Sympathetic inrush currents in transformer energisation

Author:
Abdull Halim, Hana

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SYMPATHETIC INRUSH CURRENTS IN TRANSFORMER ENERGISATION

Hana Abdull Halim

Supervisor: A/Prof. Toan PHUNG

A thesis in fulfilment of the requirements for the degree of

Doctor of Philosophy

School of Electrical Engineering and Telecommunications
Faculty of Engineering
The University of New South Wales
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Abstract 350 words maximum: (PLEASE TYPE)

Power transformers are critical components of the electricity networks. It is common knowledge that transformer energisation causes a number of inrush problems including the sympathetic inrush current and voltage sag. With the increase of distributed generations with inherent high intermittency resulting in more switching events, the transformers are increasingly vulnerable to electrical transients.

This thesis is concerned with slow-front inrush current transients associated with transformer energisation. To perform the investigation, transformer models are developed using MATLAB/Simulink, and simulations are also carried out using PSCAD/EMTDC software. The study is initiated with the modelling using the Classic Steinmetz model. Subsequently, to improve the accuracy, the Jiles-Atherton model is considered; its parameters are based on magnetic quantities and computed via a series of differential evaluation algorithms. The results demonstrated a significant improvement of accuracy of the transformer model.

The results obtained from simulation are then validated with laboratory experiments. One, two, and/or three single-phase 16 kVA, 11kV/250V oil-immersed distribution transformers are used to analyse inrush transients under different energisation cases. Special focus is placed on the first inrush peak, to determine whether or not the level of the incoming inrush can be predicted. This thesis also analyses the sympathetic inrush prolonging effects on voltage sags. The impacts of flux density and system resistance as well as the number of simultaneously energised transformers are also investigated.

The contributions of this research include the development of an improved transformer model for simulating the sympathetic inrush using a combination of the classic model and Jiles-Atherton hysteresis model, the proposal of measurements to extract model parameters for transformers with only nameplate data, the design and implementation of a point-on-wave switch, the laboratory works for mitigating parallel-connected inrush transients, the assessment of the effects and characteristics of sympathetic inrush through observing waveform patterns and the prediction of the incoming peak inrush, and the analysis of voltage sag. Also, this research collates four-year information on the growing Australia’s wind energy development and pre-empt the emerging problem of sympathetic inrush in wind turbine transformers. All the above research contributions are achieved with the completion of this thesis.

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To my parents, husband, and daughter

For the endless support, love and pray
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ABSTRACT

Power transformers are critical components of the electricity networks. It is common knowledge that transformer energisation causes a number of slow-front inrush current transient problems. With the increase of distributed generations with inherent high intermittency resulting in more switching events, the transformers in service are increasingly vulnerable to electrical transients.

This thesis is concerned with transformer energisation inrush, particularly focussing on the sympathetic inrush in supply networks with parallel-connected transformers. To perform the investigation, transformer models are developed using MATLAB/Simulink, and simulations are also carried out using PSCAD/EMTDC software. The study is initiated with the modelling using the classic Steinmetz model. Subsequently, in order to improve the accuracy, the Jiles-Atherton model is considered whereby its parameters are based on magnetic quantities and computed via a series of differential evaluation algorithms. The results demonstrated a significant improvement of accuracy of the transformer model.

The findings obtained from simulation are then validated with laboratory experiments. One, two, and/or three single-phase 16 kVA, 11kV/250V oil-immersed distribution transformers are tested to examine inrush transients under different energisation cases. Special focus is placed on the first inrush peak, to determine whether or not the level of the incoming inrush can be predicted. This thesis also analyses the sympathetic inrush prolonging effects on voltage sags. The impacts of flux density and system resistance as well as the number of simultaneously energised transformers are also investigated.

The contributions of this research include the development of an improved transformer model for simulating the sympathetic inrush using a combination of the classic model and Jiles-Atherton hysteresis model, the proposal of measurement methodology to extract model parameters for transformers with only nameplate data, the design and implementation of a point-on-wave switch, the laboratory works on mitigating parallel-connected inrush transients, the assessment of the effects and characteristics of sympathetic inrush through observing waveform patterns and the prediction of the...
incoming peak inrush, and the analysis of voltage sagging. Also, this research examines the growing Australia’s wind energy development and demonstrates the emerging problem of sympathetic inrush in parallel-connected wind turbine transformers. All the above research contributions are achieved with the completion of this thesis.
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CHAPTER 1

INTRODUCTION

1.1 Background of Study

In transmission and distribution systems, transformer energisation is a fairly routine operation. However, such an operation may trigger issues such as voltage and current disturbances. The transformer itself is a vital and expensive component of the electricity supply infrastructure. Their reliability is very important to the performance of transmission and distribution of utility companies, such as TransGrid and Ausgrid in NSW, Australia, and Tenaga Nasional Berhad in Malaysia. Historically, transformer energisation and its associated transients have been investigated in various power system researches. Even though transformer energisation issues in transmission and distribution networks are well-known for a long time, the problems are becoming more and more prevalent. This is due to two major factors: (i) the electricity markets have led to an increased number of participants with frequent changes in the network topology, and (ii) the emerging trend globally towards the use of clean renewable energy (wind, solar, etc.) through distributed generation with inherently high degree of intermittency. These result in an increased number of switching operations [1, 2].

Research on transformer energisation includes studies on transformer modelling. To investigate inrush—specifically magnetising or sympathetic inrush—it is necessary to first know how to model the transformer. For low-frequency transient studies, the inrush current phenomena during energisation of the power transformer without load
should be analysed differently. However, this is not an easy task, as the calculation model must first be established. The single-phase-based equivalent representation used in most simulation software does not adequately cater for the coupling between phases and the differences caused by varying ferromagnetic core characteristics. The non-linear effect of hysteresis, peculiar losses, and remanence also require further consideration [3].

Past researches [2, 4, 5] have mainly focused on the mitigation techniques to address these issues, yet little attention has been given to the likely impacts of this solution and how this phenomenon can affect the current electricity generation industry, especially wind energy where a large number of wind turbine transformers are usually required in a typical wind farm.

One of the issues of late is the transient stability problem of wind farms. Electricity generation from the wind turbine has been developing rapidly worldwide [6] and is now being discussed in many recently published papers. The issue of transient stability becomes more vital since wind power generation is expanding to become a major part in the generation mix whilst economic constraints force utilities to build power systems with less redundancy and operate them closer to transient stability limits. As mentioned in a recent report by the International Council of Large Electric Systems (CIGRE) [1], a significant effort is needed to spread the awareness of potential problems in transformer energisation—especially in the case of wind farms—to power systems engineers, as each wind turbine generator is accompanied by its own transformer and this may generate complex sympathetic interactions among the many transformers installed in a wind farm.

In summary, this research investigates the inrush transient phenomenon during transformer energisation starting from transformer modelling. The classic Steinmetz transformer model and the advanced model of Jiles-Atherton are considered and compared. Following this, computer simulation and laboratory experiments are performed to observe the magnetising and sympathetic inrush phenomena. Also examined is the effect of voltage sag during inrush transients. Then, all the results of these investigations are presented and validated with theoretical and numerical
calculation proofs. Finally, wind farm operations in particular are exemplary of the problems studied in this research and so the thesis concludes with simulation work on the inrush transients in parallel-connected wind turbine step-up transformers.

1.2 Background Information

1.2.1 Inrush transients in transformer energisation

Transformer energisation has given rise to many cases of serious power system issues. In the case of low-frequency transients, transformers frequently encounter the phenomenon of magnetising inrush current during energising or post-fault recovery conditions. Although the steady-state magnetising current is small (typically < 2% of the rated current), its initial inrush transient is very large (>10 times the rated current). This can lead to protection mal-functioning, power quality problems such as voltage sags [7], equipment damage from excessive mechanical, thermal and electrical stresses. Mal-functioning of the system can occur in numerous ways and has many consequences [8] such as catastrophic breakdown as shown in Fig. 1.1.

![Transformer catastrophic damage resulting from protection failure](image.png)
Energisation of the transformer can cause significant inrush currents that may lead to voltage sags. Transformer energisation often draws a large inrush current, which then decays to a small magnetising current. The decay duration for the inrush current is dependent on the circuit resistance, circuit reactance, and magnetising reactance of the transformer. Since the transformer’s magnetising inductance is high, the inrush current will take a longer time to reach its steady state [1]. In [10, 11], it is observed that smaller transformers have higher inrush currents and decay quicker, while larger transformers have smaller inrush currents and decay gradually.

The initial magnetisation when switching occurs in the transformer will result in the inrush phenomenon. When a transformer is de-energised, the magnetising current will go straight to zero while the flux will tail after the hysteresis loop of the core. As a result, some remnant flux may be left in the transformer core [1] which will then affect the flux build-up in the subsequent energisation.

In any typical utility electricity supply system, one would find a large number of transformers in operation scattered throughout the network. At the point when a certain transformer is energised, the current may rise abruptly to its maximum value in the half-cycle after energisation. In the presence of other nearby transformers already in operation (energised), they may also experience induced saturation - a phenomenon known as sympathetic inrush current [12].

1.2.2 Transformer modelling for inrush study

In this research, various transformer energisation transient issues are investigated. To this end, the transformer models for inrush current transient studies are developed and modelled using calculations with the assistance of power system simulation software. The transformer model itself has to be accurate for use in further investigations.

Modelling the transformer is not an easy task. Modelling requires that a strong focus be placed in the iron core response when the transformer is energised. If the transformer can accurately predict the inrush current, it can also predict most of the switching transients. The challenges faced include obtaining a proper representation of the core
and an accurate $B-H$ characteristic curve. A model with the correct topology is necessary to predict the saturation effect in each part of the core.

Special attention must be placed on saturation, core losses, and hysteresis loops. Another important characteristic of the model is the ability of flux initialisation. For this reason, an advanced nonlinear inductance model is required. The test report data acts as an "identification card" for the transformer and is usually the only information available. The use of standard available input data imposes a limit on the detail level of a model. In relation to modelling a transformer, inrush currents during transformer energisation is considered one of the most demanding low-frequency transients [3].

1.2.3 Magnetisation inrush versus sympathetic inrush

For a better understanding of the inrush current, Fig. 1.2 illustrates a typical waveform of the inrush current in a power device.

![Fig. 1.2 Example of an inrush current waveform](image)

The inrush current is the maximum, instantaneous input current created by a device when it is first turned on. This phenomenon can be seen in many electrical devices and may result in serious damage of these devices. For this reason, overcurrent protections are usually put in place to protect the device from this harmful inrush current.
Magnetising inrush often occurs in the supply networks when energising a large non-load power transformer, which has a large inductance as well, and may result in enormous dynamic flux; hence, leading to saturation of the transformer core. This flux can result in a current with a large magnitude, which is called the magnetising inrush current. The magnetising inrush current contains a large number of high-order harmonics and large-amplitude direct current. The magnetising inrush current generally has a very high initial peak and fast decaying rate. The main risk of the magnetising inrush current is the overcurrent. This overcurrent may burn the transformer core and other devices in the grid if it occurs during a highly non-linear magnetic condition, i.e. the switch-on moment [1].

The sympathetic inrush current is generated by other transformers that are connected in series or in parallel with the affected transformer. The reason being that when a non-loaded transformer is turned on, there will be a large magnetising inrush current produced, as described previously. This magnetising inrush current will flow to the grid and cause variation in the bus voltage, consequently leading to saturation of the affected transformer core, and producing an unwanted high transient current in the adjacent transformer. This is defined as a sympathetic inrush current. Although the peak value of the sympathetic inrush current is relatively smaller than the magnetising inrush current, the former lasts longer. Sometimes, the sympathetic inrush current can keep oscillating [1]. Case studies documenting the sympathetic inrush phenomenon are reported in [13, 14].

Simulations can also confirm difference between the magnetising inrush current and sympathetic inrush current. To illustrate, two transformers namely T1 and T2 are parallel-connected for observing the sympathetic inrush. While T2 is already in operation, T1 is switched-in. T2 operates as per the rated condition when T1 is closed. By monitoring the inrush current in both T1 and T2, the resulting waveforms as per Figs. 1.3 and 1.4 are acquired.
Chapter 1

Introduction

1.2.4 Voltage sag effect from the inrush transient phenomena

[1, 7, 16] relate transformer energisation transients with RMS-voltage drop, or voltage sags that obviously affect the power quality across the supply network. The power system protection is also effected when a parallel resonance within the supply is excited by the current transients; thus causing mal-operation of the relay.
1.2.5 Transient issues in a wind farm

Future energy concerns surround the energisation of wind energy systems, where there are many wind turbines in which each wind turbine is typically accompanied by a step-up transformer before connection to the main collector grid. This situation may generate complex sympathetic transients. Wind turbine generator transformers have a relatively small power rating (several MVA, according to the wind turbine generator rating), but relatively higher inrush currents\(^1\). Therefore, power systems engineers, either in the planning or at the operational stage, need to be aware of potential problems that may arise from transformer energisation and, if necessary, study their probability of occurrence, their likely effects, and possibly evaluate various mitigation techniques that may be required to alleviate identified issues.

1.3 Problem Statement

When the transformer is energised, the excitation current can cause core saturation and result in large amplitude current transients. In the presence of this so-called magnetising inrush current, mal-operation of the protection relay may occur. The relay will therefore experience unnecessary tripping.

The magnetising inrush current can also impose some current transient on other transformers in operation nearby. Although this so-called sympathetic inrush current is related to the magnetising inrush current source, its response characteristic is different. Nevertheless, its presence can also cause problems such as mal-operation of the transformer differential protection, voltage sags, harmonic over-voltage, etc.

Thus, sympathetic inrush current is an issue that must be investigated to enable mitigation techniques to be developed. To this end, this research work performs simulations and experimentations to reveal the behaviour and extract characteristics of the sympathetic inrush current response under different operating conditions.
1.4 Research Methodology

This research involves performing transformer modelling, simulations and calculations, conducting the practical testing to obtain transformer parameters and transient energisation waveforms, and analysis of results. The investigation process is divided into four parts: transformer modelling, laboratory experiments, further related computer simulations, and data analysis. The overall project flowchart is illustrated in the block diagram of Fig. 1.5. All in all, the transformer modelling constitutes a major part of the research and its work flow is shown in Fig. 1.6.
Fig. 1.6 Transformer modelling flowchart
1.5 Objectives of the Research

The primary objective of this research is to mitigate the impact of the transient phenomenon during transformer energisation. To this end, this study aims to develop some means to produce, experimentally and numerically, the sympathetic inrush current phenomena so their response characteristics under different operating situations can be quantified accurately. This is achieved through three sub-objectives.

The first sub-objective is to perform an accurate model of the transformer to be used in the inrush transient studies. Especially when it comes to the core representation, this is a crucial step in modelling a transformer for any transient simulation. The mathematical and simulation models are also developed to observe and analyse the worst effects of the sympathetic inrush. The first phase of modelling requires the establishment of electrical parameters. Thus, the classic Steinmetz model is used. Then, to address the shortcomings in the Steinmetz model, the advanced Jiles-Atherton model is used. The transformer model is then validated and applied in the inrush transient study.

The second sub-objective is to investigate the sympathetic inrush phenomenon and the factors affecting this phenomenon. PSCAD/EMTDC software is used to simulate the phenomenon according to a case-by-case basis. With knowledge from recent research, the sympathetic inrush current phenomenon and its effect are investigated via simulations and laboratory experiments on actual transformers. To investigate the magnetising inrush and sympathetic inrush phenomena, the validated model is used to analyse the transformer energisation effect in slow-front transients, including the magnetising inrush and sympathetic inrush under various scenarios; divided according to different energisation cases. The hypotheses of the design of the network are justified via simulation results as well as laboratory measurements. Attention is paid to the first inrush peak, to determine whether or not the severity of the coming inrush could be predicted. This thesis also analyses the prolonging effects of the sympathetic inrush on voltage sags. The effects of the load and system
resistance, as well as the number of transformers that are energised are also investigated.

Lastly, as the penetration from the renewable energy is increasing dramatically nowadays, the final objective of the research is to assess the sympathetic inrush current phenomenon that occurs between wind turbine transformers. The modelling and the phenomenon are carried out in PSCAD/EMTDC. Scopes include the investigation of potential problems that may arise from the parallel-connected wind turbine transformers energisation, their effects of simultaneous energisation, and evaluation of their severity of inrush. The new findings will enable counter-measures to alleviate these identified issues.

1.6 Original Contributions

- Development of an improved transformer model using a combination of the classical Steinmetz model and the Jiles-Atherton hysteresis model for simulating network-wide sympathetic inrush between transformers

- Development of a methodology to determine various electrical parameters for the transformer model with a focus on transformers with limited practical data available

- Assessment of the characteristics of the sympathetic inrush during energisation by observing current waveform patterns and predicting the incoming peak inrush, taking into account different network connections

- Analysis of the effects caused by the sympathetic inrush during transformer energisation with a focus on voltage sags
• Analysis of power system transient issues caused by the sympathetic inrush between parallel-connected wind turbine step-up transformers.

• Development and construction of a programmable Point-on-Wave switching device as part of the test setup required for the inrush experiments. Practical inrush transient experiments can be carried out on distribution transformers.

1.7 Thesis Outline

This thesis is organised into eight chapters.

Chapter 1 presents the project background, problem statement, and aims of this research. This chapter also articulates the scopes, the main contributions and the structure of the thesis.

In Chapter 2, the literature review provides the mathematical formulation of the electrical transients in transformers and analytical approaches for calculating the magnetising inrush and sympathetic inrush currents. In addition, transformer energisation transient issues, factors that contribute to this problem, mitigation techniques, and voltage distortion issues in transformer energisation are all discussed in this chapter.

Chapter 3 presents the modelling of transformer and system components with particular emphasis on the Steinmetz and Jiles-Atherton models. This forms the basis so that numerical methods can be carried out using PSCAD/EMTDC software platform to study transformer energisation transients. It also explains how the various electrical parameters of the transformer model can be determined, including practical tests and measurement methods and estimation approaches to address the lack of practical transformer data.

Chapter 4 presents advanced transformer core modelling using the Jiles-Atherton ferromagnetic hysteresis model. The background theory of Jiles-Atherton and
Inverse Jiles-Atherton modelling is introduced, followed by the modelling steps and parameters estimation, and the $B-H$ curve generation. This chapter outlines the use of a novel transformer core model to predict the incoming sympathetic and magnetising inrush currents.

In Chapter 5, the methodology developed in Chapter 4 is implemented in the PSCAD/EMTDC environment to construct numerical models of the actual transformers used in the laboratory experiments. Based on the modelled transformers, computer simulations are performed on various network circuit connections to study transformer energisation transients.

The laboratory setup and measurements are presented in Chapter 6. Systematic energisation procedures and measurements performed on the distribution transformers are shown case by case. Experimental results on transformer energisation transients are presented and analysed. Also discussed are comparisons between the numerical simulations and laboratory measurements.

Chapter 7 consolidates, reviews, and analyses power system transient issues arose from the sympathetic inrush between parallel-connected wind turbine generator transformers and the way forward.

Chapter 8 is the conclusion which presents the main findings of this work, the research contributions, and suggestions for future research in this field.
1.8 Publications

(a) Journals:


(b) Conference Papers:


(c) Publications relevant to the field but not discussed in this thesis:


CHAPTER 2

LITERATURE REVIEW

In this chapter, the literature review covers selected journals and articles from scholars. Key subjects from previous researches including transformer energisation transients, transformer saturation and inrush current, the modelling of a transformer for inrush study, the sympathetic inrush, mitigation techniques for transient inrush, voltage distortion in transformer energisation transients, pseudo-inrush, and the transformer energisation transient effect in wind farms, are described in detail in the following sub-sections.

2.1 Transformer Energisation Transients

To protect a plant from the transient issues, it is important to understand the transient phenomenon and its impacts. Cases in the industry have shown that transformer energisation inrush transient is not only dangerous because of its large current amplitude, but also due to its rapid rate of rise. When a transformer is frequently exposed to transients, it will deteriorate due to severe mechanical and thermal stresses and may eventually fail. The high inrush current may disturb or cause failure to operation of adjacent equipment in the circuit, for example, resulting in mal-operations of power electronic converters [2] and protection relays [17, 18].
Apart from affecting power quality in terms of temporary under-voltage (sagging), the inrush currents contain many high frequency harmonics which can also lead to harmonic resonant over-voltage and the resultant electric stress can cause transformer insulation deterioration.

2.2 Transformer Modelling for Inrush Current Studies

2.2.1 The basic concept of transformer

Power transformers are regarded vital equipment in conventional power systems. They are usually the largest, heaviest, and probably the costliest component in transmission. To investigate the inrush current caused by transformer energisation, the most important aspect is the modelling of the transformer. As this research investigates the inrush phenomena in power systems, the modelling part for this study will focus on power transformers.

Fig. 2.1 shows an ideal single-phase transformer, consisting of two windings wound on a ferromagnetic core. One is the primary winding having $N_1$ turns and the other is the secondary winding having $N_2$ turns.

According to the electromagnetic induction principle (Faraday’s law), a voltage is induced in a coil due to a changing flux. The alternating magnetic flux, $\phi_m$, circulating in the core links the two windings and induces an emf in each winding, $e_1$ and $e_2$. The instantaneous values of the induced emf is related to the mutual flux as [22]:

$$e_{1,2} = N_{1,2} \frac{d\phi_m}{dt}$$  \hspace{1cm} (2.1)
Fig. 2.1 An ideal two-winding transformer [21]

The moment an AC voltage is applied in the primary winding, a back-\textit{emf} will be produced; a perfect transformer would oppose the primary applied voltage to the extent that no current would flow. The value of which will be opposite to the direction of the supply voltage [23], as expressed in equation (2.2):

\[
e_i = -N_1 \frac{d\phi_m}{dt}
\]  

(2.2)

Assuming the winding has zero resistance, then \( v_i = e_i \) where \( v_i \) is the applied voltage. If the magnitude of \( v_i \) is varied sinusoidally, the mutual flux \( \phi_m \) will also vary in the same manner. Hence:

\[
\phi_m = \phi_{mp} \sin \omega t
\]

\[
\phi_m = \phi_{mp} \sin(2\pi f) t
\]

(2.3)

where \( \phi_{mp} \) denotes the peak flux. Thus:

\[
e_i(t) = N_i \omega \phi_{mp} \cos \omega t
\]

(2.4)

By dividing the peak value in equation (2.4) with \( \sqrt{2} \), the induced voltage in \textit{rms} value, \( E_i \), is expressed in equation (2.5):
Similarly, the *rms* value in the secondary winding, $E_2$ is given by:

$$ E_2 = 4.44\phi_{mp} fN_2 $$

### 2.2.2 The $B$-$H$ curve and hysteresis

Magnetic hysteresis refers to a physical phenomenon where, under an applied alternating magnetic field, the magnetization in a ferromagnetic material retraces different paths. The degree of magnetization to the applied field is characterized in terms of the material susceptibility $\chi$ which relates the magnetization $M$ to the magnetic field strength $H$:

$$ M = \chi H $$

The magnetic flux density $B$ can be expressed in terms of $H$ and $M$:

$$ B = \mu_r (H + M) = \mu_r (1 + \chi) H = \mu_r \mu H = \mu H $$

where $\mu$ denotes the material permeability, $\mu_r$ is its relative permeability with respect to the permeability of vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m.

In the ideal transformer as described in the previous section, the permeability of the core material is assumed to be constant, i.e. equation (2.8) is a linear relationship between the magnetic flux density and the field strength. However, in an actual transformer with a ferromagnetic core, this relationship is nonlinear and exhibits hysteresis. As the flux periodically changes, the $B$-$H$ relationship depends on the magnitude of the flux density and periodic frequency. The resultant $B$-$H$ curve is a closed loop where the path over time moves in a full cycle, successively passing through points $a-b-c-d-e-f-a$ as illustrated in Fig. 2.2.
Hysteresis in the ferromagnetic material relates to the non-linear relationship between the field strength $H$ and magnetisation $M$. The phenomenon of the magnetic induction results in a lagging value response to the magnetic intensity. The magnetised and de-magnetised behaviours can be observed from the graph of Fig. 2.2. If a magnet is fully de-magnetised prior to magnetisation ($H=M=0$), the magnetisation will start at the centre point 0 following the application of a time-varying current $i(t)$. As the magnetising current increases positively, the field strength increases and the flux density increases. This curve increases rapidly at first and then approaches magnetic saturation. Point 0 to $a$ shows the saturation that follows a positive direction, with $B$ and $H$ increasing. If the magnetising current is then reduced, the magnetisation will follow a different trace (point $a$ to $b$). At zero applied field strength (point $b$), the flux will not reach zero (residual). As the applied field is reversed, the trace continues to point $c$. Point $c$ and $f$ show a zero value of flux density (positive and negative values), which are also called coercive forces. The reverse of point $a$ is point $d$. Point $b$ and $e$ correspond to the residual magnetism (or remanence).

![Fig. 2.2 The B-H curve](image)

If the coil has $N$ number of turns around the magnetic core, the magnetising current $i(t)$ establishes the flux in the core and induces a voltage across the coil:
\[
\frac{e(t)}{N} = -\frac{d\phi}{dt}
\]  

(2.9)

where \(\phi\) is the flux over the core cross-sectional area. Equation (2.9) is equivalent to equation (2.2) where the principle is the same. The negative sign in equation (2.9) indicates the opposite direction.

Hence, the energy supplied from the coil, \(W\) (in Joule) is calculated by integrating power over time. Eliminating the electrical resistance and deeming that the power is equivalent to the voltage across coil multiplied by current:

\[
W = \int e \times idt = \int \left( N \times \frac{d\phi}{dt} \right) \times idt = \int N \times id\phi
\]  

(2.10)

If \(l\) denotes the mean path length of the flux flow around the core and \(A\) is the cross-sectional area then:

\[
N \times i = H \times l
\]  

(2.11)

\[
d\phi = A \times dB
\]  

(2.12)

Thus,

\[
W = (A \times l) \times \int H \times dB
\]  

(2.13)

where \((A \times l)\) is the core volume in meter\(^3\) and \(\int H \times dB\) corresponds to the area enclosed in the \(B-H\) loop (Fig. 2.2).

With the varying current, the energy delivered to the coil over the complete cycle is equal to the physical volume of the core multiply by the area in \(B-H\) loop. This supplied energy is called the hysteresis loss.
2.2.3 Modelling system components in PSCAD to study transformer energisation transients

PSCAD is a widely-used time domain simulation tool for analysing electrical networks. Therefore, this software was selected for this study. Using PSCAD, the numerical simulation in both transient and steady state can be performed [2]. Unlike MATLAB/SIMULINK and other conventional network software, PSCAD/EMTDC is specifically customized for electromagnetic transient applications. Here, electrical devices can be presented in more detail, the transformer windings can be modelled, and the magnetic iron core included, yielding a more accurate simulation.

There are standard available transformer models in PSCAD for assessing transformer energisation transients such as the ideal approach, classical modelling approach (the same model as the saturable transformer model in ATP [25]), UMEC (Unified Magnetic Equivalent Circuit Transformer Models), Three-Phase Transformer Models, Single-Phase Transformer Models, and Auto Transformer Models.

In a transient study, the transformer data, circuit breakers, surge arresters, shunt reactors, busbar, and other components can be represented in detail using PSCAD. For the PSCAD transformer component, transformer MVA rating, winding voltage, and configuration, the knee point of the core saturation and leakage reactance between windings can be input to obtain real results [26].

2.3 Transformer Saturation and Inrush Current

The inrush current is a common phenomenon, which is generated when a transformer is switched on. The magnetising inrush will be drawn upon, where the peak is much higher than the rated current, typically about 10 times but can be even higher. The inrush pattern starts with the highest peak—depending on the switching angle and then decays to a smaller current. The decay can happen at a very rapid rate or as long as a few seconds, and in the end, probably tapering to zero [27].
Inrush current transients in transformers are caused by the magnetic flux limitations of the core and can be analysed from the magnetic flux point of view. Thus, equation (2.9) is recalled.

Hence, the flux will be integral of the voltage wave, as shown in Fig. 2.3 and equation (2.9) can be rewritten in equation (2.14) as:

\[ \varphi_m = \int edt = E \int \sin \omega t dt \]  

(2.14)

where \( E \) denotes the emf voltage and \( \varphi_m \) represents the total winding magnetic flux.

---

**Fig. 2.3 Flux in the integral of the voltage waveform**

---

**Fig. 2.4 Equivalent single-phase circuit**
Fig. 2.4 shows the equivalent circuit of a single-phase transformer where $R_s$ is the system resistance, $L_s$ is the system inductance, $r_1$ is the transformer winding resistance, and $L_1$ is the transformer inductance (leakage and magnetising). By referring to Fig. 2.4, only the magnetising current will flow through the system before the switch is closed [34]. Using Kirchhoff’s Voltage Law:

$$E = (R_s + r_1)i + \frac{d\varphi}{dt}$$ (2.15)

$$\varphi = Li$$ (2.16)

where $\varphi$ denotes the total magnetic flux and $L$ denotes the total inductance in the circuit. Then, integrating both sides over a full cycle gives equation (2.17):

$$\int_{t}^{t+T} Edt = \int_{t}^{t+T} \left[(R_s + r_1)i\right]dt + \Delta \varphi$$ (2.17)

where $\Delta \varphi$ represents the flux change in a cycle.

As this is sinusoidal, the left hand side will be equal to zero, which results in the following expression for total flux change in a cycle of $T$ of equation (2.18):

$$\Delta \varphi = -\int_{t}^{t+T} \left[(R_s + r_1)i\right]dt$$ (2.18)

If the flux is switched at zero voltage, the flux is triggered from the same origin as the voltage waveform. Here, at the end of the first cycle, the flux value will be double, denoted as $2\varphi_m$. After reaching the steady state maximum value of flux, the core will be saturated and the current will be very high. This high current is called magnetising inrush current phenomenon.

These characteristics of inrush current decay will depend on the value of resistance and reactance in the circuit, as shown in equation (2.18). The inrush current exponential decay is depending on the resistance where the decay of the inrush current is proportional to the series resistance. Once it reaches to a steady state
condition, the inrush current will settle down. Inrush currents can sometimes take up to minutes to decay in some high-rating transformers. This prolonged duration of high current can cause severe damage to the transformer. In a practical transformer, the winding resistance affects the inrush as it can dampen out the inrush waveform.

In [14], inrush was categorised into three categories, which are the energisation inrush, recovery inrush, and sympathetic inrush.

2.4 Sympathetic Inrush Current Transients

2.4.1 Sympathetic interaction between transformers

The inrush current generated due to switching-in a power transformer is a common phenomenon [4]. However, the inrush current differs from the sympathetic inrush current. The latter refers to a situation when two transformers are adjacent to each other with one of the transformers already in operation [28]. The already energised transformer will experience unexpected (induced) saturation caused by the generated inrush currents from the other transformer.

In comparison to the normal inrush current, the peak of the starting inrush current of single-transformer energisation is more severe. However, due to its unusual characteristics, when two or more transformers are connected and the transformers are energised while one of the transformers is already in operation, the sympathetic inrush current may happen for a longer duration [29].

Because of the sympathetic inrush occurring over a longer duration, other power system issues may arise, such as prolonged harmonic overvoltage. Sometimes, the transformer differential relay may also trip unnecessarily. Not only that, the noise level of other transformers linked to the network could also increase as a result [28]. Other problems such as voltage sag, excessive mechanical and electrical stresses, and even equipment damages have been reported in past researches [7, 8, 29, 30].
From the conventional inrush current calculation method, it is assumed that the transformer being energised is not connected to the other transformer. It is clear that this assumption is inaccurate, as there should be unexpected saturation effects from other connected transformer(s) [31].

Referring to Fig. 2.5, transformer T1 is the transformer already in operation while transformer T2 is the transformer in parallel with T1 and being energised. Here, T1 will experience unforeseen saturation during the inrush transient of T2. In other words, there is a ‘sympathetic’ inrush current in T1 initiated by the inrush current in T2. This coupling effect is attributed to the asymmetrical voltage drop across the system resistance of the transmission line (cables, busbars) connecting these transformers [29].

Assuming T2 has a high value of remanent flux and can be switched in at any voltage phase, the large inrush current may be drawn from the transformer. Hence, the decaying dc component will result in a large voltage drop at the common bus connecting these transformers [10]. This voltage drop will cause the saturation of T2 to drop and result in a decreasing inrush current in T2. Also, T1 is exposed to this same abrupt voltage change which will induce its own inrush current in the reverse direction [10].
In comparison with the magnetising inrush current itself, which happens concurrently with the sympathetic inrush current, the latter is found to persist in the network for a longer duration [32], even stretching to minutes [33]. In the case of the magnetising inrush only, the peak of the inrush is very high; however, it also decays fast, within just a few cycles, and usually returns back to zero. The sympathetic inrush phenomenon almost never experiences this occurrence. Fig. 2.6 and Fig. 2.7 show the waveform of the inrush and sympathetic inrush currents in the transformer, respectively.

![Fig. 2.6 Waveform of inrush current in transformer [29]](image1)

![Fig. 2.7 Waveform of sympathetic inrush current in transformers [29]](image2)
2.4.2 Sympathetic interaction analytical calculation

Fig. 2.8 Equivalent two-parallel transformer circuit

Fig. 2.4 shows the equivalent single-phase circuit while Fig. 2.8 shows the equivalent two-parallel transformer circuit.

Now, equation (2.18) can be applied to two parallel-connected transformers. From Fig. 2.8, the following expression in equation (2.19) can be obtained:

\[
\begin{align*}
\left[ \Delta \phi_1 \right] = & \int_{T} \left[ R_s + r_1 \begin{bmatrix} R_s & R_s + r_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \right] \, dt \\
\left[ \Delta \phi_2 \right] = & \int_{T} \left[ R_s + r_2 \begin{bmatrix} R_s & R_s + r_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \right] \, dt \\
\end{align*}
\]

(2.19)

From equation (2.19), it can be seen that the system resistance, \( R_s \), plays a major role in the interaction between the two transformers.

Sympathetic inrush occurs due to the offset flux, whereas inrush currents result from the induced flux. For the parallel-connected transformers, when T2 is energised, the transformer core in T1 will saturate from the offset flux created earlier. This saturation may generate the inrush current, which, in this case, is called the
sympathetic inrush. When the induced flux established from the applied voltage reaches saturation, the inrush current will be drained from the source. This inrush current passes through the system causing a voltage drop across $R_s$. Due to the completely unidirectional characteristics of the inrush current, the voltage drop across $R_s$ will be asymmetrical [5]. This asymmetrical voltage drop induces an offset flux in both T2 and T1 that is opposite in polarity to the initial induced flux; hence the reason for the opposite polarity of the sympathetic inrush current and the inrush current. On the other hand, this change also results in saturation, so as to reduce the offset flux in T2 to produce decay in the inrush current, $i_2$. At one point, the flux becomes zero; hence, $i_1$ stops increasing [35]. The increase of $i_1$ and the decay of $i_2$ can be written as equation (2.20):

$$\left[R_s + r_1\right]i_1 = -R_s i_2 \quad (2.20)$$

During sympathetic inrush current phenomenon, the following equations for currents are derived.

$$R_s i_s + L_s \frac{di_s}{dt} + r_1 i_1 + \frac{d\phi_1}{dt} = E \sin(\omega t + \alpha)$$

$$r_1 i_1 + \frac{d\phi_1}{dt} = r_2 i_2 + \frac{d\phi_2}{dt} \quad (2.21)$$

$$i_s = i_1 + i_2$$

where $r_1$ and $r_2$ are the resistance for T1 and T2 (as shown in Fig. 2.8) while $\phi_1$ and $\phi_2$ are the flux for T1 and T2, respectively.
2.4.3 Factors affecting the sympathetic inrush

2.4.3.1 Different closing angle

Consider the simple RLC equivalent circuit in Fig. 2.9 where the capacitances in the circuit are taken into consideration. S represents the circuit breaker. The source voltage is denoted as \( E = E_m \cos(\omega t + \alpha) \). \( L_s \) and \( C_s \) denote the total inductance and equivalent capacitance before the circuit breaker. \( R, L_m \) and \( C_m \) are the equivalent parameters of the simplified unloaded transformer, namely resistance representing the core loss, magnetising inductance, and input capacitance, respectively.

The circuit breaker is assumed to close at zero initial phase angle. If the resistance in the circuit is ignored and \( L_m \) is considered much larger than \( L_s \) then the primary winding voltage can be expressed as equation (2.22) [36]:

\[
e_t(t) = E_m \left(\frac{n}{n^2 - 1}\left(\sin \omega t - \frac{1}{n} \sin \omega_0 t\right)\right)
\]

(2.22)

\[
n = \frac{1}{\sqrt{\frac{L_m C_m}{\omega}}} = \frac{\omega_0}{\omega}
\]

(2.23)

The closing angle affects the winding voltage. Hence, the initial closing angle of the breaker also affects the inrush current values [36].
2.4.3.2 System resistance

One of the factors affecting the inrush phenomenon is the resistance of the supply system including the source and transmission line connecting the transformer. The system resistance will reduce the peak of the inrush amplitude and hasten the decay of the inrush. In reference to Fig. 2.8, as transformer T2 is switched in, its magnetising inrush current \( i_2 \) arises. At that instant, T1 is not yet saturated so the sympathetic inrush is also \( i_2 \) and so for transformer T1 [37]:

\[
\frac{d\phi_i}{dt} = E - L_s \frac{di_2}{dt} - R_s i_2
\]  

(2.24)

Integration over one period:

\[
\Delta \phi_l = -R_s \int_{t_s}^{t_T} i_2 \, dt
\]  

(2.25)

Referring to the above equation, the inrush in T2 will cause a flux change in T1 in the opposite direction over one period. Since \( \Delta \phi_l \) will eventually become saturated after some time, the system inrush current becomes \( i_s = i_1 + i_2 \).

Hence, \( \Delta \phi_l \) now depends on both \( i_1 \) and \( i_2 \). Thus:

\[
\Delta \phi_l = -\int_{t_s}^{t_T} R_i i_1 \, dt - \int_{t_s}^{t_T} R_i i_2 \, dt = -\int_{t_s}^{t_T} (R_s + R_i) i_1 \, dt - \int_{t_s}^{t_T} R_i i_2 \, dt
\]  

(2.26)

From the above, \( R_s \) affects the maximum peak of the sympathetic inrush as well as the decay of the inrush.
2.4.3.3 Magnetic material

The transformer core is made of magnetic materials which display non-linear magnetic permeability. Different magnetic materials have different magnetisation characteristics, as per Fig. 2.10, which depicts the flux-current curve. Since the differences in flux result in differences in saturation value; the higher the saturation value, the higher the inrush currents. When the core is in saturation, a small increment of flux will result in a large increase of the magnetising current.

![Fig. 2.10 φ-I curve](image)

2.5 Mitigation Techniques for Transformer Energisation Transients

There are numerous mitigation techniques for transformer energisation transients. For example, by introducing a pre-insertion resistor [1, 38, 39], by controlling the switching time using the point-on-wave voltage at energisation [40-42], by varying the impedance of the power supply, and by controlling the residual flux inside the transformer core during transformer energisation [41, 43]. All these mitigation techniques have been discussed in past researches. Here, the approach is to control any key factor in which the parameters will affect the inrush transient eventually, as discussed in Table 2.1.
### Table 2.1 Discussion of inrush mitigation techniques

<table>
<thead>
<tr>
<th>Parameters Controlled</th>
<th>Mitigation Method</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>The oldest mitigation strategy is to pre-insert a series resistor in the circuit breaker to energise the transformer</td>
<td>It can help reduce voltage across transformer and eventually reduce the inrush current. However, it requires retrofitting breakers (not practical). Also, breakers could be damaged if pre-insertion resistor fails to by-pass.</td>
</tr>
<tr>
<td>Point-on-wave</td>
<td>Controlling the switching times of the circuit breaker during energisation</td>
<td>Not easily implemented as the exact residual flux must be known.</td>
</tr>
<tr>
<td></td>
<td>Defining a value for the residual flux using a dc excitation coil [44]</td>
<td>Not economical and challenging.</td>
</tr>
<tr>
<td></td>
<td>Synchronised switching method with fixed delay between poles [45]</td>
<td>Installation of the new controller is costly and challenging.</td>
</tr>
<tr>
<td>Impedance</td>
<td>Increase the impedance of the power supply circuit</td>
<td>Increase the power losses that result from steady state current flowing through them.</td>
</tr>
</tbody>
</table>
2.6 Voltage Distortion Issue in Transformer Energisation Transients

2.6.1 Temporary overvoltage and harmonic resonance issues

When a transformer reaches saturation phase, harmonic sources result in resonance excitation, causing long overvoltage. This will eventually cause system failure. Even if the transformer was not continuously over-excited, the harmonics generated by the magnetising inrush current due to energisation could be sufficient to excite the resonance [1].

Both the magnetising and sympathetic inrush phenomena may produce a high peak starting current at the point of energisation. This fast-oscillatory transient current contains significant harmonics. The interaction of these harmonics with other (capacitive, inductive, non-linear) components in the system can result in harmonic resonance in the form of oscillatory un-damped or weakly damped transient over-voltages [46]. For example, when the transformer is switched-in with a high voltage cable, harmonic overvoltage may also develop.

According to IEC 60071-1, transient overvoltages can be classified as Continuous Operating Voltage, Temporary Overvoltage, Slow-Front Transient (which is also known as switching), Fast-Front Transient (Lightning), and Very Fast Front [20]. This research is concerned about the slow-front transients.

2.6.2 Voltage sag caused by transformer energisation

Voltage sag is the voltage drop or reduction that can be a result of the start-up of transformers or electric machines. The evaluation is based on its magnitude and duration. The voltage sag magnitude is the maximum voltage drop from a given reference voltage or nominal system voltage, whereas the voltage sag duration is measured between the start and end of the threshold voltage. Both could adversely affect the system operation, resulting in temporary interruptions and mal-operation of voltage-sensitive equipment connected to the system. This may further trigger
other power system transient issues. Utility companies will treat any power quality issue—even the non-periodic flickering of lights and fluctuations—as significant, as it may result in complaints from customers and penalties imposed by the electricity regulatory authority.

Past researches [16, 47, 48] have investigated voltage sag. Recent work [49, 50] evaluated the inrush-induced voltage sag caused by transformer energisation via the detection of the maximum magnitude of the sag and determining whether it would exceed the 3% voltage step change limit set by the standard ER-P28 [51, 52].

There are a few global standards that are currently used in the industry. The IEEE standard 1346-1998 chooses 10% sag of the reference voltage as the sag end and start threshold for defining the duration of the voltage sag. However, the Grid Code (U.K.) and ER-P28 suggest that only up to 3% sag is allowed [49]. For low-voltage installations in Australia and New Zealand, the voltage at the point of supply under normal service conditions should not differ from the nominal voltage by more than +10%,-6%, following AS60038—2012 Standard [53]. Furthermore, AS/NZS 3000 Standard limits the voltage drop within the customer installation due to cabling impedance to 5%. Therefore, the utilisation voltage range is +10%, and –11%. In Malaysia, the sole utility company, TNB, follows the Malaysian Distribution Code [54], which allows ±5% of the nominal voltage for medium voltage (6.6 kV–33 kV) and +10% and -6% for the low voltages of 400 V and 230 V.

To investigate the voltage sag issue, a model should first be established. The system under study should be developed using modelling software for which a validation analysis is a requirement. In [50], the system under study is done via the ATP/EMTP simulation platform while in [16], the study is done using the PSCAD/EMTDC simulation package. The validation study should be performed, taking into account field and/or laboratory results.

From the point of view of the power system operator, the most important aspect of the inrush phenomenon is the worst-case voltage sag. In [50], the worst-case voltage sag is estimated and quantified by observing the impact of the sympathetic inrush
due to other transformer energisation. It shows that a weak system with low fault level is more vulnerable to significant voltage dips and also favourable to initiating sympathetic inrush.

### 2.7 Pseudo-inrush in Transformer Re-Energisation

The pseudo-inrush phenomenon can occur during the recovery process following a voltage sag event, such as after the clearance of a fault. This is a phenomenon by which transformers already in operation are driven into saturation after a fault has been cleared and the normal system voltage is restored at the transformer terminals [1]. The process is also interchangeably referred to as “re-energisation”. This problem, which is generally more severe in weak systems, may lead to tripping by under voltage and over-current relays.

This issue was first reported in [55]. In this work, transformer saturation occurred after the sudden energising of the magnetising flux where the flux contains a dc component that takes a longer time to decay. However, it is observed that this phenomenon only occurs in a transformer with light load or no-load only. Fig. 2.12 shows the circuit for simulation of the pseudo-inrush phenomenon in this study. Here, $R_{sc}$ is used for generating the voltage sag.

![Fig. 2.11 Circuit for observing the pseudo-inrush interaction](image)

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2.8 Sympathetic Interaction in Wind Farm Integration

The rapid depletion of fossil fuels and the issue of greenhouse gases worldwide have contributed to the development of wind generation as an alternative energy source. Wind farms are now being designed and commissioned rapidly to acquire more green energy. Now, wind farms are becoming more widespread with most countries increasingly investing in this type of green energy.

Wind power is currently the lowest-cost renewable energy that can be rolled out on a large scale. In Australia, the national Renewable Energy Target has provided financial incentives for developing the lowest-cost renewable energy projects. This means that wind power would receive the most support to achieve the target in this decade [56, 57]. Thus, one must ensure that no power system issues or problems occur with wind farm operations that could increase the energy cost of this technology.

The wind farm usually accommodates hundreds of wind turbine step-up transformers [59]. Hence, the switching of these transformers would very likely cause sympathetic inrush due to the close proximity between them. The transformers are distributed among a number of cable feeders that forms the collection grid; each feeder may connect 5–10 transformers. Standard IEC 60076-16:2011 [58] raised concern about the impact of mechanical and thermal stresses on these transformers due to frequent inrush energization and de-energization transients.

The works of [7, 16, 60, 61] examined the inrush effect of voltage sag at length. All used PSCAD/EMTDC as the simulation tool. In [16], the study of inrush in wind farm grid connections was discussed. It was determined that voltage sag will occur at the point of common coupling when different numbers of wind turbine generator transformers are energised simultaneously. Two wind farm sites were investigated, one with 15 wind turbine transformers (33/0.69 kV and 1.5 MVA) and the other with 52 wind turbine transformers (33/0.69 kV and 2.6 MVA). The results show the voltage sag determined from the predicted instantaneous voltage. The sympathetic inrush phenomenon was examined in both wind farms. The results show that the
smaller wind farm should simultaneously energise fewer transformers to ensure that the voltage sag does not exceed the allowed limit. Meanwhile, for the larger wind farm, more transformers can be energised simultaneously and the sympathetic inrush is not of significant concern.

In [6], the research of wind-power stability and the transient inrush phenomenon were discussed and assessed via a series of simulations in DigSILENT/PowerFactory software. Both onshore and offshore wind farms were modelled, and the critical clearing time in different scenarios calculated. The results draw from the simulated models of two offshore wind farms (160 MW and 209 MW capacities) and onshore wind farms (2232 MW capacity in total). The study demonstrates that the transient is highly dependent on the power flow pattern.

The boost in wind power means that the plants have to subsume the control tasks that determine the stability of the power system [62]. There are many possibilities for connection configurations within a wind farm which should be considered when modelling the network.

2.9 Summary

Previously published works relevant to this study are reviewed in this chapter. All aspects including the background of the transient problem, approaches for calculating the inrush, the modelling of a transformer using PSCAD, and transformer energisation transients in wind farms are discussed. These studies serve as a guide for the researcher to identify and address the research gaps in this field.

The findings of past research can be concluded below:

- The analytical equations will only provide an estimation of the inrush in a single-phase transformer. Since the study is focused on a large-scale network, simulation tools such as PSCAD/EMTDC would be more accurate.
• Since modelling studies always focus on transformers with access to complete test report data and manufacturer data, this study will focus on the modelling of transformers with limited available data in which the lacking data is obtained via specific tests.

• The Jiles-Atherton model has been used for transformer modelling in the past. However, this model has not yet been extended to include studies on the sympathetic inrush current phenomena. Hence, this research explains the modelling method and results using this model.

• Although sympathetic interaction between transformers has been investigated, very limited practical work has been reported on this issue, and mostly based on field measurements. Thus, the laboratory development for the inrush study in this thesis will provide the flexibility to perform measurements under various circuit configurations on full-sized distribution transformers.

• Although the sympathetic interaction between wind turbine transformers has been previously addressed [49], further investigations will help assess issues arising from this interaction and its severity. Thus, this research provides a systematic analysis of this issue in detail, upon which the way forward is suggested.
CHAPTER 3

TRANSFORMER AND SYSTEM COMPONENT MODELLING IN THE STUDY OF TRANSFORMER ENERGISATION TRANSIENTS

This chapter discusses the different methods of transformer modelling, in which the transformer is modelled prior to studying the inrush current transient. All the basic tests and calculations for modelling the test object such as the parametric study and loss computation—including its dynamic behaviour and saturation effect—are presented. The Steinmetz model—embedded in the Classic transformer model in PSCAD/EMTDC—is also discussed. The modelling of the circuit breaker is briefly discussed at the end of this chapter.

3.1 Background of Transformer Modelling

3.1.1 Introduction

The transformer is a vital component, especially in bulk transmission and distribution of electricity, consisting of two or more windings and usually with a ferromagnetic core to conduct the mutual magnetic flux coupling between circuits. To model the transformer, understanding of electromagnetic characteristics is needed, including both electromechanical and electromagnetic knowledge of the transformer [63].
The detailed modelling of transformer representation is complex due to the variations in core and coil design and their complex behaviours during transient phenomena. In a transformer energisation study, the focus should be on the representation of windings and the modelling of the magnetic iron core [64, 65]. Besides that, the transformer data, iron saturation, and transformer losses should also be considered.

According to a CIGRÉ report by the Working Group WG 33-02 [66], appropriate transformer modelling for simulation should be developed for use over specific frequency ranges. The transient frequency ranges can be classified into four groups. Table 3.1 shows the modelling recommendations for these groups.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low Frequency Transients</th>
<th>Slow-Front Transients</th>
<th>Fast-Front Transients</th>
<th>Very-Fast Front Transients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-circuit impedance</td>
<td>Very important</td>
<td>Very important</td>
<td>Important</td>
<td>Negligible</td>
</tr>
<tr>
<td>Saturation</td>
<td>Very important</td>
<td>Very important</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Iron losses</td>
<td>Important</td>
<td>Important</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Eddy currents</td>
<td>Very important</td>
<td>Important</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Capacitive coupling</td>
<td>Negligible</td>
<td>Important</td>
<td>Very important</td>
<td>Very important</td>
</tr>
</tbody>
</table>
In this scope of work, transformer modelling for slow-front transients from 50/60 Hz to 20 kHz is considered. This is suitable for simulation of power system transients such as inrush current excitation, transient recovery voltage, switching overvoltage, and all phenomena originating from line energisation. Line reclosing is also in this frequency range.

3.1.2 Background of transformer modelling in this research

A detailed study of the transformer model is carried out to facilitate development of methods to minimise inrush. The transformer is a complex structure; therefore its modelling is challenging. The estimation of some parameters can also be difficult. Errors can occur both during the measurement stage and post processing [3]. In transformer energisation, the inrush current is considered one of the most demanding low-frequency transient to model. Thus, if the transformer model can correctly predict inrush current transients, it can also be utilised to predict other switching transients.

The modelling of a transformer where inrush current occurs during energisation is proposed, in line with the availability of models in PSCAD/EMTDC—a popular simulation tool for analysing power systems transients. All transformer parameters—either frequency dependent and nonlinear—as well as its physical attributes such as transformer electrical data, magnetic core saturation and hysteresis, and eddy current losses are also considered.
In this study, the test objects are three same-rated single-phase distribution transformers, 16 kVA, 11 kV/500–250 V, as shown in Fig. 3.1, namely T1, T2, and T3. Throughout the experiments and tests, the low voltage winding connection is configured for 250 V for ease of energisation.

Details of transformer design and physical construction from the manufacturer are confidential. Data from test reports is usually the only information available for transformer modelling. Even with this data available, it is already a challenge to model the transformer, in particular the iron core [3]. In this research, the only available data is from the transformer name-plate, shown in Table 3.2. Therefore, some testing is required prior to the modelling work to obtain transformer parameters. The test objects are oil-immersed distribution transformers where the windings and the core can only be roughly measured and seen from the top. Thus, it is a challenge to develop a model for inrush current studies while only relying on some limited parameters of available input data [66].
Table 3.2 Transformer name-plate data for T1, T2, and T3

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Transformer 1</th>
<th>Transformer 2</th>
<th>Transformer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated kVA</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>HV Volts</td>
<td>11000</td>
<td>11000</td>
<td>11000</td>
</tr>
<tr>
<td>LV Volts</td>
<td>500–250</td>
<td>500–250</td>
<td>500–250</td>
</tr>
<tr>
<td>HV Amps</td>
<td>1.45</td>
<td>1.45</td>
<td>1.45</td>
</tr>
<tr>
<td>LV Amps</td>
<td>32–64</td>
<td>32–64</td>
<td>32–64</td>
</tr>
<tr>
<td>HV Winding</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
</tr>
</tbody>
</table>

3.2 Transformer Modelling in PSCAD/EMTDC

In PSCAD, the transformer models are included in the Transformers Library Group in the Master Library. The two fundamental types of transformer models are the classical and UMEC models, the latter is an acronym for Unified Magnetic Equivalent Circuit. The classical model uses the Steinmetz transformer model whereas the UMEC model uses the core geometry concept. It is not possible to use the IDEAL ratio changer in PSCAD/EMTDC.

The classical models are limited to single-phase units, where the different windings are on the same leg of the core. The saturable transformer model can be represented via several configurations. The model includes leakage reactance and a magnetising branch. The core saturation is modelled using an ideal current source across the specified winding. However, the UMEC model requires the transformer dimensional data, which is, in this case, not available. Thus, the classic saturable three-phase transformer model is used instead of the UMEC model.
3.2.1 Steinmetz classical transformer model

![Three Phase Transformer Models](image)

![Single Phase Transformer Models](image)

Fig. 3.2 Classic transformer model [67]

The classic transformer model is represented in Fig. 3.2. It is modelled according to the classic transformer equivalent circuit. The model includes leakage reactance and a magnetising branch. The core saturation is modelled using an ideal current source across the specified winding [68].

For transformer energisation in an open-circuit, the magnetising current is an important component of the current drawn by the no-load transformer. It is in quadrature with the applied voltage and because of the core saturation, it contains harmonics. The current component in phase with the voltage supplies the hysteresis and eddy current losses in the core. This suggests that in steady state, the transformer core might be represented by a parallel LR circuit, where the inductance is the
magnetising inductance, $L_c$, and the resistance, $R_c$, is obtained from the no load loss, $W_o$, as per equation (3.1) [69]:

$$R_c = \frac{V^2}{W_o}$$

(3.1)

In this work, transformer modelling for slow-front transients is considered. The Steinmetz Saturable Transformer model comprises a leakage reactance and a magnetising branch. The core saturation is modelled using an ideal current source across the specified winding.

The classic Steinmetz model is a two- and/or three-winding single-phase transformer model. To construct the three-phase transformer, three two-winding saturable transformer circuits are used, as shown in Fig. 3.3. In this model, the primary branch is treated as an uncoupled $R-L$ branch, and both of the windings are handled as a two-winding transformer. The circuit representing the core is connected across the terminals of the LV winding. Other required data include the positive sequence leakage resistance, no load losses, and copper loss values. Saturation data is also needed as input [70].

Fig. 3.3 Constructing the three-phase transformer from three two-winding STCs [49]
3.2.1.1 The Steinmetz model with Jiles-Atherton Hysteresis Saturation

In general, PSCAD/EMTDC can be used for modelling and simulating electrical power systems, which can be complex and involve a wide range of different power components. However, the modelling of the transformer itself is equally challenging, especially when lacking information on the core and windings. In the PSCAD/EMTDC 4.6 software, the core magnetic hysteresis algorithm has been added to the classical transformer model in the Master Library. The algorithm includes the basic model or loop width model as well as the Jiles-Atherton model.

The Jiles-Atherton model in PSCAD follows the theory of the relationship between $B-H$ and $M-H$, as is discussed further in Chapter 4. At each time step of the numerical computation process, the current changes are calculated based on the changes in the magnetising flux. Thus, in PSCAD, the magnetising flux is computed via the integration of the magnetising voltage, as shown in equation (3.2):

$$ V \overset{\int}{\longrightarrow} \lambda \overset{\frac{1}{NA}}{\longrightarrow} B \overset{\text{JAModel}}{\longrightarrow} H \overset{\frac{1}{NI}}{\longrightarrow} I_{mag} $$

(3.2)

This equation can then solve the unknown values of $\Delta H$ and $\Delta M$ in every time step. For this research purpose, a few estimations and assumptions are made to complete the model design.

Previous investigations often model the transformer using the classical model, i.e. the Steinmetz Saturation Transformer model without the hysteresis model (as the hysteresis model was not available before PSCAD 4.6). However, the accuracy of this model is doubtful. A better representation of transformer losses (non-linear and frequency dependent) is required for a more accurate model [3]. The Jiles-Atherton and Preisach models are preferred for their capability to perform minor loop operations and de-energisation transients [71]. Theoretically, this should improve the model performance, especially the estimate of the core remanent magnetisation. Thus, in this research, the Jiles-Atherton model is chosen and its parameters are determined based on a series of differential evaluation algorithms and several
reasonable assumptions. The modelling is improved by changing the piecewise linear interpolations to differential equations.

In this research, the simulations are conducted for a single-phase, two-winding transformer based on the classical modelling approach. However, in this case, the saturation is enabled and the hysteresis is set to the Jiles-Atherton model. Note that this model is only available in PSCAD version 4.6 and above.

3.3 Basic Transformer Modelling

3.3.1 Equivalent electrical circuit model for inrush studies

The model basically represents two mutually coupled windings, as shown in Fig. 3.4, where $L_1$ and $L_2$ denote the self-inductance of windings 1 and 2 respectively, and $L_{12}$ denotes the mutual inductance. Note that the self-inductance is defined as the sum of the leakage inductance of that winding and its magnetising inductance [68].

![Fig. 3.4 Model of two mutually coupled windings](image)

Referring to Fig. 3.4 and using Kirchhoff’s Voltage Law, the voltage across the transformer coils can be formulated using equation (3.3):
\[
\begin{bmatrix}
v_1 \\ v_2
\end{bmatrix} = \begin{bmatrix}
L_{11} & L_{21} \\ L_{12} & L_{22}
\end{bmatrix} \frac{d}{dt} \begin{bmatrix}
i_1 \\ i_2
\end{bmatrix}
\]

(3.3)

To obtain the current at the transformer winding, equation (3.1) is inverted, resulting in equation (3.4):

\[
d/dt \begin{bmatrix}
i_1 \\ i_2
\end{bmatrix} = \begin{bmatrix}
L_{11} & L_{21} \\ L_{12} & L_{22}
\end{bmatrix}^{-1} \begin{bmatrix}
v_1 \\ v_2
\end{bmatrix} = \frac{1}{L_{11}L_{22} - L_{12}L_{21}} \begin{bmatrix}
L_{22} & -L_{21} \\ -L_{12} & L_{11}
\end{bmatrix} \begin{bmatrix}
v_1 \\ v_2
\end{bmatrix}
\]

(3.4)

Since the two mutually coupled inductances are identical, \(L_{12}\) and \(L_{21}\) are therefore equal. The coupling coefficient, \(K\), between the coils is expressed as equation (3.5):

\[
K_{12} = \frac{L_{12}}{\sqrt{L_{11}L_{22}}}
\]

(3.5)

In an ideal transformer, the transformer ratio is defined either as the ratio between primary and secondary voltages or the ratio between secondary and primary currents, as shown using equation (3.6) below:

\[
a = \frac{v_1}{v_2} = \frac{i_2}{i_1}
\]

(3.6)

Inputting the turn-ratio “\(a\)” in the equation (3.3), resulting in equation (3.7):

\[
\begin{bmatrix}
v_1 \\ a.v_2
\end{bmatrix} = \begin{bmatrix}
L_{11} & aL_{21} \\ aL_{12} & a^2L_{22}
\end{bmatrix} \frac{d}{dt} \begin{bmatrix}
i_1 \\ i_2 / a
\end{bmatrix}
\]

(3.7)

The full equivalent circuit for a two-winding transformer is shown in Fig. 3.5 where Tx denotes the transformer in the ideal condition, \(a:1\). \(R_1\) and \(R_2\) are the winding resistances, and:

\[
L_1 = L_{11} - aL_{12}
\]
\[
L_2 = a^2L_{22} - aL_{21}
\]

(3.8)
3.3.2 Electrical parameter computation

Usually, the no-load loss test, load loss test, and/or zero-sequence test results are presented in the transformer test report [21]. In this study, the test objects are commercial transformers for which design details from the manufacturer are not publicly available. Therefore, the open-circuit test and short-circuit test are performed prior to modelling [72]. From these tests, the values for all system resistance and inductance can be specified.

The experimental phase of this study includes open-circuit and short-circuit testing of transformers. These tests enable the determination of the equivalent circuit of the transformer. The experiment also studies the excitation current, magnetisation current, and core-loss current.

Fig. 3.6 shows an AMETEK CSW555 programmable power supply, for which the main specifications are summarised in Appendix A. This power supply is used to generate the excitation voltage for testing the transformers. It is connected to a desktop computer which is used for composing the voltage waveform. From this programmable source, the resulting output waveform can be monitored via an oscilloscope.
3.3.2.1 Open-circuit test

From the ideal electrical configuration of the transformer, the equivalent single-phase transformer circuit is derived, as per Fig. 3.5. By referring to the primary side, the transformer equivalent circuit with all the electrical parameters are shown in Fig. 3.7.

![Electrical parameters in the primary side of transformer equivalent circuit](image)

Fig. 3.6 AMETEK CSW555 programmable power supply

Fig. 3.7 Electrical parameters in the primary side of transformer equivalent circuit
To conduct the open-circuit test (also known as the no-load test), the secondary windings are first opened. The open-circuit test can be carried out either on the high voltage side or on the low voltage side. Here, the latter choice is more convenient as the mains supply is readily available to provide the rated test voltage. The measurement configuration of the open-circuit test is shown in Fig. 3.8.

![Configuration of the open-circuit test](Image)

As per Fig. 3.8, the secondary side is open-circuited while the primary side is connected to an ammeter (A), wattmeter (W), and voltmeter (V). The voltage across the primary terminal, $V_1$, is varied from zero to the rated value. When the rated primary voltage of the winding is achieved (i.e. the rated voltage of LV winding), the readings of the ammeter, wattmeter, and voltmeter are taken.

For this test, each transformer is open-circuited at the high voltage side. Then, the input voltage is increased slowly from zero to the rated voltage and then reduced until it reaches zero. Since all data recorded for the three transformers are very similar, only the open-circuit characteristic of Transformer 2 is shown here, as plotted in Fig. 3.9.
Using the readings of the voltmeter and ammeter, which represent input voltage and no-load current, respectively, all electrical parameters can be computed, as below:

The wattmeter reading yields the input power. Thus, from the power factor value, the phase angle can be calculated using equations (3.9) and (3.10):

\[
\cos \phi = \frac{P_{oc}}{\left| V_{oc} \parallel I_{oc} \right|} \quad \text{(3.9)}
\]

\[
\therefore \phi = \cos^{-1} \left( \frac{P_{oc}}{\left| V_{oc} \parallel I_{oc} \right|} \right) \quad \text{(3.10)}
\]

Next, the transformer parameters referring to the primary side is calculated via equation (3.11):

\[
I_c = I_{a} \times \cos \phi \quad \text{(3.11)}
\]
\[ I_m = I_{nl} \times \sin \phi \]  

(3.12)

Thus,

\[ R_c = \frac{V_{ac}}{I_c} \]  

(3.13)

\[ X_m = \frac{V_{ac}}{I_m} \]  

(3.14)

where \( I_{nl} \) is the no-load current, \( I_c \) and \( I_m \) are the shunt currents and \( R_c \) and \( X_m \) are the shunt resistance and magnetising reactance of the equivalent circuit, respectively. In summary, from the open-circuit test, the parameters \( I_c, I_m, R_c \) and \( X_m \) can be computed.

3.3.2.2 Short-circuit test

![Diagram of short-circuit test](image)

Fig. 3.10 Configuration of the short-circuit test

The configuration of the short-circuit test is shown in Fig. 3.10. This test is also known as the impedance test. The low voltage winding of the transformer (secondary side) is short-circuited while voltage is applied to the high voltage winding (primary side) from a variable supply source.
The voltage source is increased slowly until the rated current is reached on the secondary side. Note that only a small voltage is required to reach this rated current. Both the primary and secondary side currents are recorded.

In this connection, the iron loss (core loss), $P_{fe}$, is very small compared to the copper loss (winding loss), $P_{cu}$. Hence, for the short-circuit test configuration, the value of the iron loss can be neglected.

To determine total power input, $P_i$, equation (3.15) is used:

$$P_i = P_o + P_{cu} + P_{fe}$$

As in the no-load case, $P_o = 0$, and $P_{fe}$ can be neglected. Hence, $P_i = P_{cu}$, which is the wattmeter reading.

By referring to the primary side, $R_{eq}$, $Z_{eq}$, and $X_{eq}$ can be calculated using equations (3.16) to (3.18):

$$R_{eq} = \frac{P_{sc}}{|I_{sc}|^2}$$

(3.16)

$$Z_{eq} = \frac{V_{sc}}{I_{sc}}$$

(3.17)

$$X_{eq} = \sqrt{|Z_{eq}|^2 - R_{eq}^2}$$

(3.18)

In the above, the power, voltage, and current are measurements in the input side. In summary, from the short-circuit test, it is possible to calculate the values of full-load $P_{cu}$, $R_{eq}$, $Z_{eq}$, and $X_{eq}$.
3.3.2.3 Modelling Transformer Parameters

From the open-circuit and short-circuit tests, the data recorded is shown in Appendix B, from Table B.1 to Table B.6, respectively. Calculations for the electrical parameters are completed using formulae in Microsoft Excel. The parameters for modelling the transformers are summarised in Table 3.3.

Table 3.3 Parameters calculated from Transformer 1, Transformer 2, and Transformer 3

<table>
<thead>
<tr>
<th>Transformer parameter (unit)</th>
<th>Transformer 1</th>
<th>Transformer 2</th>
<th>Transformer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Power (kVA)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>HV level (V)</td>
<td>11000</td>
<td>11000</td>
<td>11000</td>
</tr>
<tr>
<td>LV level (V)</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>HV current (A)</td>
<td>1.45</td>
<td>1.45</td>
<td>1.45</td>
</tr>
<tr>
<td>LV current (A)</td>
<td>32-64</td>
<td>32-64</td>
<td>32-64</td>
</tr>
<tr>
<td>$I_c$ (A)</td>
<td>0.061</td>
<td>0.012</td>
<td>0.052</td>
</tr>
<tr>
<td>$I_m$ (A)</td>
<td>0.425</td>
<td>0.520</td>
<td>0.417</td>
</tr>
<tr>
<td>$R_c$ (Ω)</td>
<td>4166.67</td>
<td>3289.47</td>
<td>4166.67</td>
</tr>
</tbody>
</table>
3.4 Computation of Losses in Transformers

To model the transformer for the simulation of low frequency transients, it is important to obtain the various power losses in the transformer such as the iron losses in the core and copper losses in the windings. To this end, further experiments are required.

3.4.1 Iron core losses by injecting different voltage harmonics

As information on transformer loss is not available, the test objects, which are the transformers used in this study, were injected with different voltage harmonics. The experiment follows the IEEE Standard [73]. The transformers were energised on the HV side during the short-circuit test.

From the measurements, the following parameters can be computed. The equivalent winding resistance with respect to the $h$-th harmonic, $R_{eq-h}$, is expressed as equation (3.19):

$$R_{eq-h} = \frac{P_{sc-h}}{I_{sc-h}^2}$$  \hspace{1cm} (3.19)

For the equivalent winding impedance, $Z_{eq-h}$, equation (3.20) is used:

$$Z_{eq-h} = \frac{V_{sc-h}}{I_{sc-h}}$$  \hspace{1cm} (3.20)

Hence, to calculate the winding reactance, $X_{eq-h}$, equation (3.21) is used:

$$X_{eq-h} = \sqrt{Z_{eq-h}^2 - R_{eq-h}^2}$$  \hspace{1cm} (3.21)

where, $P_{sc-h}$ denotes the power loss at $h$-th harmonic while $V_{sc-h}$ and $I_{sc-h}$ are the RMS values of the voltage and current measured on the primary side in the short-circuit
test at the $h$-th harmonic order, respectively. The resistance and reactance values of
the tested transformer injected in different harmonics are shown in Fig. 3.11.

![Graph showing resistance and reactance values](image)

**Fig. 3.11 Resistance and reactance values of transformer injected with different harmonics**

In [74], for the oil-immersed transformer, it is assumed that 33% of total stray loss is
the winding eddy current loss. Therefore, the expression of power loss is given in
equation (3.22):

$$P_L = R_{dc}I^2 + 3P_{ec} = I^2\left(R_{dc} + 3R_{EC-h}\right)$$

$$= I^2\left(R_{dc} + 3R_{EC-h}h^2\right)$$ (3.22)

where, $R_{EC-R}$ and $R_{EC-h}$ are the winding resistance corresponding to the eddy current
loss at the rated condition and at the $h$-th harmonic order, respectively [75].

From equation (3.22), the derived equation (3.23) can be used to get $R_{EC-h}$:

$$R_{EC-h} = R_{EC-R}h^2 = \frac{1}{3}\left(\frac{P}{I^2} - R_{dc}\right)$$ (3.23)
At the $h$-th harmonic order, $R_{AC,h}$, is defined as the total winding resistance and can be defined as equation (3.24):

$$R_{AC,h} = R_{DC} + R_{EC,h}$$  \hspace{1cm} (3.24)

These transformers are both same rated, so the values are similar between them. Therefore, only the mean values are recorded. This shows that the no-load loss at fundamental frequency is not insignificant. However, if the transformer experiences harmonic pollution present in the network, the core losses will increase significantly.

![Graph showing core losses vs harmonic order](image)

**Fig. 3.12 Variation of core losses with different harmonic order**

Fig. 3.12 plots the variation of the transformer core losses at the rated voltage against the harmonic level. As expected, the no-load loss increases with higher harmonic order. From comparison of the core loss due to distorted waveform and the fundamental sinusoidal frequency, the core loss between the 50 Hz and the distorted IEC limitation waveform are plotted. Referring to Fig. 3.13, the core loss under the distorted waveform is higher than the core loss under pure power frequency. At the rated voltage in particular, the core loss increased by about 30%.
3.4.2 Loss separation using the two-frequency method

The iron core loss is the combination of the hysteresis loss and eddy current loss. Thus, to model the transformer, each loss value must be determined. Hence, the first step is to separate the constituent components in the core loss using experimental methods.

Referring to the Steinmetz empirical relationship [76, 77], the iron-core loss is defined as equation (3.25):

\[ P_c = P_h + P_e \]  

(3.25)

where \( P_c \) denotes the core loss, \( P_h \) is the hysteresis loss, and \( P_e \) is the eddy current loss, as per equations (3.26) and (3.27), respectively:

\[ P_h = k_h \times B_{max}^n \times f \]  

(3.26)
where $k_h$ and $k_e$ are constants for the material of the core, $B_{\text{max}}$ is the maximum flux density, $f$ is the applied frequency, and $n$ is in the range of 1.5–2.5 depending on the material [78]. For the silicon steel transformer, i.e. the test object, an $n$ value of 1.6 is used, referring to the typical value [79]. Combining equations (3.26) and (3.27), equation (3.28) is derived:

$$P_e = P_h + P_e = k_h B_{\text{max}}^{1.6} f + k_e B_{\text{max}}^2 f^2$$  \hfill (3.28)

According to Faraday’s law, the relationship between the induced voltage $v(t)$ and the AC magnetic flux $\phi(t) = \phi_m \sin(\omega t)$ circulating in the core is given by equation (3.29):

$$v = -N \frac{d\phi}{dt} = NAB_{\text{max}} \omega \cos(\omega t)$$  \hfill (3.29)

where $\omega = 2\pi f$, $N$ is the number of turns in the secondary winding, and $A$ is the cross-section area of the core. Hence, equation (3.30) is derived:

$$B_{\text{max}} = \frac{1}{4.44NA} \times \frac{V_{\text{rms}}}{f}$$  \hfill (3.30)

where $V_{\text{rms}}$ is the RMS secondary voltage; thus, two separate experiments can be carried out to measure the no-load loss at two different frequencies but a different voltage is applied such that the maximum flux density $B_{\text{max}}$ remains the same in both cases [80]. The measurement results from these two tests can be applied to equation (3.28) to determine the values of $k_h$ and $k_e$; hence, the hysteresis loss and the eddy current loss can be separated.
Fig. 3.14 Iron core loss in the transformer

Fig. 3.14 shows the no-load core loss separation into the eddy current loss and hysteresis loss. It can be seen that all the losses increase with the frequency as expected. For the particular case of running this oil-immersed distribution transformer at the designed frequency of 50 Hz, the eddy current loss accounts for 22.5% of the no-load loss.

3.5 Magnetic Core Saturation and Hysteresis

3.5.1 Modelling the saturation curve

In many cases, the transformer open-circuit test is the only data source available for approximating the saturation curve. However, when modelling for the equivalent circuit of the transformer, another issue arises, which is a lack of reliable data from which to obtain the parameters of the equivalent circuit, i.e. leakage inductance, non-
linear magnetising inductance for core saturation, and non-linear resistance for core loss. Thus, some optimisation strategies must be formulated and implemented.

There are two approaches to improve and extend the characterisation of the non-linear characteristic of transformers: linear extrapolation and curve fitting [3, 49]. In the linear extrapolation method, a constant slope of the saturation curve is assumed after the last point of the non-linear curve. The accuracy of this method is questionable when the two last points of the piecewise non-linear curve lie in the range of 100% to 110% excitation level [49], which means complete saturation has not yet been reached in the open-circuit test. A linear addition of the curve will result in a simple under-estimation of the current for any level beyond the last measurement point. On the other hand, curve fitting is a method of constructing a curve which provides a smoother fit of the additional artificial points of the saturation characteristic. This method is performed to add new segments of data in the non-linear curve that were not able to be obtained experimentally due to practical constraints.

3.5.1.1 Saturation curve by the Curve Fitting Point

Previously, Fig. 3.9 shows the open-circuit characteristics for the transformer. From the initial data, the graph is plotted in Microsoft Excel. However, the experimental voltage and current measurement results do not provide sufficient data to accurately model the saturation curve of the transformer. Thus, curve fitting technique is applied to extend the other points. Since the saturation curve characteristics should increase and then level out, a logarithmic trend line is chosen over the polynomial trend line to build the curve.

The logarithmic trend line option in Microsoft Excel is used to estimate more points so that the saturation characteristic of the transformer is modelled accurately. Besides Excel, the MATLAB Optimisation toolbox is also used to generate the saturation curve. From this, the curve fitting equation, \( y = 84.799 \ln(x) + 405.77 \), is obtained.
From the curve fitting equation, the extension of other points of $x$ and $y$ are computed. Fig. 3.15 shows the saturation curve achieved. Noted that the points for 250 V and below are the magnetising current versus voltage obtained from the no-load test and other points are extended by the curve fitting method.

\[
y = 84.799\ln(x) + 405.77
\]
\[
R^2 = 0.9827
\]

![Saturation curve generated by curve fitting the points](image)

From the open-circuit tests, the excitation levels range from 90% to 110% of the operating voltage. This is because the system variations are normally controlled by ±10% of the normal operating voltage [49]. Thus, the points for the saturation curve are not completed. Extension of these points is needed to form a complete core saturation curve.

Past research used two approaches for data extension, which are curve fitting and extrapolation. In curve fitting, new artificial points are generated and added to plot the nonlinear curve. On the other hand, in linear extrapolation, the final segment of the curve is linearly extended to form a constant slope for representing $\lambda/i$ characteristics in the transformer core deep saturation region. Note that in the linear
extrapolation technique, the current resulting above the 110% excitation level will be underestimated because at this point, the core has not reached deep saturation.

3.5.2 Modelling non-linearity using the hysteresis loop

For construction of the hysteresis loop, the non-linear parameters are computed from the experiment data. The non-linear piecewise linear $v$-$i$ curve from the open-circuit test is used to compute and later construct the $\lambda$-$i$ curve.

Note that as the open-circuit test data are in the form of $v_{rms}$-$i_{rms}$, it is required to convert to the points to the peak values and then substitute in the equation.

In order to construct the $\lambda$-$i$ curve, some assumptions are made:

- The $v$-$i_{rms}$ and $\lambda$-$i$ curve are symmetric with respect to the origin
- The winding resistance and the leakage inductance of the transformer are neglected.

Using ATP/EMTP, the improved saturation curve is developed. Taking value of calculated hysteresis loss and several points from the fitted curve in Fig. 3.15, the excitation voltage and current data is then converted to the flux versus currents points using the SATURA routine in ATP/EMTP, as shown in Fig. 3.16.

Here, the Frolich formula is used in the calculation. An improved equation of Frolich formula is proposed in [81] and shown in equation (3.31):

$$\lambda = \frac{i}{a + b \times |i| + c \times \sqrt{|i|}}$$

(3.31)

where $a$, $b$, $c$ are taken from the test data. In the process, the actual leakage flux waveforms are computed as the measured voltage waveform [81]. Then, the hysteresis loop is created via the “HEVIA” routine, as shown in Fig. 3.17.
Fig. 3.16 Saturation curve generated by using Frolich equation

Fig. 3.17 Hysteresis curve using ATP/EMTP
3.6 Estimation and Assumptions in the Modelling Study

For the modelled transformer, not all parameters are available. Thus, a few assumptions and estimations are considered throughout the modelling process. Note that this is in-line with the IEC standard [82] and transformer modelling standard used in [21].

Since the no-load test results and load-loss test results are not available, the open-circuit and short-circuit tests are carried out prior to the modelling. In these tests, the magnetising branch is neglected and the load loss is assumed to be zero. The transformer losses are computed using different harmonic injections and the core losses are separated using the two-frequency method, as previously explained.

All given electrical parameters whether in Ω, A, or V are also converted (normalised) into per unit. The PSCAD/EMTDC classical model parameters are to be input in the per-unit system only.

The Jiles-Atherton modelling parameters are discussed in the next chapter.

3.7 Circuit Breaker Modelling

A guideline for circuit breaker modelling is available in the literature. In [83], the importance of each of the operation in closing and opening the circuit breaker is categorised based on their frequency ranges. In this particular case (slow-front transients), the closing operation is relevant to consider, whilst opening the breaker is applicable for other situations.

In the breaker modelling of the simulations in this work, a single-phase circuit breaker is modelled as an ideal time-controlled switch. This switch opens at the first current zero crossing after the ordered tripping instant and closes at any part of the
power cycle. The closing time span modelled for this breaker consists of the summation of the common order time, $t_{order}$ and random offset time, $t_{offset}$.

For the three-phase circuit breaker modelling used in the simulations discussed in Section 5.7 later, the same modelling technique is used. Here, each pole in a three-phase circuit breaker is modelled as an ideal time-controlled switch and the random offset time, $t_{offset}$ is determined for each pole, namely $t_{offsetA}$, $t_{offsetB}$ and $t_{offsetC}$. Thus, the closing time for each pole is determined via the series of equations presented in equation (3.32):

$$T_{Aclose} = t_{order} \pm t_{offsetA}$$
$$T_{Bclose} = t_{order} \pm t_{offsetB}$$
$$T_{Cclose} = t_{order} \pm t_{offsetC}$$

(3.32)

It can be seen that in both modelling approaches, the Maximum Closing Time Span (MCTS) determines the offset closing time. However, MCTS is of uncertain value [49]. According to [84], a typical MCTS between 3 and 5 ms is suggested. In this work, MCTS is set at 5 ms.

### 3.8 Discussion and Summary

The objective of this work is to perform a detailed study of power transformers and to develop a transformer model for use in transient simulation studies. The focus is placed on transformer modelling for slow-front transients, as the research scope is on transformer energisation issues.

This chapter presents a transformer model for slow-front transients caused by 50-Hz line energisation. Three single-phase 16 kVA, 11 kV/250 V distribution transformer models are used. The classic transformer model (include the leakage reactance and magnetising branch) is adopted from the PSCAD/EMTDC Master Library and
further modelled via a combination of analytical analysis and measurements. The measurements include basic electrical parameter computation and loss computation from the open-circuit test and short-circuit test. The separation of eddy current loss is achieved using the two-frequency method. Core saturation is modelled using an ideal current source across the specified winding; the saturation curve is constructed using the curve-fitting method, generated by the MATLAB Optimisation toolbox. The circuit breaker is modelled using Maximum Closing Time Span (MCTS).

The test object only has name-plate data, which makes the modelling work challenging. A number of assumptions and estimations are therefore used in the process as previously discussed in section 3.6 and also subsection 3.5.2, thus making the modelling less accurate. However, a model established mainly from this data will be a fairly general model and has a fair capability of estimating inrush currents and switching transients. The validation of the transformer model via both the classical Steinmetz model with and without Jiles-Atherton is discussed in Chapter 5.

In summary, for modelling validation, a transformer of the same rating is employed as the test object. Since the PSCAD simulation and experimental measurements give acceptable results, the model can be relied on to obtain the transformer energisation transient. This chapter outlines the steps taken for modelling transformers with limited available data.

However, although the PSCAD modelling approach using the classic transformer via the Jiles-Atherton hysteresis model yields better accuracy, this approach requires users to have advanced skilled level and knowledge about the Jiles-Atherton model.
CHAPTER 4

IMPROVED TRANSFORMER MODELLING VIA THE JILES-ATHERTON MODEL

The chapter discusses the improved transformer modelling using the Jiles-Atherton model. The Steinmetz model was used in previous works, but some discrepancies in the results were noted. With the introduction of PSCAD 4.6, the classical model based on the Jiles-Atherton hysteresis model—an improved version of the Steinmetz model—was also provided. The Jiles-Atherton model parameters are estimated. Even with the limited data of the transformer used in this inrush study, the model still showed improved results. This chapter also investigates the accuracy of modelling the transformer core data in MATLAB/Simulink based on the Jiles-Atherton model. The Inverse Jiles-Atherton model is also tested, yielding reliable results that accurately predict the sympathetic inrush current phenomenon.

4.1 Background

Previous investigations have often modelled the transformer using the classic Steinmetz Saturation Transformer model. However, there is still doubt concerning the accuracy of this method. The modelling of transformer losses (nonlinear and frequency dependent) would be better with a more accurate model. In [66, 85], the Jiles-Atherton and Preisach models were used as they can represent minor loop operations and de-energisation transients, thus improving the estimation of the
remanent magnetisation of iron-core inductors. The modelling in previous studies lacks knowledge regarding magnetic core saturation and hysteresis characteristics. Thus, in this research, the Jiles-Atherton model is chosen and its parameters are determined based on a series of differential evaluation algorithms and several reasonable assumptions.

For iron-core modelling, the iron-core physical characteristics should be considered in which its behaviour should be represented via the relationship of the magnetic flux density, $B$, and the magnetic field intensity, $H$. To characterise the full behaviour of the core, the model should be able to plot the major and minor hysteresis loops. The classic Steinmetz model in previous transformer modelling studies can only determine the saturation curve, and not the full distribution hysteresis loops.

In this research, the modelling of the transformer, especially its iron-core, has proven to be a challenging task. The detailed manufacturer design and physical construction of the tested transformers are confidential technical information and so not disclosed to the general public. Thus, the problem is how to develop a realistic simulation model given the limited amount of commonly available input data [66].

This chapter is organised as follows: Sections 2 and 3 define and discuss transformer modelling using the Jiles-Atherton model in an effort to improve upon the classic Steinmetz model in PSCAD/EMTDC. Section 4 presents the extended model of Jiles-Atherton, which is the Inverse Jiles-Atherton. This model retains the same features of the original Jiles-Atherton but provides more flexibility in numerical field computations [86]. Simulation modelling is done using MATLAB/Simulink. Section 5 presents the execution of the parameter estimation in both cases, while Section 6 discusses the signal de-noising method used in the modelling. Finally, the experimental results are analysed to justify the proposed model.
4.2 Transformer Modelling using Jiles-Atherton

The classic Steinmetz (saturation) model is not able to produce a hysteresis loop and the transformer core data is assumed. Therefore, there is some doubt regarding the model accuracy; hence, the advanced Jiles-Atherton model is investigated. This model has the capability to represent minor loop operations and de-energisation. The Jiles-Atherton model is therefore selected because its parameters are measurable, simpler, and based on magnetic quantities.

4.2.1 Defining the Jiles-Atherton model

The Jiles-Atherton hysteresis model involves the derivation of a model that enables the connection between the physical parameters of the magnetic material [87, 88]. The relationship between the flux density \( B \), the magnetic field intensity \( H \), and the total magnetisation \( M \) is shown in equation (4.1) [89-91]:

\[
B = \mu_o \cdot (H + M)
\]  

(4.1)

where \( \mu_o \) is the permeability of free space. The anhysteretic magnetisation is expressed by equation (4.2):

\[
M_m = M_s \cdot f_e(H_e)
\]  

(4.2)

where \( M_s \) is the saturation magnetisation, \( H_e = H + \alpha M \) is the effective magnetic field, and \( \alpha \) is the inter-domain coupling factor.

The Jiles-Atherton model uses a modified Langevin function to produce a familiar sigmoid-type curve for \( f(H_e) \), as per equation (4.3):

\[
M_m = M_s \cdot \left[ \frac{1}{\tanh \left( \frac{H_e}{a} \right)} - \frac{1}{\tanh \left( \frac{H_c}{a} \right)} \right]
\]  

(4.3)
where $a$ stands for the shape parameter.

Differentiating equation (4.3) with respect to $H_e$, equation (4.4) is derived:

$$\frac{dM_{an}}{dH_e} = \frac{M_s}{a} \left[ 1 - \frac{1}{\tanh^2(H_e/a)} + \frac{1}{(H_e/a)^2} \right]$$  \hspace{1cm} (4.4)

To calculate the total magnetisation, $M$ is expressed as in equation (4.5):

$$M = M_{irr} + M_{rev}$$  \hspace{1cm} (4.5)

where $M_{irr}$ denotes the irreversible magnetisation associated with energy lost to pinning and $M_{rev}$ denotes the reversible magnetisation associated with elastic domain wall bending.

Based on equation (4.4), the final set of equations can be obtained. Introducing the $c$ parameter, the $M-H_e$ and $B-H$ loops are constructed, as shown in equation (4.6):

$$\frac{dM}{dH} = \frac{c}{\mu_0} \frac{dM_{an}}{dH_e} + \frac{M_{an} - M}{\delta k - \alpha (M_{an} - M) \left[ 1 - c \right]} \frac{dM_{an}}{dM_e}$$  \hspace{1cm} (4.6)

With any magnetisation change, equation (4.7) applies:

$$\frac{dM_{irr}}{dH} = \frac{M_{an} - M_{an}}{k \delta - \alpha (M_{an} - M_{irr})}$$  \hspace{1cm} (4.7)

where:  
$M_{an}$ is the anhysteretic magnetisation  
$M_{irr}$ = irreversible magnetisation  
$k$ is the parameter widening the curve  
$\delta$ is the sign parameter  
$\alpha$ is the molecular field parameter

The $\delta$ sign parameter varies with the direction of magnetic field intensity. Thus,
based on whether the sign of $\frac{dH}{dt}$ is positive or negative, $\delta$ will be derived using equation (4.8) [92, 93]:

$$
\delta = \begin{cases} 
+1 \text{pro} & \frac{dH}{dt} > 0 \\
-1 \text{pro} & \frac{dH}{dt} < 0 
\end{cases}
$$

(4.8)

By adding the different susceptibilities and the relationship between hysteresis parameters in [94] and omitting some redundancy, equation (4.6) can be shortened and written as equation (4.9):

$$
\frac{dM}{dH} = \frac{c \frac{dM_{\text{sat}}}{dH_c}}{1 - \alpha c \frac{dM_{\text{sat}}}{dH_c}}
$$

(4.9)

In PSCAD 4.6, the original Jiles-Atherton model is already embedded. As the parameters can be formulated in the experiment, a set of five equation parameters are used, namely $a$, $a$, $c$, $k$ and $Ms$. Subsequent research effort[95] has given rise to the development of the inverse to the original Jiles-Atherton.

In Fig. 4.1, the Jiles-Atherton parameters are indicated at different points, respectively, as shown in the hysteresis loop.
4.3 Jiles-Atherton in PSCAD/EMTDC

4.3.1 Background

In PSCAD, the transformer models are included in the Transformers Library Group of the PSCAD Master Library. There are two fundamental types of available transformer models: the classical and the Unified Magnetic Equivalent Circuit (UMEC) models. With the release of PSCAD 4.6, the classical transformer also incorporated a hysteresis algorithm. The algorithm includes two modelling methods for hysteresis, which are the basic hysteresis and Jiles-Atherton models. All the parameters in PSCAD are specified based on a per-unit system.

For this research, several parameters are estimated using differential evolution algorithms. All magnetic characteristics of the material should be input in the modelling phase. The domain flexing parameter, domain pinning parameter, parameter to adjust $k$ with $M$, inter-domain coupling, saturation anhysteretic
magnetisation, and the entire 1, 2, 3, and 4 coefficients of the anhysteretic curve are considered. Besides the Jiles-Atherton parameters, the basic parameters obtained from the transformer name plate, basic calculations, as described in [72], and other formulae to calculate the model parameters are also applied, as outlined in equations (4.10) and (4.11):

Winding leakage reactance (p.u): \[ x = \sqrt{\left(\frac{I_z}{100}\right)^2 - r^2} \] (4.10)

Load loss resistance (p.u): \[ r = \frac{P_x[kW]}{MVA_{sc test}[MVA]\times1000} \] (4.11)

In addition, the copper loss corresponds to \(I_1^2R_1\) in the primary side and \(I_2^2R_2\) in the secondary side.

The Jiles-Atherton model in PSCAD follows the theory of the relationship between \(B-H\) and \(M-H\), as discussed in Section 4.2. At each time step of the numerical computation process, the current changes are calculated based on the changes in the magnetising flux. Thus, in PSCAD [67], the magnetising flux is computed via the integration of the magnetising voltage, as shown in equation (4.12):

\[
V \xrightarrow{\lambda} \frac{\gamma}{\gamma H} [N_A \phi] \xrightarrow{\lambda = N_B \phi} [B] \xrightarrow{JAModel} [H] \xrightarrow{\frac{\gamma}{I_{N_H}}} [I_{mag}]
\] (4.12)

Thus, the unknown values of \(\Delta H\) and \(\Delta M\) can be solved in each time step. For this research purpose, a few estimations and assumptions are made to complete the model design.
4.3.2 Flux Computation

In PSCAD/EMTDC modelling, the remanent flux value is computed. From equation (4.12), the values of $\Delta H$ and $\Delta M$ are estimated and the new values of $\Delta H$ and $\Delta M$ are updated in every step [96].

Referring to [96], the simulation algorithms are defined as per equation (4.13):

$$\Delta H = Q\Delta H_{\text{max}}$$  \hspace{1cm} (4.13)

where ($0 \leq Q \leq 1$). The increment in maximum $H$ and the increment of $M$ are defined in equation (4.14):

$$\Delta H_{\text{max}} = \frac{\Delta \phi}{A\mu_0}, \Delta M = \frac{\Delta \phi}{A\mu_0} - \Delta H$$  \hspace{1cm} (4.14)

Hence, the new values of $H$ and $M$ are calculated based on their old values and the increments $\Delta H$ and $\Delta M$, as shown in equation (4.15):

$$H_{\text{new}} = H_{\text{old}} + \Delta H, M_{\text{new}} = M_{\text{old}} + \Delta M$$  \hspace{1cm} (4.15)

Recalling the $\delta$ parameter value from equation (4.8), equation (4.16) is derived:

$$\delta = \text{sign}(\Delta H) = \text{sign}(\Delta \phi)$$  \hspace{1cm} (4.16)

where $\Delta \phi$ denotes the increment flux.

4.4 Inverse Jiles-Atherton

This research aims to achieve a stable voltage-to-current conversion; thus the inverse Jiles-Atherton is applied. Moreover, the inversion of the original Jiles-Atherton model is proposed because it is known to be more suitable for numerical field calculations, as flux $B$ is known prior to the field $H$ [86].
4.4.1 Defining the inverse Jiles-Atherton

The inverse Jiles-Atherton model is described in detail below [97, 98].

The previous equation (4.5) shows the total magnetisation.

\( M_{rev} \) is the reversible magnetisation, which is given in equation (4.17):

\[
M_{rev} = c(M_{an} - M_{irr}) \tag{4.17}
\]

where \( M_{an} \) is the anhysteretic magnetisation, and \( c \) is the coefficient of proportionality.

The anhysteretic magnetisation \( M_{an} \) is described using the Langevin function in equation (4.18):

\[
M_{an} = M_s \left( \coth \frac{H_o}{a} - \frac{a}{H_o} \right) \tag{4.18}
\]

where \( M_s \) is the saturation magnetic moment of the core material and \( a \) is the shape parameter. Thus:

\[
\frac{dM_{an}}{dH_o} = \frac{M_s}{a} \left( 1 - \coth^2 \left( \frac{H_o}{a} \right) + \left( \frac{a}{H_o} \right)^2 \right) \tag{4.19}
\]

\( H_o \) in (4.18) is the effective magnetic field, which is expressed as equation (4.20):

\[
H_o = H + \alpha \cdot M \tag{4.20}
\]

where \( H \) is the magnetic field in the core, and \( \alpha \) is the inter-domain coupling factor.

The flux density, \( B \), is given by equation (4.21):

\[
B = \mu_0 (H + M) \tag{4.21}
\]
where $H$ is the magnetising field, and $\mu_0$ is the permeability of free space. Hence:

$$\frac{dM}{dB} = \begin{cases} \frac{\xi}{\mu_0[1+(1-\alpha)\xi]} & \text{if } \delta_M = 0 \\ \frac{\eta}{\mu_0[k \cdot \delta + (1-\alpha)\eta]} & \text{if } \delta_M = 1 \end{cases} \quad \text{(4.22)}$$

where:

$$\delta_M = \begin{cases} 0 & \text{if } \text{sign}(dH/dt) \cdot \text{sign}(M_{an} - M) < 0 \\ 1 & \text{if } \text{sign}(dH/dt) \cdot \text{sign}(M_{an} - M) > 0 \end{cases} \quad \text{(4.23)}$$

$$\xi = c \frac{dM_{an}}{dH_e}, \quad \eta = (M_{an} - M) + k \cdot c \cdot \delta \cdot \frac{dM_{an}}{dH_e} \quad \text{(4.24, 4.25)}$$

and

$$\delta = \begin{cases} 1 & \text{if } \text{sign}(dB/dt) > 0 \\ -1 & \text{if } \text{sign}(dB/dt) < 0 \end{cases} \quad \text{(4.26)}$$

4.4.2 Inverse Jiles-Atherton modelling programme methodology

Fig. 4.2 shows the flow chart for modelling the transformer to predict the inrush current. In this scheme, it is necessary to compute the current for a given voltage. The inverse Jiles-Atherton model described in the previous section is used. The inversion of the Jiles-Atherton model, which relies on first-order differential equations, proves practical in describing the non-linearity of the magnetic core.
Fig. 4.2 Flowchart for computing the current for a given voltage
4.5 Jiles Atherton Model Parameter Estimation

Past research [94, 99] has encountered a few convergence problems in the iterative parameter identification process. However, with more research, some modifications and extensions have also been introduced in the process, thus minimising the stated problems. In this thesis, the diagram of the Jiles-Atherton transformer model is created in a dynamic Simulink system and MATLAB m-programme to identify the most accurate parameters. The differential equation describing the Inverse Jiles-Atherton model, as shown in the previous section, is also generated. The anhysteretic magnetisation, $M_{an}$, in the Langevin function is used, which is previously expressed in equation (4.18).

To establish the hysteresis loop, all five Jiles-Atherton basic parameters $a, \alpha, c, k,$ and $M_s$ are determined via differential evaluation in the modelling process [100]. This is to define the location of the origin point, the remanence point, the coercive point, and the loop tip point in the loop.

Fig. 4.3 shows the program subroutine for establishing the Jiles-Atherton parameters.

---

**Fig. 4.3 Method for establishing the Jiles-Atherton parameters**
To identify the Jiles-Atherton parameters, a differential evolution algorithm is used in which a few sets of objective functions are applied throughout the optimisation process. To identify the parameters in this research, the differential method objective function is called the differential evolution.

Two different objective functions are used in the parameter estimation. The first function uses the discrepancy of computed and experimented magnetising currents while the second uses the discrepancy of computed and experimented inrush currents.

From [87], the mathematical formulae for the objective functions are written as per equations (4.27) and (4.28):

\[
Obj_1 = \sqrt{\frac{\sum_{j=1}^{N} (i_{m,\text{magnetise}}(j) - i_{c,\text{magnetise}}(j))^2}{N}}
\]  
(4.27)

\[
Obj_2 = \sqrt{\frac{\sum_{j=1}^{N} (i_{m,\text{inrush}}(j) - i_{c,\text{inrush}}(j))^2}{N}}
\]  
(4.28)

where \(i_{m,X}\) denotes the measured current while \(i_{c,X}\) denotes the computed current with \(j\) being either the magnetised or inrush current.

4.5.1 Case A

The Jiles-Atherton modelling is used because previous work utilising the classic Steinmetz model yielded some discrepancies. Hence, to propose better modelling of the transformer, the same transformers are used. As shown in Fig. 4.4, two single-phase 16 kVA, 11-kV/250 V oil immersed distribution transformers with only basic nameplate data available are used for the study of magnetising and sympathetic inrush transients in this thesis. Instead of using the classic Steinmetz Saturation Transformer model as in previous studies, the Jiles-Atherton model is applied due to its capability of representing minor loop operations and de-energisation. Its
parameters are evaluated via a series of differential evaluation algorithms based on a few reasonable assumptions.

In this work, all five Jiles-Atherton basic parameters are specified as per Table 4.1 considering the magnetic material, frequency, and core estimation size. A diagram of the Jiles-Atherton transformer modelling is created in a dynamic Simulink system and MATLAB m-programme to identify the most accurate parameters. To establish the hysteresis loop, the parameters are determined using differential evaluation in the modelling process [101-103]. This is to define the locations of the origin point, the remanence point, the coercive point, and the loop tip point in the loop.
Table 4.1 Jiles-Atherton parameters obtained via 1500 differential evaluation iterations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Jiles-Atherton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$</td>
<td>A/m</td>
<td>$1.19 \times 10^6$</td>
</tr>
<tr>
<td>$k$</td>
<td>A/m</td>
<td>320</td>
</tr>
<tr>
<td>$a$</td>
<td>A/m</td>
<td>141.76</td>
</tr>
<tr>
<td>$\alpha$</td>
<td></td>
<td>$0.345 \times 10^{-3}$</td>
</tr>
<tr>
<td>$c$</td>
<td></td>
<td>0.712</td>
</tr>
</tbody>
</table>

4.5.2 Case B

Fig. 4.5 Transformers for Case B
Case B is executed to improve upon the prior modelling. Case B is proposed because the transformers in Case A have limited data regarding their magnetic core. Referring to Fig. 4.5, two single-phase small-scale same-rated variac transformers are used for magnetising and sympathetic inrush transient study in this work. The Inverse Jiles-Atherton model is applied. The main aim of this work is to present an improved Jiles-Atherton model for transformer modelling to predict the inrush current.

The methodology to calculate the Jiles-Atherton original parameters is similar to that of [99]. Its parameters are evaluated using a series of differential evaluation algorithms with a few reasonable assumptions. Besides that, four more parameters, namely $D_{mean}$, $A_{mean}$, and $N$ are determined in the process. Here, the leakage inductance is also included as the ninth parameter to be identified, as it is vital to obtain the accurate leakage inductance. After including this leakage inductance value in the code and following other parameter procedures so that convergence is also achieved, the leakage inductance value is observed to be more consistent.

Fig. 4.3 shows the programme subroutines, whereas Fig. 4.6 shows the Simulink block diagram generated to obtain the hysteresis curve and inrush currents. Table 4.2 shows the upper and lower limits of the parameters to be identified.

![Fig. 4.6 Simulink block diagram](image)
Table 4.2 Upper and lower limits of the parameters to be identified

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lower limit</th>
<th>Upper Limit</th>
<th>Selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ (A/m)</td>
<td>100</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$1 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$c$</td>
<td>0.5</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>$k$ (A/m)</td>
<td>20</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td>$Ms$ (A/m)</td>
<td>$1.0 \times 10^{6}$</td>
<td>$1.5 \times 10^{6}$</td>
<td>$1.0 \times 10^{6}$</td>
</tr>
<tr>
<td>Mean $D$ (cm)</td>
<td>$4.0 \times 10^{-2}$</td>
<td>$1.0 \times 10^{-1}$</td>
<td>$4.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>Mean $A$ ($cm^2$)</td>
<td>$1.0 \times 10^{-3}$</td>
<td>$5.0 \times 10^{-3}$</td>
<td>$1.0 \times 10^{-3}$</td>
</tr>
<tr>
<td>Turns</td>
<td>100</td>
<td>700</td>
<td>100</td>
</tr>
</tbody>
</table>

4.6 Signal De-noising

The measured currents $i_1$ and $i_L$ contain noise, which makes them unsuitable for extraction of parameters in the Jiles-Atherton model. Hence, a de-noising technique i.e. the wavelet analysis was used to remove the noise in this study.

The wavelet analysis is a signal processing method in the time-frequency domain. Similar to Fourier transforms, which generate the projection of a signal in the frequency domain, the wavelet analysis is a projection in the time-frequency domain. It is an approximation of the original signal via the linear combination of wavelets.
The wavelet analysis has been widely used in many engineering fields, such as in fault detection, image processing, chemical signal analysis, and so on. Generally, the wavelet de-noising procedure involves three steps:

- **Decomposition**: The wavelet transform is used here to decompose the polluted signal. The transform method, wavelet base, and decomposing level are selected.

- **Thresholding**: A threshold is chosen and applied on all detail coefficients.

- **Reconstruction**: The signal is reconstructed using original approximate coefficients and all modified detail coefficients.

Multi-resolution analysis was adopted in the decomposition case for this study. Multi-resolution analysis is a type of discrete wavelet transform that uses a series of filter pairs. Each filter pair divides the signal into high and low frequency bands, which are also called detailed and approximate parts, respectively. The fundamentals of multi-resolution are shown in Fig. 4.7 where $f$ is the original signal, and $A$ and $D$ stand for approximations and details, respectively. The approximate coefficients with the lowest frequency ($A_3$) are retained to reconstruct the de-noised signal with modified $D_1$, $D_2$, and $D_3$.

![Fig. 4.7 Fundamentals of the multi-resolution analysis](image-url)
4.7 Results and Discussion

4.7.1 Case A

To verify the model, the transformer was energised under different switching angles. The transformer inrush current level is recorded for the energisation angle with a 45-degree increment starting from 0 to 180 degrees. The input peaks of the magnetising inrush current captured on the oscilloscope are measured and compared with the results obtained from the PSCAD transformer model. The tests were performed at each measurement angle repeatedly and after which the averages of the inrush peaks recorded.

When a single transformer is energised, the inrush current amplitude typically could reach ten times its rated current. In this case, the energisation is carried out from the low voltage side in which the rated current is 64 A, so the prospective energised current amplitude can reach about 640 A. In this experiment, the peak current measured ranges from 716 to -393 A.

Fig. 4.8 shows the large current amplitude at the beginning, which then decays substantially, similar to the characteristics of a typical inrush current [104, 105]. The decay is mainly due to the effective resistance in the power circuit. It should be noted that only the peak inrush is recorded in this laboratory work, as in many cases, the main circuit breaker will trip immediately afterwards. For the sympathetic inrush shown in Fig. 4.19, it can be seen that the values are not as large as in the case of the magnetising inrush. However, the current decays much slower.
The simulations in the current study using the Jiles-Atherton model are in closer agreement with the experimental values in the previous work of [72]. Since the laboratory experiments and the PSCAD/EMTDC simulations yield similar results, the capability of the model to accurately represent the energisation transient of a distribution transformer is therefore proven. However, it is expected that the accuracy can be improved further, especially the computation of the residual flux.
To gain further confidence in the validity of the proposed $B$-$H$ curve and its model, MATLAB is used for simulation of the same-rated transformer energisation. Before proceeding to the inrush studies, the Jiles-Atherton parameters are identified i.e. $a$, $\alpha$, $c$, $k$ and $Ms$, which are estimated in the modelling process [106]. The accuracy of the identification is crucial to enable the Jiles-Atherton model to represent the non-linearity of the iron core [107].

Fig. 4.10 shows the hysteresis loop in MATLAB. As seen from the $B$-$H$ curve, MATLAB shows a smooth fully closed loop and reveals hysteresis loss within the loop. The developed model enables the determination of the $B$-$H$ curve including consideration of the saturation effects in the magnetic material.

For further validation, MATLAB simulation is also developed for results comparison and hysteresis loop development. As the Jiles-Atherton model shows promising accuracy via the inrush modelling, further laboratory works are carried out (and shown in Case B) with smaller-rated transformers and material data to predict a more accurate incoming inrush current.
4.7.2 Case B

Fig. 4.11 Sympathetic inrush verification in Simulink

To predict the sympathetic inrush phenomenon using the designed transformer (with the Jiles-Atherton parameter identification), the transformer verification is designed in Simulink. Referring to Fig. 4.11, two transformers are connected in parallel to each other in which both of the current flowing in Transformer 1 and Transformer 2 are observed.

Transformer 2 is energised while Transformer 1 is on-line. Thus, Transformer 1 will experience unexpected saturation as a result of Transformer 2 being switched-in. Note that both transformers use the Inverse Jiles-Atherton Model, as discussed in the previous section.

Fig. 4.12 and Fig. 4.13 show the magnetising and sympathetic inrush currents recorded from the modelling simulation. As per the discussion on the analytical data of the sympathetic inrush, the magnetising inrush peak is higher compared to the
sympathetic inrush peak. The sympathetic inrush is opposite in polarity as well (to the previous magnetising inrush). Due to the small power rating of the test objects, the sympathetic inrush peak recorded is also small such that it was not able to observe the prolonged time of the inrush decay.

The results of the laboratory works are shown in Fig. 4.14 and Fig. 4.15. In this analysis, Debauchies 15 wavelet at level 6 was adopted to de-noise the measured magnetising current. Fig. 4.14 shows the voltage, magnetising current, and de-noised current. Fig. 4.15 shows a set of voltage and inrush currents. It can be seen that the
magnetising current is relatively small and heavily embedded in noise. From the initial effort, it is found that when only a magnetising current is adopted to identify the parameters in the Jiles-Atherton model, the search for suitable values becomes more difficult. In order to solve the problem, this research adopted both the magnetising current and inrush current for the identification of parameters in the Jiles-Atherton model.

![Fig. 4.14 Voltage, magnetising current, and de-noised current](image1)

![Fig. 4.15 Voltage and inrush current](image2)
The aim of this research is to demonstrate a method to determine the parameter identification from differential equations and then model a transformer to further predict the inrush currents. The proposed approach, dedicated to the Jiles-Atherton parameters identification with one modification—the addition of the leakage inductance parameter identification—is important to observe the inrush, especially the sympathetic inrush. This can be applied to experimental work to testify whether or not the final parameters have converged accurately. A comparison of measured and modelled magnetising and sympathetic inrush currents generated showed significant similarity, which indicates a high degree of agreement. In conclusion, the method proves its capability for determining the values of these parameters with minimal error; thus, the Jiles-Atherton model can be used to predict the incoming inrush current. It is also shown that the model is adequate for electromagnetic studies involving the inrush current in which the core saturation is a concern. For industrial application, the design considerations in applying this method can be scaled up to the desired power transformer according to the specific requirements.

The contrast between the theoretical data and optimisation data justify the validity of the suggested algorithm. The simulation model successfully applies the characteristics of the transformer in anticipating the approaching sympathetic inrush and magnetising inrush current when using the Inverse Jiles-Atherton theory. From the inrush current study in this work, the laboratory data of exciting current waveform and voltage show good agreement with the simulation data which proves that the simulation model can be used to predict the incoming inrush for a transformer.

4.7.3 Discussions and Challenges in using the Jiles-Atherton Transformer Model

Table 4.3 below presents the comparisons of non-linear modelling between the Steinmetz Saturation model with the Jiles-Atherton model.
Table 4.3 Comparison of non-linear modelling between the Steinmetz Saturation model and Jiles-Atherton model

<table>
<thead>
<tr>
<th>Model</th>
<th>Steinmetz model</th>
<th>Jiles-Atherton model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer core parameters</td>
<td>Assumes no knowledge beforehand</td>
<td>Parameter estimation using formula and iteration</td>
</tr>
<tr>
<td>Saturation</td>
<td>Uses curve fitting</td>
<td>Uses curve fitting</td>
</tr>
<tr>
<td>No-load losses</td>
<td>Adds a linear resistor</td>
<td>Parameter estimation</td>
</tr>
<tr>
<td>Hysteresis loop</td>
<td>Uses a different tool—ATP HEVIA for piecewise solution. Not a full loop</td>
<td>Perfect hysteresis loop distribution</td>
</tr>
<tr>
<td>Residual flux</td>
<td>Not accurate</td>
<td>Better accuracy</td>
</tr>
</tbody>
</table>

Challenges faced in Jiles-Atherton modelling include:

- Determining the best model using the Jiles-Atherton parameter estimation; especially when the transformer has a limited number of data
- Full representation of complete hysteresis
- Residual flux initialisation
- The representation of accurate model measurement data
The representation of a topologically accurate magnetic core

4.8 Summary

The improved modelling of a transformer with limited data is shown in this chapter. The hysteresis part of the study is run in PSCAD/EMTDC, yielding improved transformer modelling with the addition of the Jiles-Atherton saturation hysteresis. Here, some of the Jiles-Atherton parameters are estimated using Differential Evolution algorithms in m-code in MATLAB.

The Jiles-Atherton hysteresis model is presented to improve the same test object, as per the previous studies discussed in Chapter 3. For hysteretic iron-core modelling, the Jiles-Atherton model is applied. The electrical parameters and the curve fitting for the saturation curve are still adopted from the basic model but the Jiles-Atherton is introduced to develop the $B$-$H$ curve and also to improve the residual flux computation. By comparing the sympathetic inrush transient peak in the simulation and experiment, the results verify that the Jiles-Atherton model yields better results.

In proving the accuracy of the inrush current predictions of the Jiles-Atherton modelling, the model is then used for another transformer with known core data. In Case B, small variac transformers with known core data are used. The Inverse Jiles-Atherton is used for which the proposed core model is proven to provide better accuracy for inrush current experiments. Here, the Jiles-Atherton model parameters can be estimated and this transformer model used in predicting the magnetising inrush and sympathetic inrush currents with high accuracy.

All in all, through comparison of the model and experiment results, the following conclusions are obtained:

- The classic transformer model using Jiles-Atherton as a basis in PSCAD enables the incorporation of the hysteresis characteristics of the transformer core.
• By comparing the sympathetic inrush transient peak in the simulation and experiment, the results verify that the Jiles-Atherton model yields better results.

• Although the model of the transformer is improved, it is still not very precise. It is too complex to accurately gain all five Jiles-Atherton model parameters considering the manufacturer technical details of the test object - a commercial oil-immersed distribution transformer - are not available.

• The inverse Jiles-Atherton model is applied for the other test objects, as shown in Case B. Here, the modelling is in agreement with the laboratory works, where the peak of the inrush values is the same. Hence, the proposed model can be used to predict the sympathetic inrush current with good accuracy.
CHAPTER 5

SIMULATION OF TRANSFORMER ENERGISATION TRANSIENTS USING PSCAD/EMTDC

This chapter presents the results derived from the simulation of transformer energisation transients using PSCAD/EMTDC. The proposed classic Steinmetz single-phase transformer model with the Jiles-Atherton hysteresis model is implemented in the PSCAD/EMTDC environment. The results are derived using the developed and tested transformer model, as discussed in previous chapters. All the design parameters, including the calculated positive sequence leakage reactance with no-load losses and copper losses used in the transformer design, are considered.

5.1 Single Transformer Magnetising Inrush Current

First, a detailed PSCAD model of the transformer was created with the same parameters as the transformer used in the laboratory experiments. Fig. 5.1 shows the schematic representation of single transformer energisation designed in PSCAD. The classical transformer using the Jiles-Atherton model, as presented in Chapter 4, was implemented in this environment.
The test object used is a 16 kVA, 11 kV/250V single-phase distribution transformer. To enable practical testing in the laboratory, the transformer is back energised on the low voltage side from the 240 V, 50 Hz mains supply. The modelled transformer and the actual transformer tested in the laboratory are both rated the same (as modelled in Case A in Chapter 4).

The time domain simulation for energising the transformer is then carried out and the normal magnetising inrush with a single transformer test object observed. Next, the inrush transient is assessed through inputting the calculated and measured parameters. Then, the switching angle is increased in steps from an initial angle of 0° to affect variation in switching angle. The measured input peak currents, tabulated in Table 5.1 are later compared with the laboratory experimental results for further validation analysis.

Fig. 5.2 shows the peak inrush current generated in the first transformer energisation at the zero phase angle. The effect of varying the switching angle on the peak inrush current is next investigated. The phase angle is varied at an increment of 45°. The simulated current waveforms obtained are shown in Fig. 5.3 and their peak values are presented in Table 5.1.
Fig. 5.2 Magnetising inrush current for single transformer energisation at 0° switching angle

Table 5.1 Peak current (A) vs. switching angle (deg.)

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>717.67</td>
</tr>
<tr>
<td>45</td>
<td>602.28</td>
</tr>
<tr>
<td>90</td>
<td>321.75</td>
</tr>
<tr>
<td>135</td>
<td>-200.35</td>
</tr>
<tr>
<td>180</td>
<td>-393.44</td>
</tr>
</tbody>
</table>
Fig. 5.3 Magnetising inrush current for different switching angles: (a) 45 degrees; (b) 90 degrees; (c) 135 degrees; and (d) 180 degrees
From both Fig. 5.3 and Table 5.1, it can be seen that the peak value of the magnetising inrush current is very high compared to the normal magnetising current. When a single transformer is energised, the inrush current amplitude typically could reach more than ten times its rated current. Since the rated current is 64 A, the energised current transient is expected to reach about 640 A. Here, the highest current amplitude is 718 A at zero degree switching angle. The magnitude of the inrush current reduces when the switching-on angle increases up to 90°; it then increases in the negative direction up to 180°. Fig. 5.2 and Fig. 5.3 also show that in the single transformer energisation, the large current amplitude only occurred at the beginning, and then decays substantially, similar to the theoretical inrush current. The decay is mainly due to the small effective resistance in the power circuit.

5.2 Sympathetic Interaction between Parallel Transformers

To study the effect of the system factors on the sympathetic inrush current, the system simulation platform according to Fig. 5.4 is established. In this section, the operating condition of the two transformers, which are connected in parallel, is simulated, as well as the influence of switching angle and source resistance. In the
simulation, the transformers are connected in parallel in the same direction and modelled in PSCAD/EMTDC, as per Fig. 5.4. After T1 is energised for a long enough time (the tail of inrush current is small enough), the breaker is then closed for energising transformer T2. Thus, there will be a magnetising inrush current in T2, and a sympathetic inrush current in T1. By setting current probes marked I1 and I2, both inrush currents can be obtained. For each different switching angle, inrush results are recorded. The results of Fig. 5.5 and Fig. 5.6 are based on a 45° angle.

Fig. 5.5 Magnetising inrush recorded at T2

Fig. 5.6 Sympathetic inrush recorded at T1
Fig. 5.5 shows the current generated in transformer T2. When T2 is energised, magnetising current occurs. It can be seen that the initial current is very high and then decays. Since transformer T1 is already in operation when T2 is switched in, T1 experiences unexpected saturation followed by the occurrence of the sympathetic inrush transient. This is shown in Fig. 5.6. It is important to note the coincidence of these two events; it can be seen that the sympathetic inrush current persists in the network for a much longer duration than the inrush current for the single connected transformer.

Fig. 5.7 $B-H$ curve

Fig. 5.7 shows the $B-H$ curve generated using PSCAD software modelling based on the Jiles-Atherton method. The generated hysteresis curve does not have a good fit and is not a fully-closed loop. This differs from the same test object, which was modelled in MATLAB, as discussed in Chapter 4. Note that in PSCAD, users are limited to the Jiles-Atherton model implemented with some fixed parameters, while the MATLAB coding identifies all Jiles-Atherton parameters. Therefore, difference between these implementations is bound to occur since there are some unknown parameters assumed in the process.
The diameter and geometrical area of the core of the distribution transformers tested can be measured by opening the top cover. However, the core and windings are totally immersed in oil so it was not possible to make accurate measurements. The material property, Si-steel, is referred to in [108]. The core resistance is assumed in the process, depending on the measured core size.

### 5.3 Factors Affecting the Sympathetic Inrush Current Transients

#### 5.3.1 Effect of varying the switching angle

In this section, the effect of variation in switching angle on the characteristics of sympathetic inrush current is investigated. For each different switching angle, the corresponding inrush results are recorded. Table 5.2 shows the peak magnitude of the sympathetic inrush currents from the simulation. Fig. 5.8 shows the effect of different switching angles on the amplitude of the sympathetic inrush current. The flux for all switching angles is 1.7 T. Also, the source resistance is assumed to be 0.05 Ω, as previously modelled.

Table 5.2 Peak current of the sympathetic inrush by varying switching angle

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-122.92</td>
</tr>
<tr>
<td>45</td>
<td>-11.20</td>
</tr>
<tr>
<td>90</td>
<td>15.28</td>
</tr>
<tr>
<td>135</td>
<td>45.69</td>
</tr>
<tr>
<td>180</td>
<td>101.98</td>
</tr>
</tbody>
</table>
Fig. 5.8 Effect of varying the switching angle on the sympathetic inrush transients
(a) 0 degree, (b) 90 degrees, (c) 180 degrees
5.3.2 Effect of varying system resistance for two parallel-connected transformers

![Image of current transients for varying system resistance](image)

Fig. 5.9 Effect of varying system resistance on the sympathetic inrush transients

(a) $R_s = 1 \, \Omega$, (b) $R_s = 3 \, \Omega$, (c) $R_s = 5 \, \Omega$
To observe the effect of system resistance, the value of system resistance is varied while other parameters are kept the same. As per Fig 5.9 (a), Fig. 5.9 (b), and Fig. 5.9 (c), the values for system resistance are 1 Ω, 3 Ω, and 5 Ω respectively. It can be seen that the magnitude of the incoming inrush (current in T2, in blue colour) decreases rapidly. Besides that, the decaying duration and the peak sympathetic inrush itself (current in T1, in pink colour) are also affected. The sympathetic inrush phenomenon experienced in the on-line transformer T1 is due to the coupling between the two transformers on account of the asymmetrical voltage drop in the system resistance, $R_s$ of the transmission line feeding them; hence, the higher the $R_s$, the lower the sympathetic inrush [29, 32], as evident from the above-mentioned figures.

Fig. 5.10 shows the effect of sympathetic inrush current transients when the values of residual flux density are varied. Figs. 5.10 (a), (b), and (c) correspond to flux density of 1 T, 1.5 T and 1.7 T, respectively. From these figures, it can be seen that the peak inrush current is highly dependent on residual flux density. Fig. 5.11 shows the relationship between both sympathetic inrush at T1 and inrush at T2 with different flux density values.
5.3.3 Effect of different flux densities on the transformers

Fig. 5.10 Effect of different flux density on sympathetic inrush transients

(a) $Br = 1.0$ T, (b) $Br = 1.5$ T, (c) $Br = 1.7$ T
From Fig. 5.11, it can be seen that the effect on parallel-connected transformer energisation is similar to the single energisation, i.e. the residual magnetism will affect in the incoming generated inrush current. If the transformer is switched on at a zero angle with a positively increasing voltage wave, the positive polarity of the flux density will lead to higher values of inrush currents and vice-versa. In summary, it is clear that the peak inrush current increases with the residual flux level.

5.4 Effect of Simultaneous Energisation of Several Transformers

5.4.1 Energising inrush when several transformers are energised simultaneously

To observe the effect of simultaneous energisation of several transformers, three same-rated 16 kVA, 11 kV/250 V transformers are connected in parallel to each other.
Fig. 5.12 shows the schematic diagram drawn in PSCAD/EMTDC.

Fig. 5.12 Diagram to study the effect of simultaneous energisation in transformers

Fig. 5.13 illustrates the single-phase energisation currents when the three transformers are energised simultaneously, with no initially energised transformer. It can be seen that all three inrush currents are similar in shape and value. It should be noted that no more than three transformers should be energised simultaneously to ensure compliance with P28c [51].
Magnetising inrush occurs because there is no initially energised transformer. The current peak reached -381.5 A and then decayed rapidly afterwards.

Subsequently, the simulation is extended to investigate the effect of the inrush current when two transformers are energised simultaneously, with the first transformer already in operation. Fig. 5.14 shows the inrush current waveforms.

With the initially energised transformer, it can be seen that the sympathetic inrush phenomenon also happened. By comparing with Fig. 5.13, the inrush current without any initially energised transformer is more damped. From Fig. 5.13, the decay becomes complete after about 0.5 s, whereas in Fig. 5.14 with the initially energised transformer, the decay is prolonged.

However, if T2 and T3 are energised at different times, with T1 initially energised; different waveforms result, as shown in Fig. 5.15. From Fig. 5.14, the peak inrush is -425.3 A whereas in Fig. 5.15, the current peak is -496.1 A. For sympathetic inrush (i.e. current at T1), the peak sympathetic inrush is higher in Fig. 5.14, which is 122.32 A, while in Fig. 5.15, the peak sympathetic inrush is 98.31 A. This shows that energisation at different times may result in a higher magnetising inrush peak.
where the peak sympathetic inrush is lower but the decay time is essentially the same.

Fig. 5.14 Inrush currents when T2 and T3 are energised simultaneously with T1 initially energised

Fig. 5.15 Inrush currents when T2 and T3 are energised at different times with T1 initially energised
5.5 Inrush Current Impact from Increasing the Number of Already Energised Transformers

There are several possible scenarios of energisation. Simulations were carried out to study the difference between two cases:

a) Case 1: Energise T3 with T1 and T2 already energised
b) Case 2: Energise T2 and T3 with T1 already energised

From both cases, the inrush currents are examined to determine the worst-case energisation scenario.

By referring to Fig. 5.16 (a) and (b), the peak sympathetic inrush is \(-412.8\) A for the two already energised transformers, with the already energised transformer showing a higher peak of \(-496.1\) A. Simulation studies are then carried out to observe the impact of the number of already energised transformers on the peak sympathetic inrush. Referring to Fig. 5.17, these simulation studies show that an increase in the number of already energised transformers proportionally increases the peak sympathetic inrush current. The duration of the transient inrush is longer as well.
Fig. 5.16 (a) Case 1: Energise T3 with T1 and T2 already energised; (b) Case 2: Energise T2 and T3 with T1 already energised
5.6 Voltage Sag Investigation in Sympathetic Inrush

As part of the research on the transformer energisation problem, the voltage sag problem due to the inrush current is investigated. Voltage sag due to inrush current and sympathetic inrush is captured in the simulation—either in single or parallel-connected transformer energisation—where an assessment of voltage sag caused by transformer energisation is carried out. At first, the single transformer energisation at zero-degree switching angles is compared with the parallel-connected transformer energisation. The same switching angle, same closing time, and same residual flux are used for all the simulation works. The number of transformers being energised and the number of transformers already connected are varied.

Here, the voltage sag is defined by voltage sag duration in the verified PSCAD model. One transformer or a few transformers are energised at the same time and the depression in voltage calculated. The voltage sag measurements are tabulated in Table 5.3.
Table 5.3 Voltage sag under different energisation conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Transformer</th>
<th>Voltage sag duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energised</td>
<td>Already energised</td>
</tr>
<tr>
<td>A</td>
<td>T1</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>T1</td>
<td>T2 &amp; T3</td>
</tr>
<tr>
<td>C</td>
<td>T2 &amp; T3</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>T2 &amp; T3</td>
<td>T1</td>
</tr>
</tbody>
</table>

By comparing case A and case B in Table 5.3, it can be observed that adding the already energised transformer will increase the voltage sag duration. Comparing case B and case D, voltage sag increases with the increasing number of transformers simultaneously energised. Comparison of case A and case C reveals that more energised transformers will result in more voltage sags. Because sympathetic inrush provides a longer decay characteristic to the inrush transients, it also actually prolongs the duration of the voltage sag.

Because different equipment can be sensitive to different sag characteristics, the study of voltage sags is important for power systems. The probability distribution of voltage dip durations and knowledge of the protection system at each voltage level could be utilised for further calculations. This analysis may be extended, as the sympathetic inrush may occur due to some faults in the system, and thus affect the relay and promote unnecessary tripping in the system.
5.7 Extending the Inrush Study to a Three-Phase Transformer

5.7.1 Modelling the three-phase transformer

Three-phase transformer modelling can be complex and thus poses a difficult problem. In addition to the nonlinear behaviour and frequency-dependent nature of the transformer core, complications arise from numerous possible core configurations as well as different physical phenomena [21, 109]. Most transformer models are based on a single-phase equivalent of the three-phase transformer. The model simply relates the single-phase core to the three-phase star or delta representations. This may be sufficient for steady-state analysis but not for a transient study. The magnetic coupling between phases is ignored in a single-phase equivalent circuit, but the magnetic characteristics are important in determining the acceptable level of transformer inrush current, as demonstrated in the previous sections.

In this study, a model was developed in PSCAD using the three-phase transformer model in the master library. For simulation, the ideal transformer model is selected. The copper losses and eddy current losses are assumed to be zero. The voltage source is ideal, with a magnitude of 11 kV, 50 Hz. The system inductance and system resistance are valued at 0.01 H and 1 Ω, respectively. The switching angle is set to zero degree. To observe the inrush characteristics, saturation is enabled on winding 1. Other parameters for the transformers and the saturation values are shown in Table 5.4.
Table 5.4 Transformer 1 and Transformer 2 parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Transformer 1</th>
<th>Transformer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer kVA</td>
<td>100 kVA</td>
<td>100 kVA</td>
</tr>
<tr>
<td>Winding 1 V&lt;sub&gt;L-L&lt;/sub&gt;</td>
<td>11 kV</td>
<td>11 kV</td>
</tr>
<tr>
<td>Winding 2 V&lt;sub&gt;L-L&lt;/sub&gt;</td>
<td>415 V</td>
<td>415 V</td>
</tr>
<tr>
<td>Winding type</td>
<td>Y-Y type</td>
<td>Y-Y type</td>
</tr>
<tr>
<td>Inrush decay time constant</td>
<td>0.1 s</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Time to release flux clipping</td>
<td>0.1 s</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Air core reactance</td>
<td>0.2 pu</td>
<td>0.2 pu</td>
</tr>
<tr>
<td>Magnetising current</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Knee voltage</td>
<td>1.25 pu</td>
<td>1.25 pu</td>
</tr>
</tbody>
</table>
Fig. 5.18 shows a schematic diagram of the three-phase transformer exhibiting sympathetic inrush current. The following Figs. 5.19, 5.20 and 5.21 show the simulation results for three-phase current values, the flux linkage and the hysteresis loop, respectively. To validate this model experimentally in the laboratory, it requires a three-phase supply with two three-phase distribution transformers. This was not available so the simulation is only topologically correct. Nevertheless, the waveform patterns show that the sympathetic inrush current can be investigated in the same way as that of the single-phase system.

Fig. 5.18 Schematic diagram of the three-phase transformer in sympathetic inrush current research
Fig. 5.19 The three-phase current values from the simulation at T1 and T2 at 0°
Flux linkage at T1

Flux linkage at T2

Phase a

Phase b

Phase c

Fig. 5.20 Flux linkage values at T1 and T2 at 0°
5.7.2 Effect of varying the switching angle

The effect of variation in switching angle on the characteristics of magnetising and sympathetic inrush current to the three phase transformer is then investigated. For each different switching angle, the corresponding inrush results are recorded in per-unit values. Table 5.5 shows the peak magnitude of the magnetising and sympathetic inrush currents from the simulation whilst Fig. 5.22 and 5.23 shows the effect of different switching angles on the amplitude of the magnetising and sympathetic inrush transients, respectively.

By referring Fig. 5.22 and Fig. 5.23, it can be seen that the magnitude of both, magnetising and sympathetic inrush are varied. The highest magnitude of inrush can be seen at zero phase angle where it is 17.3 p.u for the magnetising inrush at T2 and -3.8 p.u for the sympathetic inrush at T1.
Table 5.5 Peak current of the sympathetic inrush by varying switching angle

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak of Magnetising Inrush (p.u)</th>
<th>Peak of Sympathetic Inrush (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>17.3</td>
<td>-3.8</td>
</tr>
<tr>
<td>45</td>
<td>10.8</td>
<td>-3.4</td>
</tr>
<tr>
<td>90</td>
<td>5.0</td>
<td>-1.7</td>
</tr>
</tbody>
</table>
Fig. 5.22 Effect of varying the switching angle on the magnetising inrush transients

(a) 0 degree, (b) 45 degrees, (c) 90 degrees
Fig. 5.23 Effect of varying the switching angle on the sympathetic inrush transients

(a) 0 degree, (b) 45 degrees, (c) 90 degrees
5.8 Summary

In this chapter, transformer energisation issues are comprehensively examined based on the modelled transformers. By analysing the sympathetic and normal inrush currents, the relationship and the differences between the current characteristics are revealed. It is found that both are caused by core saturation and so the factors affecting inrush are mostly the same.

By comparing the inrush in single transformer energisation and a few energisations in parallel-connected transformers, it is found that the inrush currents are in opposite direction to each other. For single transformer energisation, a very large peak current shoots up and then decays dramatically. However, for the sympathetic inrush current, the decay is longer.

The sympathetic inrush phenomenon for different energisation conditions is also simulated. When there is no initially energised transformer, the simultaneous energisation of several transformers results in a high inrush current that eventually decays, as the normal magnetising inrush characteristics apply. With an initially energised transformer, simultaneous energisation will decrease the peak time compared to different energisation times. However, the decay time is almost the same.

Next, the effect of increasing the number of already energised transformers on sympathetic inrush is investigated. Here, increasing the number of already energised transformers will proportionally increase the sympathetic inrush peak. The duration of the transient inrush is longer as well.

Special attention is placed on the relationship between sympathetic inrush and voltage sag. It is shown that adding an already energised transformer to the circuit will increase the voltage sag duration; also, the increasing number of simultaneously energised transformers will increase the voltage sag duration and more energised transformers will result in more voltage sags being recorded. Sympathetic inrush
provides longer decay characteristics to the inrush transients, thus it actually also prolongs the duration of the voltage sags.

Lastly, the simulation work is extended to a three-phase model. As the laboratory and modelling work only includes a single-phase model, the models for three-phase transformers are only topologically correct. In this case, the simulation proves that the sympathetic inrush current investigation for three-phase transformers can also be done using PSCAD/EMTDC. However, this approach requires users to have prior knowledge and real industrial data of the three-phase transformer.
CHAPTER 6

LABORATORY EXPERIMENTS AND
VALIDATION OF INRUSH CURRENT
TRANSIENTS

6.1 Background

This chapter presents the experimental procedures and results of the research. Next, the modelling simulation results are compared to the laboratory measurements to validate the model. This chapter explains in detail the series of experiments run in the laboratory to investigate inrush transients. The step-by-step procedure is also explained in this chapter. The validation of the results is discussed in the later sections. The transformer results are explained according to a case-by-case basis for the different types of transformers tested.

6.2 Pre-experimental Setup and Procedures

Before proceeding with the inrush experiments, pre-experimental works are carried out to model the transformers. As discussed in Chapter 3, the open-circuit test, short-circuit test, and loss computation are performed before proceeding with the measurement phase. Apart from other hardware requirements for the test circuit and equipment calibration, the testing requires development of the point-on-wave (POW) switch.
6.2.1 Point-on-wave design

To perform an inrush experiment, a point-on-wave (POW) switch is necessary because the inrush response is highly dependent on the energisation switching angle. As discussed in Chapter 2, both magnetising and sympathetic inrush transients are affected by the closing phase angle in relation to the 50 Hz ac voltage cycle. In this research, the point-on-wave device is designed, built and tested in the laboratory prior to the inrush experiments.

The principle of a point-on-wave (POW) switch is to trigger the circuit at any desired point on a 50-Hz sine wave from the mains. Since the transformer inrush current can draw a significant amount of current compared to its normal operation, the switching device must be carefully chosen in order to handle the high current surge and avoid potential damage. The construction of the POW switch is proposed as follows: a signal detector finds the desired switching position; a pulse generator sends the pulse at that desired position; and a relay is then triggered by the pulse to close the switch to energise the transformer.

![System block diagram of the POW switch](image)

Fig. 6.1 System block diagram of the POW switch

Fig. 6.1 shows the system block diagram of the POW switch. The main parts of this POW system are the zero voltage detector, time delay, and solid-state relay. Firstly, it is necessary to obtain a scaled-down signal of the 240V 50 Hz mains voltage...
waveform for interfacing to low-voltage electronic circuit, hence the requirement of the voltage sensor. The voltage zero level (which corresponds to 0 or 180 degree phase angle) is detected by the zero-crossing detector. This will then be fed through a pre-set time delay before generating a triggering signal at the desired energisation angle. The triggering signal is a step voltage which controls the solid-state relay switching in the supply voltage source driving the transformer.

### 6.2.2 Point-on-wave implementation

Two different methods were explored in the design of the point-on-wave. The initial attempt was to use a National Instruments data acquisition system which operates under LabVIEW (Laboratory Virtual Instrument Engineering Workbench). This software platform also provides system integration with MATLAB coding; the latter was used to control the switching timing. However, laboratory testing of this design approach revealed inconsistent control of the switching angle, possibly because of the varying execution time in MATLAB function calls. Consequently, the POW was re-designed using an MSP 430 Microcontroller - one of Texas Instruments LaunchPad™ Development Kits.

The highest clock speed for this device is 16 MHz, which is sufficient for POW switching. The microcontroller is connected and programmed via Code Composer Studio 6.1.1 (CCS by Texas Instruments) where the coding for switching operation is then loaded.

This microcontroller has 8 analogue-to-digital converter (ADC) input channels and 24 digital I/O channels for pulse outputs. The sampling rate is up to 20 kHz and it has a 10-bit ADC, which provides a voltage resolution of 2.93 mV. Based on this, a zero voltage threshold for detecting zero voltage is set at 0.05 V. The ADC can only take positive voltage for conversion. A half-wave rectifier consisting of a fast switching diode in series with a resistor is thus implemented to create the ADC input signal, as shown in Fig. 6.2.
The performance of the half-wave rectifier is then measured on the oscilloscope, as shown in Fig. 6.3 (a). Here, the switch time for the diode is taken into account in the following timing design. The logic of the POW programme of the microcontroller is similar to the original MATLAB method. The time error of the pulse position is constant and equal to the diode switching time. Since the time delay is constant, the performance of the switch can be calibrated to minimise time errors, as displayed in Fig. 6.3 (b).

The coding continually compares one sample from ADC with the zero threshold until the sample is less than or equal to the threshold. Then, the digital output pin will send a 4V control signal to the triac. In this POW switch implementation, the selected solid-state relay is a CELDUC (S0745090) 275V/50A triac. This device can withstand short-term fault current up to 700 A without damaging itself [112].

As the final interface, the design is completed with the fabrication of two separate modules. The first box is the triac with the heat sink (the POW switch) and the second is the microcontroller with the voltage sensor (the POW controller), shown in Fig. 6.4 (a) and Fig. 6.4 (b), respectively.
The triac needs to have appropriate thermal design to withstand from overheating. During transformer switching and de-switching, the triac’s temperature will increase rapidly at the peak currents. A heat sink with suitable cooling fins is thus put in place to absorb and dissipate heat quickly, so as to protect the triac from overheating, as shown in Fig. 6.4 (a). Among the main considerations for heat sink selection are the transient thermal loading and the steady-state loading of the relay [111].

Fig. 6.3 Oscilloscope waveforms for: (a) Half-wave rectifier performances, (b) Calibrate switch at 0 degrees
specification of the performance is thermal resistance, which is typically expressed in °C/W as the temperature increase per watt of heat.

Fig. 6.4 Final interfaces for: (a) The triac with the heat sink, (b) The POW controller unit

The POW switch module has the on/off button together with one input (connected by T-junction cable—one to oscilloscope and the other to the POW controller) and two outputs. For the POW controller module, the 50-Hz AC input cable pin is placed at the front while the CH1, CH2 output, and the reset button are placed at the back. The controller box is also connected to the software via USB.
Fig. 6.5 shows the transformer is connected with the designed POW switch. This laboratory setup provides the capability to perform extensive measurements involving very high current transients; otherwise, it would not be possible to investigate this type of power transformers, which is typically installed in real-life medium-voltage distribution networks.

The power supply and POW system are connected as follows:

- The 240 V 50 Hz AC power is supplied by a programmable voltage source CSW5550 from California Instruments, as shown in Fig. 6.6.
The output of the power supply is connected to the input terminal of the triac and measured using a voltage sensor that is connected to the ADC of the microcontroller, as shown in Fig. 6.7.

The microcontroller is connected to the coding via the Code Composer Studio 6.1.1.

The 4 V voltage output pin is connected to the control input of the triac.

A high-range clip-on current probe is attached to the wire between the triac and the transformer under test to measure the inrush current.

![Fig. 6.6 Programmable power supply system](image1)

![Fig. 6.7 Voltage sensor and microcontroller](image2)
6.3 Experimental Setup and Procedure

The general connection of the sympathetic inrush current experiment is shown in Fig. 6.8. In the initial stage of this research, a small-scale experiment was performed, as discussed in Case A. Here, 3 kVA, 240 V/120 V transformers are used. Subsequently, two or three 16 kVA, 11 kV/250 V Tyree oil-immersed distribution transformers are used as the main experimental setup in this research.

Generally, the procedure for energising the transformers to observe the sympathetic inrush experiment is as follows:

- Connect the transformers in parallel as per the experimental setup in Fig. 6.8. Leave the secondary side of the transformer as an open-circuit.
- Connect the current probe to monitor the primary side of the transformer.
- Set the digital oscilloscope on single-trigger mode; this allows for the capture of the current waveform once a certain threshold magnitude is exceeded.
• Close the test bay gate so that the automatic safety interlock is on which enables the test supply.

• Use the Code Composer Studio embedded in the desktop computer and set the energisation switching angle for the transformers.

• Run the programme to switch in Transformer 1

• As Transformer 1 is still on-line, switch in Transformer 2.

• Record the captured waveforms and transfer to computer.

• Use MATLAB to find the value of peak inrush.

Note: During the course of laboratory testing, not all switching angles are able to switch both transformers. In some cases, if the first magnetising inrush current peak is very high, it can trip immediately the upstream circuit breaker in the main supply switchboard.

6.3.1 Case A

Two 3 kVA, 240 V / 120 V transformers are connected in parallel with the primary sides connected to a 240 V supply, as shown in Fig. 6.9. Both transformers are unloaded on the secondary side. Two current probes are attached to the primary side of both transformers to measure the current waveforms, as shown in Fig. 6.10.
Prior to the experiment, the parameters of the transformers must be determined for modelling purposes in later stages. Thus, short-circuit and open-circuit tests are conducted. The results are shown in Table 6.1.
Table 6.1 Electrical parameters computed from the open-circuit and short-circuit tests

<table>
<thead>
<tr>
<th>Electrical Parameters</th>
<th>Transformer 1</th>
<th>Transformer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_c$ (Ω)</td>
<td>5031.63</td>
<td>4593.40</td>
</tr>
<tr>
<td>$X_m$ (Ω)</td>
<td>662.59</td>
<td>639.39</td>
</tr>
<tr>
<td>$R_{eq}$ (Ω)</td>
<td>0.863</td>
<td>0.874</td>
</tr>
<tr>
<td>$X_{eq}$ (Ω)</td>
<td>0.999</td>
<td>0.998</td>
</tr>
</tbody>
</table>

From Table 6.1, those resistance and reactance values are referring to the electrical parameters shown in the transformer equivalent circuit of Fig. 3.7. Here, values of $R_c$ and $X_m$ are computed from the open-circuit test whereas values of $R_{eq}$ and $X_{eq}$ are calculated from the short-circuit test, based on the formulae derived in Section 3.3.2.

### 6.3.2 Case B

This case involves three single-phase 16 kVA, 11kV/250 V same-rated oil-immersed distribution transformers. Their nameplate data are given in Table 3.2. From the open-circuit and short-circuit tests shown in Chapter 3, these transformers show very similar electrical characteristics. The transformer modelling is presented in detail in Chapter 3 and Chapter 4.

Laboratory testing is carried out to observe the sympathetic inrush current phenomenon and to verify the accuracy of the Jiles-Atherton model with the laboratory results. In the experiment, either two or three transformers are connected in parallel with open-circuit on the high voltage side. Fig. 6.11 (a) shows the setup.
photos and Fig. 6.11 (b) shows the inside of the transformer, when the top cover has been removed.

For testing, the first transformer is energised and stays on while the other transformer is subsequently energised at different excitation angles. The inrush current in the first transformer when the second transformer is energised is then recorded (sympathetic inrush).

Fig. 6.11 (a) Experimental setup for the sympathetic inrush current experiment, (b) View on the inside of the test object (oil-immersed distribution transformer) in Case B
6.4 Magnetising Inrush Current Experiment

To observe the inrush current, the transformers are energised under different switching angles. The transformer inrush current level is recorded together with the energisation angle. The input peaks of the magnetising inrush current captured on the oscilloscope are measured and compared with the simulation results obtained from the PSCAD transformer model. The test procedure is similar to the sympathetic inrush experiment but only one transformer is energised.

6.4.1 Case A

To observe the magnetising inrush current in single transformer energisation, only Transformer 1 is energised; the results are shown in Table 6.2 and Fig. 6.12.

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-36</td>
</tr>
<tr>
<td>45</td>
<td>-32.9</td>
</tr>
<tr>
<td>-45</td>
<td>27</td>
</tr>
<tr>
<td>-20</td>
<td>36.8</td>
</tr>
</tbody>
</table>
Fig. 6.12 Magnetising current for single transformer energisation in Case A by varying the switching angle: (a) 20 degrees, (b) 45 degrees, (c) -45 degrees, (d) -20 degrees
6.4.2 Case B

Table 6.3 Results of peak magnetising inrush recorded by varying the switching angle

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>716.2</td>
</tr>
<tr>
<td>45</td>
<td>620.1</td>
</tr>
<tr>
<td>90</td>
<td>398.2</td>
</tr>
<tr>
<td>135</td>
<td>-200.8</td>
</tr>
<tr>
<td>180</td>
<td>-300.5</td>
</tr>
</tbody>
</table>

Table 6.3 shows the peak inrush current for single transformer energisation for Case B. The tests were performed at each measurement angle repeatedly and after which the average of the inrush peaks is recorded. Some typical waveforms are plotted in Fig. 6.13.
Fig. 6.13 Magnetising current for single transformer energisation in Case B by varying the switching angle: (a) 0 degrees, (b) 90 degrees, (c) 180 degrees
6.5 Sympathetic Inrush Current Experiment

6.5.1 Case A

Since changing the switching angle changes the magnitude of magnetising inrush current, this inherently means that, the magnitude of sympathetic inrush currents should also vary with switching angle. The following experiments are therefore conducted to observe the changes in sympathetic inrush current as the switching angle is changed.

The experimental results for case A are shown in Fig. 6.14. The blue waveform corresponds to the sympathetic inrush while the red trace represents the normal magnetising inrush.
Fig. 6.14 Sympathetic inrush current for two parallel-connected transformers in Case A by varying the switching angle: (a) 20 degrees, (b) 45 degrees, (c) 90 degrees
6.5.2 Case B

Fig. 6.15 shows results of the sympathetic inrush current experiment with varying switching angle and using two parallel-connected distribution transformers (T1 and T2). The blue waveform corresponds to the sympathetic inrush at T1 while the red trace represents the normal inrush at T2. From this figure, it can be seen that normal inrush can be much higher as compared to the sympathetic inrush occurring in the adjacent transformer; however, the latter prolongs the inrush duration.

Before T2 is closed, a small magnetising current is already flowing through T1. The offset flux is currently unperceivable, as the current is very small. Then, T2 is closed. At this point, a large inrush current will occur, causing an asymmetrical voltage at the common point. The offset flux then increases abruptly and changes the small inrush at T1 to the larger inrush current at T1.

As a larger inrush current occurs at T1, an offset flux in T2 will result. Hence, the sympathetic inrush current phenomenon occurs and at one turning point, its peak of sympathetic inrush is reached.

After reaching the peak of sympathetic inrush, the sympathetic inrush will be in steady state. As per the sympathetic process, the voltage caused by the current at T2 during one half-cycle will decrease. Then, the voltage sag induced by the sympathetic current will result in a longer decaying phase. Comparing the single magnetising inrush in the single transformer energisation, the decay there is faster and will eventually reach zero. Here, the decaying process will be longer, and the normal inrush will be overtaken by the sympathetic inrush in the later stage.
Fig. 6.15 Sympathetic inrush current for single transformer energisation in Case B by varying the switching angle: (a) 0 degrees, (b) 90 degrees, (c) 180 degrees
Table 6.4 Results of magnitude current recorded by varying the switching angle in the sympathetic inrush experiment

<table>
<thead>
<tr>
<th>Switching angle (degree)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-122.92</td>
</tr>
<tr>
<td>45</td>
<td>-11.2</td>
</tr>
<tr>
<td>90</td>
<td>15.28</td>
</tr>
<tr>
<td>135</td>
<td>45.69</td>
</tr>
<tr>
<td>180</td>
<td>101.98</td>
</tr>
</tbody>
</table>

The sympathetic inrush currents for different switching angles from 0 degrees to 180 degrees are determined and shown in Table 6.4. The absolute peak of sympathetic inrush current occurs at around zero and 180 degrees. The peak inrush current of T1 is higher and the test has to be repeated during laboratory work, as most of the time, the relay is tripped before the second transformer can be energised.

6.6 Validation Work and Discussion

To verify the model, the transformer is energised under different switching angles. The transformer inrush current is recorded for the energisation angle from 0 degrees with a 45-degree increment until reaching 180 degrees. The input peaks of the magnetising inrush current waveform captured on the oscilloscope are measured and compared with the results obtained from the PSCAD transformer model.

The tests are performed at each measurement angle repeatedly and the average of the inrush peaks recorded. After completion of each switching experiment, the demagnetisation (degaussing) of the transformer is performed to ensure that any unwanted residual magnetisation is completely removed.
Fig. 6.16 shows comparison between the magnetising inrush current obtained through laboratory experiments and computer simulations. In the figure, the blue dashed line represents the simulation result with the Jiles-Atherton hysteresis algorithm; the red solid line shows the previous transformer model in the Steinmetz model only; and the green dotted line plots the experimental result.

Fig. 6.16 Result comparison between simulations (with Jiles-Atherton hysteresis model and only the Steinmetz model) and the laboratory experiment for magnetising inrush.

Fig. 6.17 Results comparison between simulations (with Jiles-Atherton hysteresis model and only the Steinmetz model) and the laboratory experiment for sympathetic inrush.
Similarly, Fig. 6.17 shows comparison between the sympathetic inrush current obtained through laboratory experiments and computer simulations.

Fig. 6.13 (a) shows a large current amplitude at the beginning, which then decays substantially, similar to the characteristics of the typical inrush current [104, 105]. The decay is mainly due to the effective resistance in the power circuit. It should be noted that only the peak inrush is recorded in this laboratory work, as in most cases, the circuit breaker would trip immediately after. For sympathetic inrush, it can be seen that the values are not as large as per the magnetising inrush; however the current can take forever to decay.

Fig. 6.16 and Fig. 6.17 show the results of comparing the peak currents recorded in the laboratory measurements and the modelling—with or without the Jiles-Atherton Hysteresis model. By comparing the peak of magnetising inrush in Fig. 6.16 and the peak of sympathetic inrush in Fig. 6.17, the peak of the currents of both transformers are observed to be opposite in angle.

By comparing with the previous work in [72], the simulations in the current study using the Jiles-Atherton model provides closer agreement with the experimental values. Since the laboratory experiments and the PSCAD/EMTDC simulations yield similar results, the capability of the model to accurately represent the energisation transient of a distribution transformer is demonstrated. It is anticipated that the accuracy can be improved further, however, especially the computation of residual flux.

6.7 Summary

This chapter covers the laboratory works and measurements of inrush current transients. Prior to the inrush experiment, a point-of-wave switching unit is built to form part of the test circuit. The design initially used a National Instruments Data Acquisition system and later replaced by a Texas Instruments MSP 430 Microcontroller. Transformer energisation is conducted under two different scenarios. The first is single transformer energisation to measure magnetising inrush,
whilst the second is with two parallel transformers to measure sympathetic inrush. For both experiments, two types of transformers are tested: case A uses smaller rating transformers of 3 kVA, 240/120 V and case B uses 16 kVA 11 kV/250V distribution transformers. Case A is set up for a pre-run test while case B is the main transformer used throughout this research for both experiment and modelling.

Experimental results reveal that as the switching angle is varied, the inrush currents also vary. For single transformer energisation of case B, the highest current magnitude is 716 A (at switching angle of 0 degrees) which is 11 times higher than the rated current, 64 A. However, the magnetising inrush current will quickly decay to zero. For parallel-connected transformers, the results show the current magnitude for sympathetic inrush of -122.92 A and 101.98 A at 0 degrees and 180 degrees, respectively.

The main differences that can be observed between the normal magnetising inrush and the sympathetic inrush currents are the longer decaying time in the latter and their opposite polarity. As sympathetic inrush prolongs decaying time, it can lead to voltage sagging.

In summary, the simulations using the transformer model of Jiles-Atherton yield good agreement to the experimental values. The magnitude differences between the simulation and experiment are acceptable. As the laboratory experiments and the simulation tool, PSCAD/EMTDC, yield similar results, it confirms the model can be used to predict the response of transformer energisation inrush transients.
CHAPTER 7

SYMPATHETIC INRUSH BETWEEN WIND TURBINE TRANSFORMERS

7.1 Background of Study

Transformer energisation is not a new issue in transmission and distribution networks. In fact, nowadays, this field is becoming more relevant due to the major changes in power network development. In a recent report by Working Group C4.307 of CIGRÉ [1], there are two significant reasons that justify studies on this issue:

(i) Liberalisation of electricity markets has led to an increased number of participants with frequent changes in the network topology, thus leading to the possibility of increased switching operations. The expected increase in the penetration of off-shore renewable energy resources will increase the utilisation of cable circuits to enable their integration into on-shore electricity grids as well as their own internal networks.

(ii) Energisation of off-shore renewable energy systems, where each wind turbine generator is accompanied by its own transformer, may generate complex sympathetic interactions [1]. Sympathetic inrush will happen either in cascaded or parallel connected transformers, when a no-load transformer is energised [113].
Moreover, IEC 60076-16:2011 [58] reported that frequent switching in wind turbine transformers can expose these transformers to mechanical and thermal stresses due to the energisation transient. In off-shore wind farms, the system designer is more concerned about losses of the transformer due to the high costs this could incur, rather than the transient phenomena. Any impact to the wind turbine generator and voltage stability should, however, be taken seriously. Wind turbine generator transformers have a relatively small power rating (several MVA, according to the wind turbine generator rating), but relatively higher inrush currents [1]. In a large-scale wind farm, sympathetic inrush currents on the wind turbine transformers are more significant.

Thus, the inrush transient issue in wind farms and its impact on the wind turbine generator are of a major concern to the stakeholders in this field. In wind farm energisation, there are two potential factors to consider: the voltage sag experienced at the point-of-common coupling between the electrical system of the wind farm; and the sympathetic interaction between wind turbine transformers.

Therefore, power systems engineers, either at the planning or at the operational stage, need to be aware of the potential problems that may arise from transformer energisation and, if necessary, study their probability of occurrence, their likely effects, and possibly evaluate various mitigation techniques that may be required to alleviate these identified issues.

7.1.1 Past research

The power quality of the energy delivered is a major issue for wind farm operators [114]. This inrush between transformers may cause voltage sag and fluctuations on the grids. Real industrial incidents have been reported in recent research [115][116]. This type of sympathetic interaction has even been listed as one of the major challenges in connecting off-shore wind farms [117].

Zhang et al. [116] posited that transformer energisation in wind farms may cause prominent overvoltage and may eventually break down the transformer insulation. In
China alone, several tripping incidents have already been reported. The main research has been on the effect of the feeder cable length and its relationship to the energised feeder. In [115], field studies of inrush interaction between two 33/11 kV transformers in a Lafaya substation (Nigeria) were carried out. Simulation modelling for the inrush study was conducted by observing the inrush and later varying the tap changer position to observe any changes in the inrush current peak. This work clarified when to mitigate and how to mitigate the inrush current so to improve the voltage quality and the network stability.

In [118], the author simulated three switching events in two different simulation programs, namely the Power Factory and PSCAD. The current research is important because no work has yet been done to compare the behaviour of standard models of electrical devices in off-shore wind farms of the Power Factory and PSCAD. The results are subsequently compared via measurements and the voltage dip assessed. Finally, general guidelines to energise the collection grid in large wind farms are suggested.

Several works regarding voltage disturbance due to sequential energisation of different numbers of transformers in wind farms have previously been carried out in [16][119]. Meanwhile, in [114, 120], the sympathetic interaction during transformer energisation in wind farms was studied. In this case, several transformers were energised simultaneously, and the voltage sag and overvoltage calculated.

### 7.2 Wind Energy and the Development

#### 7.2.2 Wind farms in Australia

Decreasing fossil fuel sources and the issue of greenhouse gas mitigation worldwide have contributed to the need for development of wind generation as an alternative clean energy source. A large number of wind farm installations have been designed and commissioned. Nowadays, wind farms are becoming more prevalent, and are increasingly receiving more attention in most countries. One of the world’s best
wind resources can be found in the south-western, southern, and south-eastern regions of Australia [121] where wind power is currently the lowest-cost renewable energy that can be rolled out on a large scale. Following this, the national Renewable Energy Target (RET) has provided an incentive to build the lowest cost renewable energy projects. This means that wind power would most likely be the main technology that will receive wide-reaching support in this decade [122].

However, the last of the lingering uncertainty from the Prime Minister at that time, Tony Abbott, and his government’s review regarding the Renewable Energy Target (RET) has been washed out from the industry’s system [122]. With no political support from the government for renewable energy [123], the 2016 figures recorded the lowest total annual capacity commissioned since 2004 [122]. However, investor confidence has been restored. Furthermore, the wind sector is now gearing up for the end of the year with the expectation of a demand increase again in 2017. The development of wind farm energy in Australia from 2013–2016 is tabulated in Table 7.1 [56, 57, 122, 124].

Table 7.1 Four years of wind farm development in Australia

<table>
<thead>
<tr>
<th>Years</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wind farms</td>
<td>68</td>
<td>71</td>
<td>76</td>
<td>79</td>
</tr>
<tr>
<td>Number of wind turbines</td>
<td>1639</td>
<td>1866</td>
<td>2062</td>
<td>2106</td>
</tr>
<tr>
<td>Total generation (MW)</td>
<td>3240</td>
<td>3807</td>
<td>4187</td>
<td>4327</td>
</tr>
<tr>
<td>% of all renewable energy</td>
<td>27</td>
<td>30.9</td>
<td>33.7</td>
<td>30.8</td>
</tr>
<tr>
<td>% of all electricity generation</td>
<td>4.0</td>
<td>4.16</td>
<td>4.9</td>
<td>5.32</td>
</tr>
<tr>
<td>Equivalent number of households that can be powered</td>
<td>1.3 million</td>
<td>1.37 million</td>
<td>2.24 million</td>
<td>2.45 million</td>
</tr>
</tbody>
</table>
At the end of 2016, wind turbines totalling 867 MW in capacity have been installed and expected to be commission in 2017 and 2018. Another 523 wind turbines from 13 different wind technologies have begun development or are under construction for this year, 2017 [122]. The aim is to cut greenhouse gas emissions by 5%–15% by 2020 from its 2000 emission levels through an emission trading scheme - the Carbon Pollution Reduction Scheme (CPRS) [66]. As wind generation will be a significant part to help achieving this target, it is important to ensure that potential issues or problems associated with wind generation do not occur and that the energy cost does not increase.

7.3 Transformer and System Modelling for Transient Studies of Wind Farms

The abrupt increase in offshore renewable energy systems in which each wind turbine generator is accompanied by a transformer will result in sympathetic interactions occurring between them [1]. Increased switching will occur with an increased number of networks for the current customers. As mentioned previously, increased switching will also increase the complexity of the sympathetic inrush. Hence, careful design of the systems and the use of efficient protection devices are important, as the cost of maintenance for switching transients in a wind farm is expensive [120].

Electromagnetic transient (EMT) simulation is a powerful tool for performing transformer and system modelling for transient studies in wind farms, specifically, PSCAD/EMTDC; the wind network model in these simulation models comes complete with all the machine models - whether synchronous, permanent magnet, and so on - including cable and transmission models, all the protection settings, controller tuning, and transformer models. Power system quality studies and system validation can also be performed using this simulation platform.

A number of past researches have purely focused on modelling wind system simulations. In [125], an analysis of transient over-voltages (TOVs) and their propagation in cable systems was performed [126]. This investigation was conducted
using a wind farm including cables and vacuum circuit breakers, the two essential components in any MV cable system. These are discussed in detail and modelled using PSCAD/EMTDC. Here, the cable systems are characterised through both simulations in PSCAD/EMTDC and laboratory experiments, which represent a section of the wind power plant [127]. However, past modelling research for wind farms have focused only on fault studies to test the protection system. Among these include voltage flicker studies and harmonic studies [128]. On the other hand, studies on sympathetic inrush are very much lacking.

7.4 PSCAD Simulation of Inrush Studies between Wind Turbine Transformers

7.4.1 Grid connected wind turbines study

In the power distribution grid, a local issue may affect other parts and the operation of the network. An emergency stop in wind turbine output could change the nominal power [129] and any imbalance between generation and the consumption will have an impact on the frequency control [130]. One of the issues is the inrush current transients. If the transient is severe, it may damage the components and reduce the transformer lifetime [131] because of its high peak of inrush.
Fig. 7.1 Wind farm distribution system under study
7.4.2 The wind turbine transformer

By referring to Fig. 7.1, the “wind” box on the top left of the figure refers to the wind turbine transformers connected with the auxiliary load. The wind turbine transformers are modelled in the sub-schematic page. For modelling the wind turbine transformer, a classical 3-phase 2-winding 680V/11kV transformer was directly connected to a type 1 wind turbine. In PSCAD, a 3-phase classical model of a transformer is represented by three separate single phase transformer models without coupling between phases. The simulation started with two equal and same rated wind turbine transformers connected in parallel. The sub-schematic page of the wind farm under study is shown in Fig. 7.2.

![Fig. 7.2 Wind turbine transformers under study](image-url)
Chapter 7  Sympathetic Inrush between Wind Turbine Transformers

The wind turbine transformer designed is a step-up transformer from the induction machine voltage to a medium voltage. For this transformer, the saturation was modelled on the secondary winding by the basic hysteresis model embedded in PSCAD/EMTDC 4.6. The basic hysteresis model is based on the loop width and represented by a $\lambda$-I characteristic curve.

7.4.3 The circuit breaker

The circuit breaker is modelled using time-controlled 3-phase breaker. Each circuit breaker consists of only one breaker operation and the circuit breaker is open at the initial state. The breaker operation follows the set controlled time and all the poles can be controlled separately.

7.4.4 The wind turbine generator

For the wind turbine generator (WTG) that accompanied with this transformer, this type 1 wind turbine is characterised by a squirrel-cage induction generator (SCIG). The WTG connected directly to the step-up transformer is embedded in the PSCAD master library. In this project, the induction machine is connected to each transformer on the low voltage side. The turbine rotates at a speed that closely follows the 50 Hz and a negative slip will occur if the turbine rotates faster than that frequency. Under steady state, a given wind speed will be almost at linear turbine speed.

7.4.5 Inrush current study

As highlighted in CIGRÉ [1], the parallel connection of generators connected with wind turbine transformers may introduce complex sympathetic inrush. The procedure to study the inrush in a wind farm using PSCAD/EMTDC is presented in this subsection. To investigate the transients in a wind farm network, a complete
model of the transformer and network is required. To isolate the phenomenon, a simplified model only would be sufficient [120].

The grid-connected wind turbines are shown in Fig. 7.2. The simplified wind power system consists of blades, wind turbines, generators and must be connected to the distribution network through a transformer.

7.4.5.1 Inrush current study for a single energisation of wind turbine transformer

Before proceeding to observe the interaction of two parallel-connected transformers, it is important to check the phenomenon when there is an energisation of a single transformer. The PSCAD/EMTDC simulation is first run by omitting transformer T2. Thus, only one transformer is energised in the system. Fig. 7.3 shows the current when T1 is energised on its own without any adjacent transformer connected to the system.

![Fig. 7.3 Current when only transformer T1 is energised](image)

Fig. 7.3 shows that normal inrush current occur at T1, started at 1s as defined in the circuit breaker timing. The peak inrush current is about 15 p.u. and then subsequently decays.

7.4.5.2 Inrush current study for 2 parallel-connected wind turbine transformers
To observe the presence of sympathetic inrush between wind turbine transformers, the study is continued with two same rated parallel-connected transformers and each of them accompanying the auxiliary load. Transformer 2 is energised against the same rated Transformer 1 which is already online.

The controlled circuit breaker for T1 is now removed and the circuit breaker T2 is set to close at 1 s. At this time instant, the inrush transients occur at transformer T2 with a peak inrush of 37.6 p.u. as shown in Fig. 7.4. Referring to Fig. 7.5, it shows that the steady-state current from the preceding energisation for T1 is about 1 p.u.
However, after T2 is energised, the sympathetic inrush occurred, and the peak of the sympathetic inrush is now 3.3 p.u.

The simulation results proved that the sympathetic inrush current transients also occur between the wind turbine transformers. However, the severity is depending on many factors, the transformer rating, the generator rating and the connected grid.

The complexity of the inrush between wind turbine transformers is expected to increase proportionally with the number of parallel connected transformers. The simulation is then continued with adding the parallel-connected wind turbine transformers to the system.

### 7.4.5.3 Inrush current study for 3 parallel-connected wind turbine transformers

In the section that follows, another wind turbine transformer, T3 is connected in parallel to T1 and T2. T1 is already online while T2 and T3 are energised simultaneously at 0.5 s. Fig. 7.6 (a) shows the magnetising inrush at T2, Fig 7.6 (b) shows the magnetising inrush at T3 while Fig. 7.7 shows the sympathetic current at transformer T1.

Now, the inrush current at energised transformer(s) between Fig. 7.6 and Fig. 7.4 are compared. It is found that when one wind turbine transformer with one already energised transformer, the decaying rate is faster compared to when two transformers are energised simultaneously with the same already energised transformer. The peak current is almost the same; however, if more transformers are connected, the inrush current exhibits longer duration.
These simulation studies also show that by increasing the number of transformers, the peak of the sympathetic inrush appears to increase proportionally. It can be seen in both Fig 7.5 and Fig. 7.7. When there are two parallel-connected transformers, the peak of sympathetic current inrush is 3.32 p.u. When there are three parallel-connected transformers, the peak of sympathetic inrush is reached to 3.81 p.u. The duration of the transient inrush is longer as well.

As a typical wind farm often consists of variety number of wind turbine transformers, engineers should be aware of this power system protection issue besides finding the most feasible design for a minimum cost.
7.4.5.4 Inrush current study for 5 parallel-connected wind turbine transformers

The inrush currents caused by simultaneously energising several wind turbine transformers in one feeder are investigated. The sympathetic inrush phenomenon occurred is also simulated. Using the model shown in Fig. 7.8, only one transformer, T1 is already on-line. Then, after 1 s, transformers T2, T3, T4 and T5 are energised simultaneously.

Fig. 7.9 is referred. At T1, the peak stead-state current is about 1.0 and -1.0 p.u. After T2, T3, T4 and T5 were simultaneously energised at the same time, sympathetic inrush occurred at the adjacent transformer T1. It can be seen that the peak current increases to 3.85 p.u. and then decays. However, the decaying rate is very slow.
Fig. 7.8 Several wind turbine transformers under study

Fig. 7.9 Sympathetic inrush at T1
Fig. 7.10 (a) Magnetising inrush at T2, (b) Magnetising inrush at T3, (c) Magnetising inrush at T4, (d) Magnetising inrush at T5
Fig. 7.10 (a), (b), (c) and (d) show the magnetising current at T2, T3, T4 and T5, respectively. All the currents are in equal shape and waveform with the peak current at 40 p.u. Comparing with Fig. 7.6, it can be seen that the peaks are higher in this energising condition. Hence, it is observed considerable increase of both sympathetic and magnetising inrush when there are more parallel-connected transformers energised simultaneously in the systems.

7.4.5.5 Inrush current study for parallel-connected transformers with different loads

This section describes another cluster of parallel-connected transformers in the external grid of wind farm. Here, two same rated transformers with different loads are connected to one bus. Fig. 7.11 shows the system under study where previously in Fig. 7.1; it is located at the lower right side of the whole wind farm network.

Fig. 7.11 Parallel-connected transformers with different loads under study
Both T1 and T2 are similar in terms of its rating and other electrical parameters. At T1, a hydro generator is connected whereas a wound rotor induction machine is connected at T2. In this modelling simulation, T1 is already energised in the system. At 1 s, T2 is then energised.

In Fig. 7.12, the current generated in T1 is presented. At 1 s where T2 is energised, the peak current spikes last for several cycles and then returned to the steady state.

![Fig. 7.12 Sympathetic inrush at T1](image1)

![Fig. 7.13 Magnetising inrush at T2](image2)
Referring to Fig. 7.13, the inrush current can be seen at the first transformer energisation. However, the decay is not significantly identified as it depends on the loading. When the transformers are in no-load condition, the winding current will be equal to the magnetising current while in loaded transformers; the winding current will include the load components.

### 7.5 Summary

In this chapter, transformer energisation issues between wind turbine transformers are studied. The chapter started with the background review of the rapid wind farm development in Australia over the last four years. The intention is to highlight the emerging significance of this issue at present.

The simulation modelling for the wind turbine transformer associated with the wind turbine generator connected is presented in this chapter. The modelling, the transformer core saturation hysteresis and the simulations are run in PSCAD/EMTDC, yielding some new observations.

By analysing the sympathetic and normal inrush current, the relationship and the differences between the current characteristics are studied. It is found that wind turbine transformers experienced both phenomena too, with the sudden increase in core saturation to the energised transformer.

By adding more wind turbine transformers, it is observed notable increase in the peak of sympathetic inrush. The sympathetic inrush phenomenon for the transformers with different load is also simulated. It is observed that the transformer which is already switched-in also experiences unexpected saturation in the interaction of the parallel-connected transformer energisation. With loaded parallel-connected transformers, the interaction between energised transformer and the already on-line transformer is found, however, the prolong decay cannot be seen as the decay characteristics are depending on the load components.
7.6 The Way Forward

To move forward in researching the subject, the focus should be placed on the inrush current in wind farms, as the wind farm itself is highly complicated and consists of many components to model. On the other hand, efforts could also be put into simulating each and every one of the components and switching events. Nevertheless, the accuracy of the results will be limited by the accuracy of the simulation tool.

The research should cover all parts related to the wind farm grid connection. There are different possible connections of wind farms and network configurations depending on the geographical environment as well as different loads and interconnection points. However, in this research, it is not possible to cover all these points. Future work may specifically address these sympathetic inrush issues based on the type of connection and place focus on modelling specific aspects rather than everything as a whole.

On-going important work is being done in the IEEE on switching transients induced by transformer-breaker interaction, as there are plenty of these components in the collection grid. However, it would not be possible to achieve significant results without the participation of the manufacturers of transformers and circuit breakers in the development phase.

PSCAD/EMTDC is a powerful tool that can be investigated in more depth in this research. Adequate models of DG (distributed generation), network, power electronics, and control and protection devices are available in the time domain.
CHAPTER 8

CONCLUSION AND FUTURE WORK

8.1 Conclusion

This research presents transformer energisation issues, namely sympathetic inrush current interaction, starting with transformer modelling and followed by simulation and experimental verification. Then, further simulation studies are carried out and discussed. The scope of this research also includes a review of sympathetic inrush current between wind turbine transformers, a simplified simulation, and the way forward.

For the initial stages of transformer modelling studies, the classic Steinmetz model is used. To model the transformer, advanced numerical techniques are capitalised on and experimental tests are performed. Standard commercial oil-immersed pole-mounted distribution transformers are used as test object in laboratory experiments; these transformers have limited technical specification data available. Hence, the modelling work includes characterisation measurements (open-circuit test and short-circuit test) from which the transformer electrical parameters are computed. Then, the iron core losses are determined via laboratory work by injecting different voltage harmonics. Further, the eddy current loss and the hysteresis loss can be extracted from the core losses by using the two-frequency method. This transformer model is tested using PSCAD/EMTDC. The results show good inrush characteristics and patterns. However, there is some discrepancy; in particular the resultant $B-H$ characteristic is not a fully distributed hysteresis loop.
This work also reports the advancement of the Steinmetz model in PSCAD/EMTDC, which includes the Jiles-Atherton model in the core saturation. Modelling via Jiles-Atherton had been shown to give more accurate results, and thus it is chosen for this study. The improvement is confirmed when the Jiles-Atherton hysteresis model is applied to the same test object as per studies discussed in Chapter 3. Some parameters of the model are estimated using differential evolution algorithms. The electrical parameters and the curve fitting for the saturation curve are still adapted from the basic model but the Jiles-Atherton model is introduced to develop the $B$-$H$ curve. The remanent flux is computed throughout the process. Even with limited transformer data, this model still yields some improvement to the inrush studies. By comparing the sympathetic inrush transient peak in the simulation and experiment, the results verify that the Jiles-Atherton model is indeed better.

To further study the accuracy of the inrush current predictions via Jiles-Atherton modelling, this model is tested with another transformer with known core data. Hence, small variac transformers are used. In this case, the inverse Jiles-Atherton is used to estimate the model parameters. As the magnetising current is small for these low-rating transformers, it is necessary to apply de-noising technique (i.e. wavelet analysis) to remove noise from the measured signals. The resultant model is found to provide better agreement with inrush current experimental results.

For the modelling and simulation, PSCAD/EMTDC is used as the simulation tool in this research. The energisation inrush responses for a single transformer and parallel-connected transformers are studied. By analysing the sympathetic and normal magnetising inrush currents, the relationship and the differences between their characteristics are revealed. It is found that both are caused by transformer core saturation and hence the factors affecting inrush are mostly the same. By comparing the inrush in single transformer energisation and energisations in parallel-connected transformers, it is found that the inrush currents are in opposite polarity to each other. For single transformer energisation, the current ramps up to a very large peak and then it decays dramatically. However, for the sympathetic inrush current, the decay is longer.
According to the simulation and experimental results, the following factors affecting the inrushes can be drawn:

- The switching angle will vary the peak of the inrush amplitude.
- The increasing of system resistance values will reduce the peak of the inrush amplitude and hasten the decay of the inrush.
- The residual flux level will increase the peak of the sympathetic inrush and vary the decay characteristics.

When several transformers are energised simultaneously with the initially energised transformer, the occurrence of the sympathetic inrush phenomenon can be observed. When there is no initially energised transformer, the simultaneous energisation of several transformers results in a high inrush current that eventually decays and more damped, as the normal magnetising inrush characteristics apply. With an initially energised transformer, simultaneous energisation will decrease the peak time compared to different energisation times. However, the decay time is almost the same.

Simulation studies are further carried out to observe the impact of the number of already energised transformers on the peak sympathetic inrush. These simulation studies also show that by increasing the number of already energised transformers, the peak of the sympathetic inrush and the decay time appear to increase proportionally.

Moving on now to consider on the relationship between sympathetic inrush and voltage sag, it is shown that sympathetic inrush provides longer decay characteristics to the inrush transients, thus it actually also prolongs the duration of the voltage sag. It is also revealed that adding an already energised transformer to the circuit and increasing number of simultaneously energised transformers will result in more severe voltage sags being recorded.

The laboratory works were then performed to validate the developed PSCAD/EMTDC model and verify the mentioned phenomena. Unlike other previous studies which carried out the research based solely on computer simulations or
together with some field measurements, a laboratory experimental setup was developed in this research which enables more flexibility in being able to measure inrush currents in full-size distribution transformers under different excitation configurations. The method of building the point-on-wave switching using MSP 430 microcontroller is also presented in the process.

For the laboratory experiments, the first phenomenon to observe is single transformer energisation to measure the magnetising inrush, whilst the second is with two parallel transformers to measure the sympathetic inrush. The test objects were two types of transformers: case A uses smaller rating dry-type transformers of 3 kVA, 240/120 V and case B uses 16 kVA 11 kV/250V oil-immersed distribution transformers. Case A is set up for a pre-run test while case B concerns the main distribution transformers used throughout this research for both experiment and modelling. All transformers tested are single-phase type.

Through analysing the inrush transients in the laboratory, it was shown that significant differences between the normal magnetising inrush and the sympathetic inrush currents can be seen in the opposite polarity. The results show a good agreement and verify that the proposed model can be used for predicting the inrush current phenomenon.

Experimental results reveal that as the switching angle is varied, the inrush currents also vary. For single transformer energisation of case B, the highest current magnitude is 716.2 A (at switching angle of 0 degrees) which is 11 times higher than the rated current, 64 A whilst for parallel energisation, the highest sympathetic inrush current magnitude is at 101.98 A (at switching angle of 180 degrees).

Chapter 7 reviewed the recent development of wind energy generation in Australia over the last four years. Simulations are carried out to investigate the sympathetic inrush current phenomenon between parallel-connected wind turbine transformers. By analysing the sympathetic and normal magnetising inrush, the relationship and differences between the current characteristics are studied. It is found that parallel-connected wind turbine transformers experienced both phenomena too. Adding more wind turbine transformers increases the peak of inrush transients. Also, voltage sag is
noted; there is slight difference between two and four wind turbine transformers energised simultaneously. For the sympathetic inrush in transformers with different loads, it is observed that the transformer which is already switched-in also experiences unexpected saturation. However, the prolong decay cannot be seen as the decay characteristics depend on the load components. For the way forward, sympathetic inrush studies should address the sympathetic inrush issue by exploring the type of connection and focusing on modelling this issue rather than the topic as a whole.

In summary, this thesis explores the sympathetic inrush phenomena via transformer modelling, computer simulations and laboratory experiments on full-sized distribution transformers. It was able to demonstrate good agreement between simulation and experimental results. All in all, the objectives set out in the thesis have been achieved.

8.2 Future Work

The following areas are recommended for further work:

a) Transformer modelling

- The accuracy of the Jiles-Atherton parameters can be investigated further. Although these parameters critically influence the modelling results, they cannot be easily estimated. This study found it prohibitive to accurately obtain all five parameters of the model due to lack of technical details of the test object—a commercial transformer. The information is confidential which could not be obtained from the manufacturer. As mentioned in [3], it would be beneficial if transformer manufacturers and utility companies provide in-factory test reports as well as additional relevant data.

- Transformer core materials such as grain-oriented steel are highly anisotropic. Future work can be done by extending upon the features of the
Jiles-Atherton model, taking into account the effects of anisotropic materials in the modelling.

b) Laboratory experimental works

- For the transformer core dimensions in this study, the author could only rely on a rough measurement (by opening the top cover of the oil-filled transformer). A more accurate measurement should therefore be performed if the transformer can be de-tanked. Alternatively, access to full design details of the transformer from the manufacturer would be ideal.

- In this study, it was not able to control the residual flux in the core due to the overriding protection from the main circuit breaker upstream. Because of safety regulations, it is not possible to bypass this setup. For the majority of the time, only the peak inrush was able to be recorded because of the sudden tripping of the main circuit breaker shortly after. The data concerning the decay characteristics is useful information. Further work in a controlled laboratory setting may yield all the data needed for these transient studies.

c) Sympathetic inrush in wind farms

- In this research, the sympathetic inrush between wind turbine transformers was investigated based on computer simulations only; there are no field data on inrush transients from wind farms. Future work should focus on modelling actual wind farm network connections and components to study the effect of grid topology on the field-measured inrush transient characteristics.
## APPENDIX

### Appendix A: Programmable Voltage Source Parameters

Table A.1 Programmable voltage source fundamental parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Per Phase</strong></td>
<td>16 A in 115-156 V range</td>
</tr>
<tr>
<td></td>
<td>8 A in 230-312 V range</td>
</tr>
<tr>
<td></td>
<td>AC, DC or AC+DC mode</td>
</tr>
<tr>
<td><strong>Frequency Range</strong></td>
<td>40 Hz to 5 kHz</td>
</tr>
<tr>
<td><strong>Max Total Harmonic Distortion</strong></td>
<td>0.25% max, 40 to 100 Hz</td>
</tr>
<tr>
<td></td>
<td>0.5% max to 500 Hz</td>
</tr>
<tr>
<td></td>
<td>1% max to 1 kHz plus 1% kHz to 5 kHz</td>
</tr>
<tr>
<td><strong>Frequency Resolution</strong></td>
<td>40 Hz to 81.90 Hz (0.01 Hz)</td>
</tr>
<tr>
<td></td>
<td>81.91 Hz to 819 Hz (0.1 Hz)</td>
</tr>
<tr>
<td></td>
<td>820 Hz to 5000 Hz (1 Hz)</td>
</tr>
</tbody>
</table>
Table A.2 Ametek CSW555 measurements

(All specifications are at 25°C unless noted otherwise)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy (±)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2 counts</td>
<td>0.01: 16 to 81.91 Hz</td>
</tr>
<tr>
<td></td>
<td>0 to 45°C</td>
<td>0.1: 82.0 to 819.0 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1: 820 to 5000 Hz</td>
</tr>
<tr>
<td>RMS Voltage</td>
<td>±0.1% of range from 5 to 156 or 10 to 312 volts. Above 1 kHz add 0.2%/kHz</td>
<td>0.01 Volt</td>
</tr>
<tr>
<td>RMS Current</td>
<td>±1% of range add ±1.5%/kHz above 500 Hz</td>
<td>0.001 Amp</td>
</tr>
<tr>
<td></td>
<td>Ranges: 0.5 to 16A; 156V range</td>
<td>Multiply by 3 for 1-phase mode</td>
</tr>
<tr>
<td></td>
<td>0.5 to 8A; 312V range</td>
<td></td>
</tr>
<tr>
<td>Peak Current</td>
<td>±5% of range. 40 to 500 Hz; add ±1%/kHz 500 to 5 kHz</td>
<td>0.01 Amp</td>
</tr>
<tr>
<td></td>
<td>Ranges: 0 to 56A; 156V range</td>
<td>Multiply by 3 for 1-phase mode</td>
</tr>
<tr>
<td></td>
<td>0 to 28A; 312V range</td>
<td></td>
</tr>
<tr>
<td>VA Power</td>
<td>±2.5% of range, DC or 40 to 500. Add ±1%/kHz above 500 Hz.</td>
<td>1 VA</td>
</tr>
<tr>
<td></td>
<td>Ranges: 1.8kVA; 3-phase mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.6kVA; 1-phase mode</td>
<td></td>
</tr>
<tr>
<td>Real Power</td>
<td>±2.5% of range, DC or 40 to 500. Add ±1%/kHz above 500 Hz.</td>
<td>1 W</td>
</tr>
<tr>
<td></td>
<td>Ranges: 1.8kW; 3-phase mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.6kW; 1-phase mode</td>
<td></td>
</tr>
<tr>
<td>Power Factor (&gt;0.2kVA)</td>
<td>±5% of range at full power. 40 to 500 Hz. Add ±1%/kHz above 500 Hz.</td>
<td>0.01</td>
</tr>
<tr>
<td>Temperature Coefficient</td>
<td>&lt;±50 ppm for all functions above 1%</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>2 counts (0 to 45°C)</td>
<td>0.01: 16 to 81.91 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1: 82.0 to 819.0 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1: 820 to 5000 Hz</td>
</tr>
<tr>
<td>Phase</td>
<td>±2°, 40 to 500 Hz, add ±2%/kHz above 500 Hz (0 to 45°C)</td>
<td>±1° for outputs above 20 VRMS</td>
</tr>
</tbody>
</table>

Current and Power Accuracy specifications are percent of Range. The Ranges are listed below.
Measurement bandwidth is limited to 16 kHz.
Appendix B: Open-circuit and Short-circuit Tests
Table B.1 Data recorded from the open-circuit test of Transformer 1

<table>
<thead>
<tr>
<th>Input (V)</th>
<th>Current (A&lt;sub&gt;rms&lt;/sub&gt;)</th>
<th>Power (W)</th>
<th>Apparent Power (VA)</th>
<th>Power factor</th>
<th>Peak Current (A)</th>
<th>High Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.020</td>
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<td>0</td>
<td>0.44</td>
<td>0.042</td>
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<tr>
<td>40</td>
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<td>1</td>
<td>0.58</td>
<td>0.052</td>
<td>1.66</td>
</tr>
<tr>
<td>60</td>
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<td>2</td>
<td>0.73</td>
<td>0.055</td>
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<td>0.82</td>
<td>0.055</td>
<td>3.51</td>
</tr>
<tr>
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<td>0.028</td>
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<td>0.91</td>
<td>0.055</td>
<td>4.37</td>
</tr>
<tr>
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<td>0.91</td>
<td>0.059</td>
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</tr>
<tr>
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<td>4</td>
<td>0.92</td>
<td>0.063</td>
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</tr>
<tr>
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<td>6</td>
<td>0.87</td>
<td>0.075</td>
<td>7.20</td>
</tr>
<tr>
<td>180</td>
<td>0.041</td>
<td>5</td>
<td>4</td>
<td>0.78</td>
<td>0.097</td>
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<tr>
<td>200</td>
<td>0.052</td>
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<td>10</td>
<td>0.69</td>
<td>0.119</td>
<td>8.90</td>
</tr>
<tr>
<td>220</td>
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<td>9</td>
<td>16</td>
<td>0.59</td>
<td>0.152</td>
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<td>0.66</td>
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<td>0.081</td>
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</tr>
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<td>0</td>
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<td>1.67</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>0.49</td>
<td>0.033</td>
<td>0.81</td>
</tr>
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</table>
Table B.2 Data recorded from the short-circuit test of Transformer 1

<table>
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<tr>
<th>Input (V)</th>
<th>Current (A $rms$)</th>
<th>Power (W)</th>
<th>Power factor</th>
<th>Peak Current (A)</th>
<th>Crest Factor</th>
<th>Current Measured (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.133</td>
<td>2</td>
<td>0.80</td>
<td>0.191</td>
<td>1.43</td>
<td>6.31</td>
</tr>
<tr>
<td>40</td>
<td>0.266</td>
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<td>0.80</td>
<td>0.378</td>
<td>1.42</td>
<td>12.63</td>
</tr>
<tr>
<td>60</td>
<td>0.399</td>
<td>19</td>
<td>0.80</td>
<td>0.566</td>
<td>1.42</td>
<td>18.93</td>
</tr>
<tr>
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<td>0.754</td>
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<tr>
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<td>31.50</td>
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<td>1.130</td>
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<td>37.77</td>
</tr>
<tr>
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<tr>
<td>200</td>
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<td>211</td>
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<td>1.881</td>
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<td>55.10</td>
</tr>
<tr>
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<td>135</td>
<td>0.80</td>
<td>1.504</td>
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<td>49.00</td>
</tr>
<tr>
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<td>12.61</td>
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Table B.3 Data recorded from the open-circuit test of Transformer 2

<table>
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<th>Input (V)</th>
<th>Current (A rms)</th>
<th>Power (W)</th>
<th>Apparent Power (VA)</th>
<th>Power factor</th>
<th>Peak Current (A)</th>
<th>High Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.028</td>
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<td>0.90</td>
<td>0.052</td>
<td>3.44</td>
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<tr>
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<td>0.95</td>
<td>0.054</td>
<td>4.33</td>
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<tr>
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<td>0.033</td>
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<td>0.96</td>
<td>0.061</td>
<td>5.20</td>
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<th>Peak Current (A)</th>
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Table B.5 Data recorded from the open-circuit test of Transformer 3

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<th>Apparent Power (VA)</th>
<th>Power factor</th>
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<th>High Voltage (kV)</th>
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REFERENCES


N. Chiesa, "Power Transformer Modelling Advance Core Model," Masters Degree, Department of Electrical Engineering, Faculty of Engineering, Polytechnic University of Milan, Milan, Italy, 2005.


[120] I. Arana, A. Hernandez, G. Thumm, and J. Holboell, "Energization of Wind Turbine Transformers With an Auxiliary Generator in a Large Offshore Wind Farm During


