example the Daubechies wavelet family. DWT is similar to multi resolution analysis (MRA), where the analysis involves four filters. Two filters are used during decomposition (High Pass (H) and Low Pass (L)) and the other two filters are used during
reconstruction (High Pass \(H'\) and Low Pass \(L'\)). The high pass filters \(H\) and \(H'\) can be the same filters or different filters, depending on the applications. The same goes for low pass filters \(L\) and \(L'\). The low pass filter \(L\) is orthogonal to the high pass filter \(H\). The high pass filter of MRA is the mother wavelet and the low pass filter is the scaling factor.

Members of Daubechies mother wavelets are named corresponding to the number of filter points. For example db4 has 4 points and db8 has 8 points. The filter points must be even number. A small filter point provides a low frequency resolution and a larger filter point provides a high frequency resolution. A few members of Daubechies mother wavelets are depicted in Figure 4.14.

![Wavelet Graphs](image)

**Figure 4.14**: Daubechies mother wavelet (a) db2, (b) db3, (c) db4, (d) db5, (e) db6, (f) db10

As can be seen, the mother wavelets are getting smoother as the number of coefficient increases and the frequency resolution is also better as the number of coefficient increases.

Note that some authors use the number of vanishing moments instead of the number of filter point to describe members of a family of mother wavelets. “Vanishing moments means that the wavelet can correlate with a linear, quadratic or higher order polynomial and obtain small or zero correlation coefficients”[109]. A wavelet has \(p\) vanishing moments if and only if the wavelet scaling function can generate
polynomials up to degree p−1. Detailed explanation on vanishing moments and mother wavelet families can be found in specialized books on wavelet transform such as [110, 111]. MATLAB uses the number of vanishing moments to describe a mother wavelet. Thus \( db2 \) in MATLAB refers to a 4-filter point and \( db4 \) refers to an 8-filter point Daubechies mother wavelet, and so on. Figure below shows some examples of other mother wavelets.

![Haar, Shannon or Sinc, Daubechies 4, Daubechies 20, Gaussian or Spline, Biorthogonal, Mexican Hat, Coiflet](image)

**Figure 4.15 : Example of mother wavelets [109]**

As can be observed from the examples of mother wavelets, they are symmetric, either of even symmetry or odd symmetry. Typically, the functions are normalized, \( \| \psi \| = 1 \) and centered at \( t = 0 \).

In wavelet transform, the mother wavelet is initially specified as the basis function. This basis function plays the same role as the sine and cosine functions in Fourier analysis. Then the dilated and translated version of the mother wavelet is generated. The dilated and translated mother wavelet is denoted by the following equation.

\[
\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi \left( \frac{t - b}{a} \right) \tag{4.11}
\]

where \( a \) is the dilated parameter, \( b \) is the translated parameter and \( \frac{1}{\sqrt{a}} \) is a normalization factor.
The contracted mother wavelet corresponds to high frequency and the dilated mother wavelet corresponds to low frequency. They are used in different applications. Typically, the former is used in temporal analysis of the signal while the latter is used for frequency analysis. Figure 4.16 shows the contracted and the dilated mother wavelet, and how the dilated or contracted mother wavelet is translated during the wavelet transformation process.

![Wavelet Transform Diagram](image)

**Figure 4.16: Dilated and translated mother wavelets [109]**

The way a mother wavelet is translated and dilated distinguishes between the continuous wavelet transform (CWT) and the discrete wavelet transform (DWT). CWT refers to a mother wavelet that can dilate at every scale, which is from that of the original signal up to some maximum scale determined by the analysis. The CWT also refers to continuous in terms of translating smoothly. On contrary, DWT refers to discrete dilation and translation.

### 4.2.3 Continuous Wavelet Transform

The continuous wavelet transform is defined by the following equation:

$$WT(t) = \int_{-\infty}^{\infty} x(t)\psi(t)dt$$  \hspace{1cm} (4.12)

where $x(t)$ is the signal to be transformed and $\psi(t)$ is the *mother wavelet*.

Equation (4.12) is the simplest form of a wavelet transform equation. However, since the mother wavelet can be translated (shifted) and dilated (expanded) during transformation, substituting (4.11) into (4.12) leads to another form of a wavelet transform.
\[ WT_{a,b}(t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi \left( \frac{t-b}{a} \right) dt \]  
(4.13)

Referring to (4.13), the wavelet transform is the inner product between the input signal, \( x(t) \) and the mother wavelet, \( \psi(a,b) \). Rewriting (4.13) leads to

\[ WT\{x(a,b)\} = \langle x, \psi_{a,b} \rangle = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \cdot \psi_{a,b}(t) dt \]  
(4.14)

Equation (4.14) proves that the wavelet transform is the correlation between input signal \( x(t) \) and the mother wavelet, \( \psi_{a,b}(t) \). As known from digital signal processing, the correlation between two signals produce coefficients. These coefficients give information how well the signal correlates with the mother wavelet. In other words, the values of coefficients are large if the signal matches well with the mother wavelet and small if the signal does not match the mother wavelet well.

During transformation, the mother wavelet is translated or moved along the signal at various scales (contracted or translated). The window is shifted along the signal and for every position the spectrum is calculated. Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. At the end, the result will be a collection of time-frequency representations of the signal, all with different resolutions. A sample of fundamental mode of ferroresonance voltage signal that is transformed using CWT in MATLAB is depicted in Figure 4.17. The sample signal is transformed using the ‘db5’ mother wavelet with the scale from 1 to 32. Figure 4.17 (a) shows the voltage signal, Figure 4.17 (b) is the db5 mother wavelet, Figure 4.17 (c) is the time-frequency plane and Figure 4.17 (d) is the 3D representation of the time-frequency plane. The dark colour represents lower coefficients and the light colour represents the higher coefficients.
The scale that represent the y-axis of the time-frequency plane in figure (c) and (d) represents the degree to which the wavelet is compressed or stretched. Low scale values compress the wavelet and correlate better with high frequencies. The low scale CWT coefficients represent the fine-scale features in the input signal vector. High scale values stretch the wavelet and correlate better with the low frequency content of the signal. The high scale CWT coefficients represent the coarse-scale features in the input signal.

In CWT, the translation and dilation are done smoothly, where the wavelet coefficients are calculated at every possible scale (dilation) and position (transition). It means that the values of variables $a$ and $b$ can vary arbitrarily from minus infinity to infinity. However, if the dilation and transition are performed discretely, it is more...
efficient and the result is as accurate as the CWT. This form of wavelet transformation is called Discrete Wavelet Transform.

### 4.2.4 Discrete Wavelet Transform

Continuous dilation and translation of mother wavelet in CWT generates substantial redundancy due to transformation from a one dimension time domain into a two dimension time and frequency domains. Thus, in order to efficiently perform a wavelet transform, the mother wavelet can be dilated and translated discretely. This Discrete Wavelet Transform (DWT) follows certain discrete expansion patterns determined by the parameters ‘\(a\)’ and ‘\(b\)’. The discrete wavelet transform is defined by the following equation:

\[
WT_{a,b}(n) = \frac{1}{\sqrt{a}} \sum_{0}^{N-1} x(n) \psi \left( \frac{n - b}{a} \right)
\]

where \(x(n)\) is the signal to be transformed and \(\psi\) is the mother wavelet. The dilation variable \(a\) is an exponential rather than linear. The values of \(a\) and \(b\) are selected by the following equations

\[
a = a_0^m \tag{4.16}
\]

\[
b = nb_0 a_0^m \tag{4.17}
\]

where \(a_0 > 1\) is the dilation factor and \(b_0\) is the translation factor that depends on \(a_0\), and \(m, n\) are positive integers. These choices of parameters modify the mother wavelet equation in (4.11) to

\[
\psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \psi \left( \frac{t - nb_0 a_0^m}{a_0^m} \right) \tag{4.18}
\]

The simplest choice of \(a_0\) is 2 so that the frequency axis is sampled by the power of two [92]. The power of two dilation and transition are called dyadic scales and positions. The value of \(b_0\) is chosen to be 1 so that the time axis also have dyadic sampling [112]. Thus the final equation for discrete wavelet transform is given by:
\[
\psi_{m,n}(t) = \frac{1}{\sqrt{2^m}} \psi \left( \frac{t - n2^m}{2^m} \right) \quad (4.19)
\]

4.2.4.1 Level of Decomposition and Relationship with Frequency Band

The maximum number of wavelet decomposition levels for DWT is determined by the length of the original signal and the particular mother wavelet being selected. If the number of samples is \(2^n\), then the maximum level of decomposition is given by:

\[
\text{Max Level} = \log_2 n \quad (4.20)
\]

In theory, the decomposition can proceed until the signal consist of a single sample, however, in practice, the level is selected based on the nature of the signal, or on a suitable criterion such as entropy.

Each of the decomposition level corresponds to a specific frequency band. In this example, the maximum frequency would be half of the sampling frequency, satisfying the Nyquist frequency, which is 5000 Hz. If the signal is decomposed into a number of level that is less than the maximum level of decomposition, the highest level will contain the rest of the lower frequencies.

Figure 4.18 shows the relationship between the frequency and the level of decomposition.

![Figure 4.18: Relationship between frequency and level of decompositions](image)

**Figure 4.18: Relationship between frequency and level of decompositions**
The decomposition of the fundamental mode ferroresonance voltage signal in Figure 4.19(a) into 7 decomposition levels is shown in Figure 4.19(c). The voltage signal is decomposed using DWT for 7 levels of decomposition using the same mother wavelet ‘db5’ shown in Figure 4.19(b). The frequency axis (level) for DWT is not as smooth as in CWT (scales) in Figure 4.17 because the dilation of the mother wavelet is performed discretely. The 7 levels of frequency band are obviously seen from the figure. The y-axis is log in scale because $a=2^m$ and the x-axis is linear in scale. The coefficient is high at level 7 before 0.1s because the signal frequency is 60Hz, which falls in the level 7 frequency band. After 0.19s, the coefficient is higher at level 6 and 5, referring to the frequency between 60Hz and 240Hz. Level 1 consists of a high frequency component, which is due to the discontinuity in the signal. It can be seen at 0.05s where there is a change in the signal due to switching, level 1 has noticeable coefficient and at 0.055 the coefficient at level 1 is bigger than at 0.005 due to the changes in the magnitude and frequency of the signal. After 0.19s, level 1 coefficient is more obvious due to the discontinuity of the signal during sustained fundamental mode ferroresonance.
Figure 4.19: DWT of fundamental mode ferroresonance signal

The plot of coefficients values in Figure 4.19 might not be useful for some applications. Thus, the value of the coefficients can be represented in terms of signals with respect to each level of decomposition. These signals can be manipulated further as discussed in the following section.

4.2.4.2 Multi resolution Analysis (MRA)

Equation (4.15) is similar to finite impulse response (FIR) filter equation as given in (4.21) and (4.22). This is why DWT is also known as multi stage filter bank and Multi-resolution Analysis (MRA) [112, 113].

\[
DWT(m, n) = \frac{1}{\sqrt{a_0^m}} \sum_{0}^{N-1} x[k] \psi [a_0^{-m} n - k]
\]  

(4.21)

\[
y[n] = \frac{1}{c} \sum_{0}^{N-1} x[k] h[n - k]
\]  

(4.22)

In MRA, there are two function involved, namely the wavelet function and the scaling function. The wavelet function (mother wavelet) generates Detail coefficients \((D)\) and
the scaling function generates *Approximation coefficients* \( A \). This can be mathematically presented as

\[
    f(t) = \sum_{k} c_0(k) \phi(t - k) + \sum_{j=0}^{j-1} \sum_{k} d_j(k) 2^j \psi(2^j t - k)
\]

(4.23)

where \( \phi(t) \) is the scaling function, \( \psi(t) \) is the wavelet function, \( c_0 \) is the scaling coefficient, \( d_j \) is the wavelet coefficient at level \( j \) and \( J \) is the maximum level of decomposition.

The scaling coefficient is also known as the *Approximation Coefficient* and the wavelet coefficient is also known as the *Detail Coefficient*. The scaling function can also be dilated and translated as given by the following equation.

\[
    \phi(a,b) = \frac{1}{\sqrt{a}} \phi\left(\frac{t-b}{a}\right)
\]

(4.24)

The wavelet function and scaling function can be interpreted as finite impulse response (FIR) of high pass, \( h[n] \) and low pass filters, \( g[n] \), respectively. The process of dilation of the mother wavelet and the scaling function to extract high frequency and low frequency components of the signal is equivalent to filtering the signal through high pass and low pass filters. Figure 4.20 shows the decomposition of a sample voltage signal \( x[n] \) in Figure 4.17 (a), into three levels of decompositions. The signal \( x[n] \) is decomposed into level 1 *Detail coefficients*, \( D1 \) and *Approximation coefficients*, \( A1 \). The decomposition process consists of filtering and down sampling. The filter outputs after subsampled by 2 are given by the following equations:

\[
    y_{low}[n] = \sum_{k=-\infty}^{\infty} x[k] g[2n - k]
\]

(4.25)

\[
    y_{high}[n] = \sum_{k=-\infty}^{\infty} x[k] h[2n - k]
\]

(4.26)

where \( y_{low}[n] \) corresponds to \( A1 \) and \( y_{high}[n] \) corresponds to \( D1 \). The *Approximation coefficients*, \( A1 \) are further decomposed into the second level of decomposition to produce another *Approximation coefficients*, \( A2 \) and *Detail coefficients*, \( D2 \). The
process is repeated for $A_2$ to obtain $A_3$ and $D_3$. Further decomposition can be repeated if higher resolution is desired.

![Figure 4.20: DWT Three Levels of Decomposition](image)
Figure 4.21 shows the decomposition of the fundamental mode ferroresonance signal into 7 different levels of decomposition.

![Figure 4.21: Sample signal and seven levels of Detail coefficient waveforms](image-url)
Depending on the application of the wavelet transform, each \textit{Detail} and \textit{Approximation} waveform can be manipulated further to extract features for signal classification purpose. One of the common parameters is to find the energy of the \textit{Detail} and \textit{Approximation} coefficients. From Parseval’s Theorem, if the scaling function and wavelets form an orthonormal basis, then the energy of the distorted signal can be partitioned in terms of expansion coefficients [90] given by:

\[
\int |f(t)|^2 \, dt = \sum_{k=-\infty}^{\infty} |c(k)|^2 + \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} |d_j(k)|^2
\]  

(4.27)

where \(c(k)\) is the \textit{Approximation} coefficient and \(d_j(k)\) is the \textit{Detail} coefficient at level \(j\).

The percent energy of each decomposition level is calculated for the sample signal in Figure 4.21 and is plotted in Figure 4.22.

\[
\sum_{k=-\infty}^{\infty} |d_j(k)|^2 * 100\% \quad \text{(4.28)}
\]

where \(j\) denotes the level of decomposition.
The energy concentrates in level 7 because level 7 has a frequency band between 78Hz to 0Hz, which consists of 60Hz frequency. The second harmonic and third harmonic are also present in the signal as shown in level 6 and 5, however, the percentage is very low. Note that the total energy of the Detail coefficients do not sum up to 100% because the remaining energy is distributed in the Approximation coefficients, \( c(k) \), which is not shown here.

These energy levels could be used as the features to classify a certain signal. One of the applications of MRA is to localize property in time and partitioning the signal energy at different frequency bands. This will present the frequency content of the distorted signal that can be applied to detect and diagnose defect and provide early warning of impending transient or power quality problems. However, most of the time, these values are manipulated further so that a feature can be extracted. For example in classifying power quality disturbances signals, Gaouda in [90] used the standard deviation of the Detail coefficients while [114] used the ratio of standard deviation to the mean of the Detail coefficients. This thesis uses the same method above to extract features for classification of ferroresonance modes. The sections below describe the application of MRA in transient detection and feature extraction.

### 4.2.5 Detection of a Transient

One of the special characteristics of wavelet transforms is localisation in time whereby the WT is able to detect the time when an abnormality occurs in a signal. This characteristic is very useful in the detection of any special occurrence in the signal. This section describes the detection of transient occurrences in ferroresonance signals. The detection is performed using wavelet transforms because the wavelet transform is able to locate the changes in time (localize in time). A signal that consists of period 1 and period 2 as shown in Figure 4.23 is used.
The objective is to find the time $t_1$, which is the time when the signal goes into the transient period. Time $t_1$ is important because it detects the inception of the ferroresonance. Time $t_1$ is the indicator for the start of the classification algorithm. The algorithm starts analysing the transient period and analyse some features for ferroresonance mode classification.

The detection process is divided into two stages as shown in Figure 4.24. The first stage is the pre-processing where the mother wavelet (MW) and the threshold value are chosen. The second stage is the detection process itself, where the chosen MW and the threshold value are used to detect the time $t_1$.

4.2.5.1 Choosing the Threshold Value and the Mother Wavelet

In pre-processing, there are two parameters that need to be chosen, which are the mother wavelet (MW) and the threshold value. The threshold value is the level 1
Detail coefficients value at time $t_1$ where the transient started. Figure 4.25 shows the time domain signal (in black) superimposed with the level 1 Detail coefficients waveform (in blue).

![Figure 4.25: Voltage signal (black) superimposed with Detail coefficients waveform (blue)](image)

During the changes in time domain signal at time 0.1s when the switching occurred, there is a high Detail coefficients magnitude of the detail waveform. The time when the Detail coefficients gets high is defined as time $t_1$. In order to detect the time $t_1$, the value of the coefficient is compared to the threshold value. The threshold value is a value that determines whether a transient has occurred or otherwise.

A simple algorithm is developed to choose the two parameters as shown in Figure 4.26. In order to know which mother wavelets (MW) are the most appropriate for this detection, all mother wavelets in MATLAB for DWT are tested. The MWs are put in an array. The algorithm begins by testing the first mother wavelet. An initial threshold value is chosen arbitrarily as 30. The signal is then decomposed using the ‘wavedec’ function in MATLAB into one level of decomposition and the chosen MW. The wavedec function is a MATLAB function that decomposes the signal into Detail coefficients and Approximation coefficients. Normally, one or two level of signal decomposition is adequate to discriminate disturbances from their background because the decomposed signals at lower scales consists of high time localization. As far as detection in power quality disturbances is concerned, two-scale signal
decomposition of the original signal is adequate to detect and localize the time when a transient occurs. Thus, level 1 Detail coefficients are used to detect the transient occurrence in this research.

The Detail coefficients are then reconstructed to obtain the blue waveform in Figure 4.25. The first coefficient value is compared with the initialized threshold value. If the coefficient value is smaller than the threshold value, another coefficient value is compared and the process is repeated until the coefficient value is larger than the threshold value. When the coefficient value is larger than the threshold value, the time associated with the threshold value is compared to the actual time. If the time is less than the actual switching time, then the process is repeated until the time is the same as or later than the actual switching time. The coefficient value and the time associated with the coefficient value are recorded. The recorded coefficient value will be used as the threshold value for the detection process.

The algorithm is performed on 15 samples of three different ferroresonance modes; fundamental, subharmonic and chaotic. 21 mother wavelets are tested. The results of the detection transient time $t_1$, and the threshold value for each mother wavelet are tabulated in Table 4.3. As can be seen from the table, some of the mother wavelets are able to detect the transient time consistently for 15 different samples such as $db5$, $db6$, $db7$, $db8$, $sym5$, $sym6$, $sym7$, $coif3$, $coif4$ and $rbior1.5$, $rbior2.6$, $rbior2.8$, $rbior6.8$. These mother wavelets produce two different detection times, which is 0.1004s and 0.0998s. Due to the sampling frequency that is chosen during simulation, time 0.1000s was not available in the simulation. Thus the closest time was 0.0998s and 0.1004s.

$Db5$, $db6$, $sym6$, $sym8$ and $rbior2.6$, $rbior2.8$, $rbior6.8$ have detection time of 0.1004s and the rest of mother wavelets have detection time of 0.0998s. Since the actual switching time is at $t=0.1s$, the 0.0998s is the time before the switching. Thus 0.1004s is chosen as the switching time with only 0.4% second of inaccuracy. The possible mother wavelets and threshold values should be either $db5$, $db6$, $sym6$, $sym8$ or $rbior2.6$, $rbior2.8$ and $rbior6.8$. According to [94], $db6$ works well in most of the detections cases, thus $db6$ is the chosen mother wavelet to be used in this detection process.
Referring to Table 5.1 on the $db6$ results, different ferroresonance modes have different \textit{Detail} coefficient values, ranging from 400 to 540, as highlighted. Thus 400 is chosen as the threshold value for the detection of ferroresonance transient.

![Flow chart of pre-processing to choose a mother wavelet](image)

\textbf{Figure 4.26: Flow chart of pre-processing to choose a mother wavelet}
Table 4.3: Results of detection time $t_l$ and coefficient values in choosing the threshold voltage

<p>|        | db5     |        | db6     |        | db7     |        | db8     |        | db9     |        | Sym5    |        | Sym6    |        | Sym7    |        | Sym8    |        | Coif3   |        | Coif4   |        |
|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|--------|---------|
|        | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value | time    | Coef Value |
| Subh 1 | 0.1004  | 433.94   | 0.1004  | 526.51   | 0.0998  | 420.78   | 0.0998  | 427.28   | 0.0998  | 419.77   | 0.0998  | 792.36   | 0.1004  | 732.25   | 0.1009  | 615.19   | 0.1004  | 752.61   | 0.1004  | 565.2    | 0.1009  | 730.35   |
| Subh 2 | 0.1004  | 438.19   | 0.1004  | 535.48   | 0.0998  | 429.01   | 0.0998  | 453.94   | 0.0998  | 488.74   | 0.0998  | 819.43   | 0.1004  | 756.38   | 0.1009  | 725.55   | 0.1004  | 797.53   | 0.1004  | 594.43   | 0.1009  | 700.00   |
| Subh 3 | 0.1004  | 436.91   | 0.1004  | 532.05   | 0.0998  | 426.23   | 0.0998  | 441.13   | 0.0998  | 463.73   | 0.0998  | 810.23   | 0.1004  | 748.23   | 0.1009  | 687.26   | 0.1004  | 781.97   | 0.1004  | 584.01   | 0.1009  | 713.03   |
| Fund 1 | 0.1004  | 325.94   | 0.1004  | 459.05   | 0.0998  | 298.80   | 0.0998  | 325.51   | 0.1034  | 708.12   | 0.0998  | 496.18   | 0.1004  | 464.44   | 0.1035  | 767.83   | 0.1004  | 413.73   | 0.1004  | 409.33   | 0.1004  | 360.25   |
| Fund 2 | 0.1004  | 295.17   | 0.1004  | 420.04   | 0.0998  | 270.16   | 0.0998  | 298.69   | 0.0998  | 233.36   | 0.0998  | 444.92   | 0.1004  | 417.12   | 0.1035  | 389.33   | 0.1004  | 371.63   | 0.1004  | 375.88   | 0.1004  | 338.16   |
| Chao 1 | 0.1004  | 419.07   | 0.1004  | 518.96   | 0.0998  | 397.95   | 0.0998  | 382.79   | 0.1024  | 386.96   | 0.0998  | 716.23   | 0.1004  | 664.12   | 0.1014  | 548.91   | 0.1014  | 638.94   | 0.1004  | 505.34   | 0.1009  | 702.28   |
| Chao 2 | 0.1004  | 424.93   | 0.1004  | 519.27   | 0.0998  | 406.47   | 0.0998  | 394.64   | 0.1014  | 468.33   | 0.0998  | 744.37   | 0.1004  | 689.21   | 0.1014  | 722.00   | 0.1004  | 678.58   | 0.1004  | 523.72   | 0.1009  | 730.80   |
| Chao 3 | 0.1004  | 410.07   | 0.1004  | 518.88   | 0.0998  | 386.98   | 0.0998  | 374.18   | 0.1014  | 518.38   | 0.0998  | 684.18   | 0.1004  | 635.21   | 0.1019  | 659.01   | 0.1004  | 597.46   | 0.1004  | 488.46   | 0.1009  | 646.36   |
| Chao 4 | 0.1004  | 399.49   | 0.1004  | 517.43   | 0.0998  | 374.27   | 0.0998  | 367.06   | 0.1019  | 717.14   | 0.0998  | 650.06   | 0.1004  | 604.61   | 0.1024  | 534.72   | 0.1004  | 473.63   | 0.1009  | 571.7     |
| Chao 5 | 0.1004  | 395.05   | 0.1004  | 516.00   | 0.0998  | 369.80   | 0.0998  | 365.27   | 0.1019  | 744.58   | 0.0998  | 639.43   | 0.1004  | 594.71   | 0.1024  | 395.02   | 0.1004  | 545.19   | 0.1004  | 469.11   | 0.1009  | 545.21   |</p>
<table>
<thead>
<tr>
<th></th>
<th>Coif5</th>
<th>Bior 5.5</th>
<th>Bior 6.8</th>
<th>Reverse Bior 1.5</th>
<th>Reverse Bior 2.6</th>
<th>Reverse Bior 2.8</th>
<th>Reverse Bior 3.7</th>
<th>Reverse Bior 3.9</th>
<th>Reverse Bior 6.8</th>
<th>D Meyer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subh 1</td>
<td>0.1009</td>
<td>1173.98</td>
<td>0.0998</td>
<td>473.36</td>
<td>0.1014</td>
<td>604.42</td>
<td>0.0998</td>
<td>735.6</td>
<td>0.1004</td>
<td>697.59</td>
</tr>
<tr>
<td>Subh 2</td>
<td>0.1009</td>
<td>1163.85</td>
<td>0.0998</td>
<td>491.07</td>
<td>0.1014</td>
<td>572.58</td>
<td>0.0998</td>
<td>755.44</td>
<td>0.1004</td>
<td>715.81</td>
</tr>
<tr>
<td>Subh 3</td>
<td>0.1009</td>
<td>1171.05</td>
<td>0.0998</td>
<td>485.03</td>
<td>0.1014</td>
<td>587.21</td>
<td>0.0998</td>
<td>748.79</td>
<td>0.1004</td>
<td>709.76</td>
</tr>
<tr>
<td>Subh 4</td>
<td>0.1009</td>
<td>1174.35</td>
<td>0.0998</td>
<td>479.17</td>
<td>0.1014</td>
<td>597.8</td>
<td>0.0998</td>
<td>742.18</td>
<td>0.1004</td>
<td>703.87</td>
</tr>
<tr>
<td>Subh 5</td>
<td>0.1009</td>
<td>1163.87</td>
<td>0.0998</td>
<td>462.65</td>
<td>0.1014</td>
<td>607.24</td>
<td>0.0998</td>
<td>723.24</td>
<td>0.1004</td>
<td>686.36</td>
</tr>
<tr>
<td>Fund 1</td>
<td>0.1004</td>
<td>325.62</td>
<td>0.103</td>
<td>381.56</td>
<td>0.1004</td>
<td>370.38</td>
<td>0.0998</td>
<td>482.39</td>
<td>0.1004</td>
<td>459.92</td>
</tr>
<tr>
<td>Fund 2</td>
<td>0.1004</td>
<td>314.16</td>
<td>0.104</td>
<td>374.41</td>
<td>0.1004</td>
<td>344.83</td>
<td>0.0998</td>
<td>433.47</td>
<td>0.1004</td>
<td>413.32</td>
</tr>
<tr>
<td>Fund 3</td>
<td>0.1004</td>
<td>302.52</td>
<td>0.104</td>
<td>522.48</td>
<td>0.1004</td>
<td>330.7</td>
<td>0.0998</td>
<td>412.04</td>
<td>0.1004</td>
<td>393.02</td>
</tr>
<tr>
<td>Fund 4</td>
<td>0.1009</td>
<td>406.94</td>
<td>0.103</td>
<td>515.2</td>
<td>0.1004</td>
<td>383.63</td>
<td>0.0998</td>
<td>545.06</td>
<td>0.1004</td>
<td>519.53</td>
</tr>
<tr>
<td>Fund 5</td>
<td>0.1019</td>
<td>442.56</td>
<td>0.103</td>
<td>491.48</td>
<td>0.1004</td>
<td>380.73</td>
<td>0.0998</td>
<td>512.42</td>
<td>0.1004</td>
<td>488.66</td>
</tr>
<tr>
<td>Chao 1</td>
<td>0.1009</td>
<td>1042.27</td>
<td>0.1019</td>
<td>687.88</td>
<td>0.1014</td>
<td>533.99</td>
<td>0.0998</td>
<td>676.86</td>
<td>0.1004</td>
<td>643.36</td>
</tr>
<tr>
<td>Chao 2</td>
<td>0.1009</td>
<td>1116.39</td>
<td>0.0998</td>
<td>442.44</td>
<td>0.1014</td>
<td>584.83</td>
<td>0.0998</td>
<td>699.02</td>
<td>0.1004</td>
<td>663.75</td>
</tr>
<tr>
<td>Chao 3</td>
<td>0.1009</td>
<td>926.9</td>
<td>0.1019</td>
<td>448.52</td>
<td>0.1014</td>
<td>448</td>
<td>0.0998</td>
<td>650.67</td>
<td>0.1004</td>
<td>618.8</td>
</tr>
<tr>
<td>Chao 4</td>
<td>0.1009</td>
<td>786.83</td>
<td>0.1035</td>
<td>649.94</td>
<td>0.1019</td>
<td>965.42</td>
<td>0.0998</td>
<td>622.02</td>
<td>0.1004</td>
<td>592.17</td>
</tr>
<tr>
<td>Chao 5</td>
<td>0.1009</td>
<td>739.92</td>
<td>0.1035</td>
<td>745.11</td>
<td>0.1019</td>
<td>902.7</td>
<td>0.0998</td>
<td>612.73</td>
<td>0.1004</td>
<td>583.16</td>
</tr>
</tbody>
</table>
The second stage of the detection process is the actual detection. The chosen mother wavelet and threshold value of 400 from the pre-processing stage are used. The detection process is depicted in Figure 4.27.

Figure 4.27: Flow chart of detection process
The data window size of $5T_0$ that consists of period 1 and period 2 signal portions are processed. The signal is decomposed into one level decomposition using the $db6$ mother wavelet to obtain level 1 Detail coefficients. The coefficients are then reconstructed to obtain the level 1 Detail coefficients waveform. Each value in the waveform is compared to the threshold value which is 400. The process is repeated until the coefficient value is larger than the threshold value. The time when the coefficient value is larger than the threshold value is considered to be the time $t_i$. The algorithm is tested on 72 voltage signals depicted in Figure 3.17. Out of 72 simulations, there are three simulations that does not give the correct time as shown in Table 4.4. The result leads to 95.8% accuracy.

<table>
<thead>
<tr>
<th>Sim No</th>
<th>Detected Time</th>
<th>Sim No</th>
<th>Detected Time</th>
<th>Sim No</th>
<th>Detected Time</th>
<th>Sim No</th>
<th>Detected Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0993</td>
<td>19</td>
<td>0.1004</td>
<td>37</td>
<td>0.1004</td>
<td>55</td>
<td>0.1004</td>
</tr>
<tr>
<td>2</td>
<td>0.0993</td>
<td>20</td>
<td>0.1004</td>
<td>38</td>
<td>0.1004</td>
<td>56</td>
<td>0.1004</td>
</tr>
<tr>
<td>3</td>
<td>0.0993</td>
<td>21</td>
<td>0.1004</td>
<td>39</td>
<td>0.1004</td>
<td>57</td>
<td>0.1004</td>
</tr>
<tr>
<td>4</td>
<td>0.1004</td>
<td>22</td>
<td>0.1004</td>
<td>40</td>
<td>0.1004</td>
<td>58</td>
<td>0.1004</td>
</tr>
<tr>
<td>5</td>
<td>0.1004</td>
<td>23</td>
<td>0.1004</td>
<td>41</td>
<td>0.1004</td>
<td>59</td>
<td>0.1004</td>
</tr>
<tr>
<td>6</td>
<td>0.1004</td>
<td>24</td>
<td>0.1004</td>
<td>42</td>
<td>0.1004</td>
<td>60</td>
<td>0.1004</td>
</tr>
<tr>
<td>7</td>
<td>0.1004</td>
<td>25</td>
<td>0.1004</td>
<td>43</td>
<td>0.1004</td>
<td>61</td>
<td>0.1004</td>
</tr>
<tr>
<td>8</td>
<td>0.1004</td>
<td>26</td>
<td>0.1004</td>
<td>44</td>
<td>0.1004</td>
<td>62</td>
<td>0.1004</td>
</tr>
<tr>
<td>9</td>
<td>0.1004</td>
<td>27</td>
<td>0.1004</td>
<td>45</td>
<td>0.1004</td>
<td>63</td>
<td>0.1004</td>
</tr>
<tr>
<td>10</td>
<td>0.1004</td>
<td>28</td>
<td>0.1004</td>
<td>46</td>
<td>0.1004</td>
<td>64</td>
<td>0.1004</td>
</tr>
<tr>
<td>11</td>
<td>0.1004</td>
<td>29</td>
<td>0.1004</td>
<td>47</td>
<td>0.1004</td>
<td>65</td>
<td>0.1004</td>
</tr>
<tr>
<td>12</td>
<td>0.1004</td>
<td>30</td>
<td>0.1004</td>
<td>48</td>
<td>0.1004</td>
<td>66</td>
<td>0.1004</td>
</tr>
<tr>
<td>13</td>
<td>0.1004</td>
<td>31</td>
<td>0.1004</td>
<td>49</td>
<td>0.1004</td>
<td>67</td>
<td>0.1004</td>
</tr>
<tr>
<td>14</td>
<td>0.1004</td>
<td>32</td>
<td>0.1004</td>
<td>50</td>
<td>0.1004</td>
<td>68</td>
<td>0.1004</td>
</tr>
<tr>
<td>15</td>
<td>0.1004</td>
<td>33</td>
<td>0.1004</td>
<td>51</td>
<td>0.1004</td>
<td>69</td>
<td>0.1004</td>
</tr>
<tr>
<td>16</td>
<td>0.1004</td>
<td>34</td>
<td>0.1004</td>
<td>52</td>
<td>0.1004</td>
<td>70</td>
<td>0.1004</td>
</tr>
<tr>
<td>17</td>
<td>0.1004</td>
<td>35</td>
<td>0.1004</td>
<td>53</td>
<td>0.1004</td>
<td>71</td>
<td>0.1004</td>
</tr>
<tr>
<td>18</td>
<td>0.1004</td>
<td>36</td>
<td>0.1004</td>
<td>54</td>
<td>0.1004</td>
<td>72</td>
<td>0.1004</td>
</tr>
</tbody>
</table>
4.2.6 Feature Extraction

Feature extraction is defined as transforming input data into a set of features. The features extracted are able to represent the signal in different forms that can be manipulated to perform the desired task such as classification. The type of features are very dependent on the signal being analysed. For example in image processing, colour, texture and edges are the common features being extracted to identify certain image. In a power system, all of feature extraction is mainly used in the classification of the signal, particularly in the power quality problems and the transient analysis. For example, Robertson in [93] used the extrema representation of the Detail coefficients waveform as features to classify power systems transients.

This section discusses the application of wavelet transform in distinguishing different modes of ferroresonance. The features are being extracted from the sustained and the transient periods of different modes of the ferroresonance voltage signals. The objective is to distinguish different modes of ferroresonance in the sustained and transient periods. These obtained features may be used in the classification of ferroresonance modes in the future.

As in detection, the feature extraction process also requires pre-processing. The feature extraction process is divided into two stages, as shown in Figure 4.28. The first stage is the pre-processing, where the mother wavelet (MW) is chosen. The second stage is the feature extraction process, where the chosen MW is used to extract features from different modes of ferroresonance voltage signals.

**Figure 4.28: Feature extraction process**
4.2.6.1 Pre-processing: Choosing the Mother Wavelet

This section describes the pre-processing, which is the process to find the most appropriate mother wavelet to be used in decomposing the signal. Choosing the right mother wavelet is very important in order to obtain the expected results. The choice of mother wavelet depends on the application and the nature of the analyzed signal. Most of the applications use a mother wavelet that is most similar to the signal that is being analyzed. For example in [109], it is mentioned that the Mexican Hat mother wavelet is often used in vision analysis because the properties of the mother wavelet are similar to the human eyes. The author in [115] proposed an algorithm to choose a mother wavelet for analyzing power system fault transients by using the root mean square error between the original and the reconstructed signals. The result showed that symlet5 was the most suitable mother wavelet with the least root mean square error. For harmonic and interharmonics signals in [116], the dmey mother wavelet is the most suitable mother wavelet with the least mean square error. In other areas such as in medicine, [117] shows that other mother wavelets are more suitable for that particular application. Other publications on selection of mother wavelets can be found in [118]. In this thesis, the energy of Detail plot is used as the criteria in choosing the most appropriate mother wavelet. This mother wavelet will be used in the feature extraction of different modes of ferroresonance voltage signals. The process is depicted in Figure 4.29.

The voltage signals of three different modes of ferroresonance; fundamental, subharmonic and chaotic; are analyzed. Besides the ferroresonance voltage signals, another signal is also being analyzed, which is ‘no ferroresonance’ voltage signal. The no ferroresonance voltage signal is defined as the damping voltage signal after the switch is opened. This voltage signal does not lead to sustained ferroresonance but it will damp out and lead to no sustained ferroresonance phenomenon.
Figure 4.29: The Process of choosing the mother wavelet

There are six different sample signals that are processed, which are one fundamental mode voltage signal, one subharmonic mode voltage signal, two different chaotic mode voltage signals and two different no ferroresonance voltage signals. Two samples are taken from the chaotic mode voltage signals and no ferroresonance voltage signals because they have different waveforms during sustained period. The signals are shown in Figure 4.30. Some of the sustained period of the voltage signals are depicted in Figure 4.31. The system condition for which all of these different ferroresonance mode occur has been explained in Section 3.4
Figure 4.30: Samples of analysed signals (a) fundamental (b) subharmonic (c) chaotic 1 (d) chaotic 2 (e) no ferroresonance 1 (f) no ferroresonance 2
In order to determine which mother wavelet is the most appropriate for this transformation, all 21 different mother wavelets available for DWT in Matlab’s toolbox were tested. An algorithm to obtain the energy of each Detail is depicted in Figure 4.32.
Firstly, a list of mother wavelets is built and the first mother wavelet is tested. The voltage signal is decomposed using the maximum level of decomposition. The maximum level is calculated using the ‘wmaxlev’ function in MATLAB, where the function returns the value of the maximum level that can be applied to the signal. Different mother wavelets leads to different maximum levels of decomposition, depending on the number of filter points of each mother wavelet, as depicted in Table 4-5. For this analysis, 8 levels of decomposition are sufficient to discriminate between the subharmonic and the fundamental mode of the ferroresonance voltage signals. The Detail of how many levels a signal can be decomposed into has been discussed in Section 4.2.4.1.

Next, the voltage signal is decomposed using the chosen mother wavelet into the calculated level of decomposition. The energy of Detail and Approximation is calculated using the ‘wenergy’ function. This function calculates the energy of each level using (4.28). Lastly, the energy of each level is plotted. The process is repeated.
until all mother wavelet have been tested. By visual observation, the mother wavelets that can provide the best plot that can obviously distinguished between different modes of ferroresonance is chosen as the most appropriate mother wavelet.

<table>
<thead>
<tr>
<th>Type</th>
<th>Db5</th>
<th>Db6</th>
<th>Db7</th>
<th>Db8</th>
<th>Db9</th>
<th>Sym5</th>
<th>Sym6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition Level</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Sym7</th>
<th>Sym8</th>
<th>Coif3</th>
<th>Coif4</th>
<th>Coif5</th>
<th>Bior5.5</th>
<th>Bior6.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition Level</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Rbior1.5</th>
<th>Rbior2.6</th>
<th>Rbior2.8</th>
<th>Rbior3.7</th>
<th>Rbior3.9</th>
<th>Rbior6.8</th>
<th>DMey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition Level</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4.33 depicts the energy of the Detail coefficients for each tested signal with respect to different mother wavelets. As depicted in the graphs, the mother wavelets with decomposition levels equal to 8 have distinguished the energy distribution for different modes of ferroresonance. This is due to the sampling frequency of the signal, which is 7692 Hz. The detailed explanation of the relationship between the sampling frequency and the level of decomposition is described in Section 4.2.4.1. The results of different mother wavelets corresponds to the energy distribution with respect to the level of decomposition, and their distinguished features are summarized in Table 4-6.
Figure 4.33: Percent energy plots of Detail coefficients for 21 different mother wavelets

Table 4-6: Results of Energy Distribution

<table>
<thead>
<tr>
<th>Mother Wavelet</th>
<th>Energy Distribution for Voltage Signal Decomposing Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types</td>
<td>Maximum Level</td>
</tr>
<tr>
<td>Dmey</td>
<td>4</td>
</tr>
<tr>
<td>Rbio6.8</td>
<td>7</td>
</tr>
<tr>
<td>Rbio3.9</td>
<td>6</td>
</tr>
<tr>
<td>Rbiior3.7</td>
<td>7</td>
</tr>
<tr>
<td>Rbiior2.8</td>
<td>7</td>
</tr>
<tr>
<td>Rbiior2.6</td>
<td>7</td>
</tr>
<tr>
<td>Rbiior1.5</td>
<td>8</td>
</tr>
<tr>
<td>Bior6.8</td>
<td>7</td>
</tr>
<tr>
<td>Bior5.5</td>
<td>7</td>
</tr>
<tr>
<td>Coif5</td>
<td>6</td>
</tr>
<tr>
<td>Coif4</td>
<td>6</td>
</tr>
<tr>
<td>Coif3</td>
<td>7</td>
</tr>
<tr>
<td>Sym8</td>
<td>7</td>
</tr>
<tr>
<td>Sym7</td>
<td>7</td>
</tr>
<tr>
<td>Sym6</td>
<td>7</td>
</tr>
<tr>
<td>Sym5</td>
<td>8</td>
</tr>
<tr>
<td>Db9</td>
<td>7</td>
</tr>
<tr>
<td>Db8</td>
<td>7</td>
</tr>
<tr>
<td>Db7</td>
<td>7</td>
</tr>
<tr>
<td>Db6</td>
<td>7</td>
</tr>
<tr>
<td>Db5</td>
<td>8</td>
</tr>
</tbody>
</table>

The summary in Table 4-6 shows that $rbior1.5$, $sym5$ and $db5$ mother wavelets have the highest energy distribution in all test signals making them the best mother wavelet.
candidates to be used in the feature extraction process. Consider the three distinguished mother wavelet results as shown in Figure 4.34, mother wavelets $db5$ and $rbior1.5$ shows that the fundamental mode ferroresonance has energy concentration in level 7 and the subharmonic mode ferroresonance has energy concentration in level 8. The energy distribution for the chaotic mode and the no ferroresonance signals are distributed in level 6, 7 and 8. Even though the chaotic and no ferroresonance signals have the same energy distribution, no ferroresonance signal has lower energy compared to chaotic mode signal.

For the $sym5$ mother wavelet, the energy distribution for the fundamental mode signal is concentrated in level 6. For the subharmonic mode signal, the energy distribution is concentrated in level 8, and for the chaotic mode signal the energy distribution is distributed between levels 6, 7 and 8, with higher concentration in levels 7 and 8. The energy distribution for no ferroresonance signals is also distributed in levels 6, 7 and 8 but at lower energy percentage compared to the chaotic mode signal.

Comparing the three possible mother wavelets, $db5$ is the best choice of the mother wavelets to be used in the feature extraction process. The features of each signals is presented in Table 4-7 where these features can be used for the future classification process.
Table 4-7 : Different features of ferroresonance signals

<table>
<thead>
<tr>
<th>Types</th>
<th>Energy Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Mode</td>
<td>level 7</td>
</tr>
<tr>
<td>Subharmonic Mode</td>
<td>level 8</td>
</tr>
<tr>
<td>Chaotic Mode</td>
<td>level 6, 7 and 8 with average energy is more than 30%</td>
</tr>
<tr>
<td>No Ferroresonance</td>
<td>level 6, 7 and 8 with average energy is less than 30%</td>
</tr>
</tbody>
</table>

4.2.6.2 Feature Extraction Process

From the pre-processing, it is concluded that the ‘db5’ mother wavelet is the best mother wavelet to be used in distinguishing different modes of ferroresonance voltage signals. The same algorithm is used to find the features for different modes of ferroresonance voltage signals in the sustained and the transient periods. The voltage signal is decomposed into eight levels of decomposition using the db5 mother wavelet. The data window is set to $5T_0$. The algorithm uses the energy distribution of Detail coefficients in each decomposition level as the feature. The energy for each level of Detail coefficients is calculated and the energy distribution is plotted with respect to their levels. Figure 4.35 shows the flow chart of the feature extraction process. The algorithm is performed on the sustained ferroresonance signal and the transient ferroresonance signals.
4.2.6.3 Sustained Signals

There are 72 voltage signals that are simulated by varying grading capacitance from 325pF until 7500pF. The value parameters for simulating different mode of ferroresonance are shown in Table 4.8.

Table 4.8: Parameters to simulation 72 ferroresonance signals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>325pF to 7500pF with 50pF increment for each simulation</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>187794.2136 V</td>
</tr>
<tr>
<td>Switching Time</td>
<td>0.1s</td>
</tr>
</tbody>
</table>
Figure 4.36 shows the plots of 72 voltage signals of different ferroresonance mode.

72 sustained ferroresonance signals are extracted from these signals from 0.5s until 1s. Each of this voltage signal is decomposed into eight levels of decomposition using ‘db5’ mother wavelet. The energy distribution of the Detail coefficients with respect to the eight decomposition levels is plotted in Figure 4.37 for all 72 signals with various capacitance values.

Figure 4.36 : Voltage signal for grading capacitance variation

Figure 4.37 : Detail coefficients energy plots using db5 mother wavelet for 72 voltage signals
To distinguish which value of grading capacitance resulted in which ferroresonance mode, the modes of sustained ferroresonance voltage signals are summarized in Figure 4.38. For simplicity, the value of each capacitance is represented by a simulation number. The simulation number on the x-axis refers to different values of grading capacitance ranging from 325pF until 7500pF. The relation between the values of capacitance and the simulation number is that the consecutive value of the capacitance is increased by 50pF from the previous value. This means that Simulation number 1 refers to a grading capacitance value of 325pF, Simulation number 2 refers to 375pF, Simulation 3 refers to 425pF and so on.

![Figure 4.38: Summary of sustained ferroresonance mode of Figure 3.17 by observation](image)

In order to verify the energy distribution for each ferroresonance mode corresponding to Table 4-7, the energy distribution is plotted according to each ferroresonance mode in four different plots as depicted in Figure 4.39. The plots are categorized by their mode according to simulation number as tabulated in Table 4-9.

**Table 4-9 : Simulation number for each ferroresonance mode**

<table>
<thead>
<tr>
<th>Types</th>
<th>Simulation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Mode</td>
<td>37-43,45-72</td>
</tr>
<tr>
<td>Subharmonic Mode</td>
<td>3-10,12</td>
</tr>
<tr>
<td>Chaotic Mode</td>
<td>13,19-21,23-25,27-30,32-36</td>
</tr>
<tr>
<td>No Ferroresonance</td>
<td>1-2,11,14-18,22,26,31,44</td>
</tr>
</tbody>
</table>


Figure 4.39: The *Detail coefficients* energy plots for each mode: (a) fundamental, (b) subharmonic, (c) chaotic and (d) no ferroresonance

The plots show that the fundamental mode has energy concentration at level 7 and the subharmonic mode has energy concentration at level 8. However, the chaotic mode and the no ferroresonance signals require further analysis because some of the no ferroresonance signals have energy levels that are more than 30%. This value contradicts with the feature described in Table 4-7 where no ferroresonance signals have an energy level of less than 30%. The features for fundamental mode ferroresonance signals and the subharmonic mode ferroresonance signals are consistent with the features that is summarized in Table 4-7. The features of the sustained ferroresonance mode signal are shown in Table 4-10.
Table 4-10: Features of the sustained ferroresonance signals

<table>
<thead>
<tr>
<th>Types</th>
<th>Energy Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental Mode</td>
<td>level 7</td>
</tr>
<tr>
<td>Subharmonic Mode</td>
<td>level 8</td>
</tr>
<tr>
<td>Chaotic Mode</td>
<td>level 6, 7 and 8</td>
</tr>
<tr>
<td>No Ferroresonance</td>
<td>level 6, 7 and 8</td>
</tr>
</tbody>
</table>

4.2.6.4 Transient Signals

The same methodology is applied to the transient period of voltage signals. The objective is to find any feature than can be extracted for each ferroresonance mode during the transient period. Due to the similarity between the transient periods of each ferroresonance mode, two different input waveforms have been investigated as depicted in Table 4-11. The first waveform is the voltage signal and the second waveform is the correlation signal between the sustained period and the transient period.

Table 4-11: Type of waveform for transient feature extraction

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Input Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis 1</td>
<td>Voltage Signal</td>
</tr>
<tr>
<td>Analysis 2</td>
<td>Correlated signal</td>
</tr>
</tbody>
</table>

Energy Distribution of the Detail Coefficients of the Transient Voltage Signal

The first analysis is to calculated energy distribution using the transient period of voltage signals for each ferroresonance mode. The same algorithm in as Figure 4.35 is used. The transient voltage signals for each ferroresonance mode are decomposed into eight levels of decomposition using the db5 mother wavelets. The 72 transient signals retrieved from the same voltage signals are analysed. The size of the data window is $5T_0$. Samples of the transient period voltage signal for different modes of ferroresonance and no ferroresonance are depicted in Figure 4.40. Table 4.12 shows the parameters for simulation of the transient signals.
Table 4.12: Parameters for simulation of the transient ferroresonance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fundamental Mode</th>
<th>Subharmonic Mode</th>
<th>Chaotic Mode</th>
<th>No Ferroresonance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading Capacitance</td>
<td>5061 pF</td>
<td>625 pF</td>
<td>5061 pF</td>
<td>325 pF</td>
</tr>
<tr>
<td>Shunt Capacitance</td>
<td>10450 pF</td>
<td>10450 pF</td>
<td>10450 pF</td>
<td>10450 pF</td>
</tr>
<tr>
<td>Source Voltage</td>
<td>187794.2136 V</td>
<td>187794.2136 V</td>
<td>150235.3709 V</td>
<td>187794.2136 V</td>
</tr>
<tr>
<td>Switching Time</td>
<td>0.1 s</td>
<td>0.1 s</td>
<td>0.1 s</td>
<td>0.1 s</td>
</tr>
</tbody>
</table>

Figure 4.40: Sample signals for transient period of ferroresonance mode: (a) fundamental, (b) subharmonic, (c) chaotic (d) no ferroresonance

The plots of the energy distribution of the Detail for different ferroresonance modes are depicted in Figure 4.41. These plots refers to the same simulation number as in Table 4-9 for different ferroresonance modes.
Figure 4.41: Energy distribution for transient period of different ferroresonance mode: (a) fundamental, (b) subharmonic, (c) chaotic, (d) no ferroresonance

From the plots above, all the signal energy are concentrated at level 6. The fundamental mode has percent energy more than 10% while the subharmonic mode has percent energy which is less than 10%. However, the chaotic mode and no ferroresonance have percent energies which are more than 10% and less than 10%, respectively. Based on this simulation signals, for the transient period, the energy of the Detail do not have feature that can be used as feature extraction to classify the transient period of different mode of ferroresonance. Another analysis is conducted using the instantaneous power signal.

**Energy Distribution of Detail Coefficients of Correlated signal**

Another analysis is conducted to distinguish different modes of ferroresonance by using the correlated signals between the sustained and the transient period. Only two
sustained ferroresonance signals; sustained fundamental and sustained subharmonic, are considered here as summarized in Table 4-13.

**Table 4-13 : Two types of correlated waveforms for feature extraction process**

<table>
<thead>
<tr>
<th>Case</th>
<th>Sustained Signal</th>
<th>Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: Correlated Waveform 1</td>
<td>Fundamental Mode</td>
<td>Fundamental, Subharmonic, Chaotic, No Ferroresonance</td>
</tr>
<tr>
<td>Case 2: Correlated Waveform 2</td>
<td>Subharmonic Mode</td>
<td>Fundamental, Subharmonic, Chaotic, No Ferroresonance</td>
</tr>
</tbody>
</table>

The transient period of all different modes of ferroresonance voltage signals are correlated with the sustained period of fundamental and subharmonic modes. For example, for case 1 above, the sustained fundamental mode voltage signal as in Figure 4.42(a) is correlated with the fundamental mode of ferroresonance transient period signal such as in Figure 4.42(b). The resultant correlated waveform is shown in Figure 4.43(a). Samples of other correlated waveforms for are depicted in Figure 4.43(b), (c) and (d) for subharmonic, chaotic and no ferroresonance signals, respectively.

![Figure 4.42: Sample voltage signals for (a) sustained period of fundamental mode and (b) transient signal of fundamental mode](image)
Figure 4.43: Samples of correlation waveforms of sustained fundamental mode with: (a) transient fundamental, (b) transient subharmonic, (c) transient chaotic, (d) transient no ferroresonance

These waveforms are then processed using the same algorithm as in Figure 4.35 to produce the plots for energy distribution of Detail coefficient as shown in Figure 4.44.

Figure 4.44: Detail coefficients energy distribution for four different correlated signals
Referring to Figure 4.44, the fundamental mode has energy concentrated at level 7, the subharmonic and the chaotic mode have their energy concentrated at level 6 and 7 while the no ferroresonance signal has its energy concentrated at level 6. These energy concentrations at different levels are the distinguishing features for different modes of ferroresonance during the transient period.

The energy plots of Detail coefficients of the correlated signals between sustained fundamental and 72 transient voltage signals in Figure 3.17 are shown in Figure 4.45. The energy distribution is not obvious so the plots are separated according to their mode as depicted in Figure 4.46. As can be seen, for the fundamental mode and the subharmonic mode, the energy concentrations are consistent for all the tested signals. The energy for the transient fundamental mode concentrates at level 7 and the energy for the transient subharmonic mode concentrates at level 6. However, the transient chaotic mode and the transient no ferroresonance have energies concentrated at level 6 and 7. Thus, based on this simulation, it is not possible to use the energy of Detail coefficients of the correlated signals as features for distinguishing between different modes of transient ferroresonance signals.

![Energy plots of Detail coefficients](image)

Figure 4.45: Energy plots of Detail coefficients for correlated signals between sustained fundamental and 72 voltage signals in Figure 3.17 using db5 mother wavelet
The University of Manchester

Signal Analysis

Figure 4.46: Energy plots of Detail coefficients for correlated signal for (a) fundamental mode (b) subharmonic mode (c) chaotic mode (d) no ferroresonance mode

The same analysis is performed on case 2, where different mode of ferroresonance transient signals are correlated with the sustained subharmonic mode ferroresonance as described in Table 4-13. A sample of correlated signal is shown in Figure 4.47(a) and the energy plots of Detail coefficients of the four different correlated signals are shown in Figure 4.47(b).

Figure 4.47: A sample of correlated signal between a sustained subharmonic signal and a transient signal and (b) the Detail coefficient energy distribution for four different correlated signals
As can be observed from the energy plot, there is no difference between any of the energy distribution of the correlated signals. All three modes of ferroresonance signals and the no ferroresonance signal have energies concentrated at level 8. This is shown by the plots of energy distribution of Detail coefficients for the 72 voltage signals correlated with the sustained subharmonic in Figure 4.48. Thus, it is concluded that based on these simulated signals, the transient voltage signals of different ferroresonance modes do not have distinguishing features that can be used for feature extraction process.

![Energy Distribution Plot](image)

**Figure 4.48:** Energy plots of Detail coefficients for correlated signals between sustained subharmonic and 72 voltage signals in Figure 3.17 using db5 mother wavelet

### 4.3 Chapter Summary

The main objective of this chapter is to perform signal analysis on different modes of ferroresonance signals using Fourier and wavelet transforms. Fourier analysis is used to find the magnitude spectrum of the ferroresonance signal. The results of the magnitude spectrums have validated the characteristic of sustained ferroresonance mode voltage and current signals in the literature. It shows that different modes of ferroresonance have different frequency components. It can be observed from sustained ferroresonance that the voltage and current of all three modes of ferroresonance have spectra of different magnitudes. The fundamental mode has a spectrum that is the odd multiples of the system frequency. For the subharmonic
mode, there exist sub-frequencies \((1/n)\) of the system frequency. For the chaotic mode, the spectrum has a broadband frequency. These distinguished features are consistent with the classification of ferroresonance modes described by researchers in most publications.

In the transient period of ferroresonance voltage signals, all of the magnitude plots have continuous spectra. This is due to the non-periodic signal during the transient period. The modes of ferroresonance cannot be concluded by just looking at the magnitude spectrum. No distinguished characteristic or feature can be extracted from the transient period of different ferroresonance mode using the Fourier transform.

The limitation of Fourier Transform is observed when all three periods of ferroresonance signal is transformed using FFT. The transformation did not show the time when the transient occurred. Thus, FFT is not applicable in the detection of the inception of the transient.

Two main applications of wavelet transform are the detection of the inception of the transient and extraction of features for ferroresonance signals classification. It was confirmed that the choice of mother wavelets plays an important role when performing wavelet transform. The choice of mother wavelets depends on a few criteria such as the similarity of the analysed signal with the mother wavelet. The mother wavelet can also be arbitrarily chosen based on experience of other researchers. In this thesis, a mother wavelet is chosen very carefully by developing an algorithm to test all mother wavelets available for 1-dimensional DWT in the MATLAB’s toolbox. By developing an algorithm and testing all mother wavelets available in the toolbox, choosing the best mother wavelet is justifiable. From the result of the analysis, the choice of mother wavelet are narrowed down into a few suitable mother wavelets. From these few suitable mother wavelets, one mother wavelet is chosen which will provide the best expected output. It is observed that the chosen mother wavelets in these analyses are similar to the signal being analysed. These choices have validated the guideline given in the literature that a mother wavelet is usually chosen based on its similarity to the analysed signal.

Another important parameter when performing a wavelet transform is the level of decomposition. The level of decomposition depends on the number of samples in the
analysed signal and the aim of the analysis. For detection purposes, 1 level decomposition is sufficient to provide the information sought. However, for feature extraction, the user should have some idea of the frequency band of each level of Detail coefficients to determine how many levels are required to obtain the expected results.

The results of detection shows that level 1 Detail coefficients successfully detects the inception of the transient for each mode of ferroresonance with almost 100% accuracy.

The results of feature extraction shows that feature extraction of sustained ferroresonance signals is able to distinguish the fundamental and the subharmonic modes ferroresonance. However, the chaotic mode requires further analysis so that it can be distinguished from the no ferroresonance signals. On contrary, from this simulated signals, the transient period of all different modes ferroresonance are unable to be distinguished. Further analysis should be performed before the transient period of ferroresonance signals can be classified.
Chapter 5

5 Real Data Analysis

This chapter presents the real case of ferroresonance phenomenon occurred in a voltage transformer. The real signal is analysed using Fourier transform and wavelet transform to validate the results obtained from Chapter 4. The beginning of the chapter provides a real case scenario of the ferroresonance occurrence. Then Fourier Transform and wavelet transform analyses are conducted using the real data. The limitation of the data is that only fundamental mode is available. Other modes are not available to be tested on the algorithm.

5.1 Field Test Data

The field test data is obtained from M. Val Escudero which has been reported in [38, 43]. Ferroresonance had occurred at a new 400kV substation in Ireland. The system frequency is 50 Hz. The substation is equipped with inductive voltage transformers and circuit breakers with grading capacitors. Switching operation performed during commissioning had caused two inductive voltage transformers being driven into sustained ferroresonance. The single line diagram is shown in Figure 5.1.

![Figure 5.1: Single line diagram of the line bay involved in ferroresonance [43]](image-url)
During the incident, the line disconnector (DL) was open and the busbar disconnector was closed. The ferroresonance was initiated by opening the circuit breaker (CB). When the circuit breaker was open, the inductive Voltage Transformers (VTs) were de-energized through grading capacitance of the open circuit breaker.

The ferroresonance measurements were taken from a protection relay. Sustained overvoltage of 2p.u. were recorded in two phases. Figure 5.2 shows the recorded waveforms of the sustained fundamental mode ferroresonance at two phases. The data is recorded for 1700ms. The normal period is between 0ms to 200ms. The transient period is between 200ms and 600ms and the sustained fundamental mode is between 600ms and 1700ms.

![Figure 5.2: Field recordings of ferroresonance waveforms; phase ‘a’ (red), phase ‘b’ (green), phase ‘c’ (blue)](image)
5.2 Fourier Transform

Fourier transform is conducted on the real data in order to find the magnitude spectrum of the sustained and transient period. Figure 5.3(a) and (b) show the 1700ms of recorder signal that consists of period 1, period 2 and period 3 of fundamental mode ferroresonance voltage signal and its FFT, respectively.

![Figure 5.3: Real recording of fundamental mode ferroresonance (a) voltage signal (b) its FFT](image)

The FFT of the three period signal shows the magnitude spectrum of 50Hz and the third and fifth odd harmonics. There are some broadband frequency between 0Hz and 50Hz and also between 50Hz and 100Hz. However, the magnitude is very small if compared to the fundamental frequency.

**Sustained Signal**

Figure 5.4(a) shows the sustained part of the real recording of the voltage signal of fundamental mode ferroresonance. The system frequency is 50Hz and the sampling frequency is 1kHz. In the FFT, there exists third harmonic and fifth harmonic in the signal. Seventh and ninth harmonics also present but their magnitudes are very small. This FFT has validated the characteristic of the fundamental mode whereby the fundamental mode ferroresonance consists of the fundamental and its multiple, especially the odd multiples.
Figure 5.4: Real recording of sustained fundamental mode ferroresonance (a) voltage signal (b) FFT

Transient Signal

Figure 5.5(a) shows the real recording of the transient part of voltage signal of fundamental mode ferroresonance and Figure 5.5(b) shows its FFT. It can be observed from the FFT, the main component of the transient signal is still 50Hz. However, the odd harmonics are not obvious in the signal. There exists subharmonics in the transient part of the fundamental mode ferroresonance, such as 20Hz and 35Hz.

Figure 5.5: Real recording of transient fundamental mode ferroresonance (a) voltage signal (b) FFT
5.3 Wavelet Analysis

The same signal is analysed using wavelet transform for detection of transient and feature extraction.

5.3.1 Detection

The detection algorithm is tested on the real signal. The threshold value that is used in the simulation signal cannot detect the start of the transient correctly. This is due to two main reasons: (a) the frequency of the signal, which is 50Hz, not 60Hz and (b) the noise in the real signal that appears in the Detail coefficient of level 1 decomposition. Therefore, the threshold value is increased to 500 and the transient was detected at 230ms which is 30ms after the switch is open.

5.3.2 Feature Extraction

The real signal is processed to find any distinguished feature between different modes of ferroresonance. Both of the sustained and transient of the voltage signals are being analysed.

Simulation signals in Chapter 4 are referring to 60Hz system while this real signal is based on 50Hz system. Thus, the features extracted from of the real signal will not be the same as the simulated signal. However, the methodology is the same. As mentioned in the previous chapter, the decomposition of a signal using WT depends on two important values, which are the sampling frequency and the number of samples.

5.3.2.1 Sustained Signal

For sustained signal analysis, the voltage signal of 512 samples is extracted from 800ms to 1311ms. This real signal has a sampling frequency of 1kHz. In theory, the signal can be decomposed into 8 decomposition levels. However, the function `maxlevel` in MATLAB proposed a maximum level of 5 decomposition levels. Referring to this levels, the frequency band of each level is shown in Figure 5.6. As
can be seen, fundamental frequency of 50Hz will fall within level 4. Thus the sustained fundamental ferroresonance should have the higher energy concentrated at level 4.

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>31.25 Hz</td>
</tr>
<tr>
<td>4</td>
<td>62.5 Hz</td>
</tr>
<tr>
<td>3</td>
<td>125 Hz</td>
</tr>
<tr>
<td>2</td>
<td>250 Hz</td>
</tr>
<tr>
<td>1</td>
<td>500 Hz</td>
</tr>
</tbody>
</table>

Figure 5.6: Relationship between frequency and level of decompositions

Figure 5.7: The sustained voltage signal and the corresponding Detail coefficient waveforms for each level of decomposition
The sustained fundamental mode ferroresonance voltage signal is decomposed into 5 levels of decomposition. The analysed voltage signal and the *Detail* coefficient waveforms for each level of decomposition are shown in Figure 5.7. The energy of each level is calculated and as expected, the energy of the signal is concentrated at level 4 as shown in Figure 5.8. Both phase *a* and phase *c* signal are analysed and both signals produces the same features.

![Energy Distribution](image)

**Figure 5.8**: The *Detail* coefficients energy plots of the sustained signals for phase *a* and *c*

### 5.3.2.2 Transient Signal

For the transient signal, two different waveforms are analysed: the voltage signal and the correlated signal as discussed in Chapter 4.

**Voltage signal**

For transient voltage signal analysis, the voltage signal of 256 samples is extracted from 200ms to 456ms. In theory, the signal can be decomposed into 7 decomposition levels. However, the function *maxlevel* in MATLAB proposed a maximum of 4 decomposition levels. Since the sampling frequency is 1kHz, the frequency band of each level is the same as in Figure 5.6. The energy concentration should be at level 4 as well.
The transient fundamental mode ferroresonance voltage signal is decomposed into 4 levels of decomposition. The analysed voltage signal and the Detail coefficient waveforms for each level of decomposition for phase $a$ and phase $c$ are shown in Figure 5.9 and Figure 5.10, respectively.

**Figure 5.9**: The transient voltage signal of phase $a$ and the corresponding *Detail* coefficient waveforms for each level of decomposition
The transient voltage signal is concentrated at level 4 shown in Figure 5.11. Both phase a and phase c signals are analysed and both signals produce the same features.

Figure 5.10: The transient voltage signal of phase c and the corresponding Detail coefficient waveforms for each level of decomposition

The energy of each level is calculated and as expected, the energy of the transient voltage signal is concentrated at level 4 shown in Figure 5.11. Both phase a and phase c signals are analysed and both signals produce the same features.
The sustained voltage signal of fundamental mode ferroresonance is correlated with the transient signal of the fundamental mode. Figure 5.12 (a) and (b) show the transient signal and the sustained signal, respectively. The correlated waveform is shown in Figure 5.13. The function `maxlevel` in MATLAB proposed a maximum level of 6 decomposition levels. Since the sampling frequency is 1kHz, the frequency band of each level is the same as in Figure 5.6. The energy concentration should be at level 4 as well.

**Correlated signal**

Figure 5.11: The *Detail* coefficients energy plots of the transient signals for phase *a* and *c*

Figure 5.12: Field recording of (a) sustained signal (b) transient signal of fundamental ferroresonance mode

Figure 5.13: Correlated signal between sustained fundamental signal and transient fundamental signal of ferroresonance’s real recording signal
The correlated waveforms are decomposed into 6 levels of decomposition. The *Detail* coefficient waveforms for each level of decomposition are shown in Figure 5.14 and the energy plot is shown in Figure 5.15.

![Details Coefficient Waveforms](image)

*Figure 5.14 : Field recordings of ferroresonance waveforms*
5.4 Chapter Summary

The main objective of this chapter is to perform signal analysis on the real signal. This real signal is taken from a ferroresonance case that happened between grading capacitances of open circuit breakers and a voltage transformer. The results of Fourier transform are consistent with simulation results relative to the system frequency of 50Hz.

The threshold value of the detection process have to be increased due to the different sampling frequency and noise in the real signal. The algorithm could detect the time with a slight delay from the exact switching time.

The sustained fundamental mode voltage signal able to give some feature, where the energy is concentrated at level 4. The level of the decomposition is not the same as the simulated signal because the sampling frequency and the system frequency of the real voltage signal is not the same as the simulated signal. However, the methodology is applicable to both system frequencies.
Chapter 6

6 Putting it All together

This chapter summarizes the main conclusions derived from the results obtained in this thesis. Some recommendations and directions for future work are included at the end of the chapter.

6.1 Conclusion

The main objective of this thesis was to develop algorithms that can assist future mitigation or elimination of ferroresonance system. The literature review of ferroresonance in Chapter 2 has indicated that a lot of system configurations in power systems are prone to ferroresonance which involve power transformers and voltage transformers. Four most commons configurations of power systems that are prone to ferroresonance are discussed in details. Any of these configurations can produce either or both sustained fundamental and subharmonic modes ferroresonance. The other two modes, quasi periodic and chaotic are mentioned as part of ferroresonance in the literature. However, both modes were not encountered in the sustained period but instead, they only appear in the transient period of ferroresonance signals. It can be concluded that ferroresonance modes do not depend on system configurations but instead depend on the system parameters and initial conditions when the ferroresonance occurred. For example the same configuration that involves voltage transformers can produce both sustained fundamental and subharmonic modes. It would be beneficial if the mode of ferroresonance can be linked to the initial condition or parameters that initiated the event so that an appropriate mitigation actions can be implemented.
The preventive actions are also discussed such as avoiding single phase switching on certain transformer configuration, using a transformer that have a higher knee point or using different type of transformer core design. Existing mitigation procedures that are reported in the literature were highlighted with respect to power transformers and voltage transformers. Most of the mitigation methods that involves voltage transformers are either connecting the resistors directly to the transformers, or connecting the reactor and capacitors in series, or using active device to mitigate the problem. Some authors have mentioned the need of intelligent signal processing tools in mitigating ferroresonance as the existing mitigation actions are application specific. One method does not suit for all configurations. For example, different values of damping resistor that is connected during ferroresonance must be a correct value and the duration of the connection also have to be manually monitored.

Ferroresonance research trends show that two areas are growing in ferroresonance study, which are the study in obtaining an accurate transformer model for ferroresonance modelling and the analysing of ferroresonance signals. Most of the processing of ferroresonance signals are performed to distinguish ferroresonance signals from other transient overvoltage signals. These analyses were based on the sustained periods. The ferroresonance studies that are related to wavelet transform are limited to classifying ferroresonance from other transient, but not on the ferroresonance mode itself.

In Chapter 3, a ferroresonance circuit is modelled using a transient program called ATP-EMTP. Sensitivity studies have been conducted on the ferroresonance model. The simulations have proved the impact of parameter variation towards the occurrence of ferroresonance and their mode, as discussed in the literature. The impact can be seen from the 3D voltage versus time plots and the summary of the ferroresonance modes.

The main objective of the signal analysis in Chapter 4 is to show the advantage of using wavelet transform over Fourier transform as a tool for future ferroresonance mitigation device or system. The FT is not able to detect the time of transient and was not able to localize in time. The spectrum of FTT cannot provide at what time the frequency component exists in the signal. On contrary, WT is able to provide the time with respect to the frequency component exists in the signal. The time of transient
inception is successfully detected. This information is very useful in improving the mitigation action because it could provide a better idea on when a damping resistor should be connected, what is the appropriate values of the resistor and how long the resistor should be connected. This analysis shows the limitation Fourier transform has as monitoring algorithm because it lacks of localization in time ability. The limitation of Fourier Transform is overcome by wavelet transform.

Feature extraction is successful in extracting features in the sustained period of ferroresonance voltage signals. Different modes of ferroresonance can be distinguished by looking at the energy level of the Detail coefficients of the decomposed voltage signals. After decomposing different mode of ferroresonance signal, using db5 mother wavelets into 8 level of decomposition, feature of each ferroresonance mode are determined. Fundamental mode has concentration of energy at level 7 and subharmonic has concentration of energy at level 8. Chaotic mode and no ferroresonance mode both have energy concentration between level 6, 7 and 8.

Further analysis was conducted using wavelet transforms to extract some features from the transient periods. However, based on these simulated signals, it was concluded that the transient periods cannot be used for classification of ferroresonance mode. Further investigation should be performed in order to distinguish the fundamental and subharmonic modes from chaotic and no ferroresonance signals. Some recommendations are discussed in the next section.

The real signals that were analysed in Chapter 5 showed that the fundamental mode ferroresonance has energy concentration at level 4. Since the real signals have system frequency of 50Hz and the simulation signals are 60Hz, the feature is different. However, the same methodology is applicable to the signals and produced equivalent results.

The literature review have increased the understanding of ferroresonance generation in the real power system, mitigation and elimination methods and the application of signal processing in solving ferroresonance problems. This knowledge is essential in developing the algorithm for ferroresonance signal analysis. The successful detection of the inception of the transient has proved the capability of wavelet transform to detect the abnormalities in the signal and able to localize the changes in time. WT is
far better than FT in developing a robust algorithm for ferroresonance mitigation. The decomposition levels can be analysed according to each level and with respect to time. It is shown in the FFT analysis that the sustained, transient and all three periods of ferroresonance signals provide the frequency component of the signal without giving any information on the time. However, by using WT, the signal can be analysed further and more information can be retrieved from only one transformation. The level of decomposition is also an advantage because each level gives different information. The analysis can focus on just one level of decomposition or focus on all level of decompositions. With only one decomposition in wavelet analysis, multiple analysis can be conducted to understand the signal better. The signal analysis in this thesis is in its preliminary stage, therefore more room for improvements are expected in the future to realize the real time ferroresonance mitigation device or system.

6.2 Future Works and Recommendation
The objective of the research presented in this thesis has successfully been achieved. Further analysis could be conducted in finding the features for the transient period of the ferroresonance signals according to their mode. A few recommendation are:

1. To use other values beside energy of the Detail coefficients as parameter for feature extraction. For example statistical value such as the standard deviation, mean or variance of the coefficients.

2. To use the wavelet packet transform (WPT) in the feature extraction process. WPT is able to decompose the Detail coefficients into another low and high frequency components. This approach could scrutinize the high frequency components of each decomposition level as it does for the low frequency component of the Approximation coefficients.
7 References


The University of Manchester

References


8 Appendices

8.1 Appendix A

Figure 8.1: Fundamental Mode for Ferroresonance Voltage Signal

Figure 8.2: First Harmonic for (a) 32, (b) 64 and (c) 128 samples per 16 ms window
8.2 Appendix B

Published Journal Paper