Distribution Transformer Incipient Fault Automatic Detection and Monitoring
"DTFaultLoc"

Guilherme Rodrigues Freire

Thesis to obtain the Master of Science Degree in Electrical and Computer Engineering

Supervisor: Prof. Paulo José da Costa Branco

Examination Committee
Chairperson: Prof. Célia Maria Santos Cardoso de Jesus
Supervisor: Prof. Paulo José da Costa Branco
Member of the Committee: Dr. José Eduardo Gomes Oliveira

October 2020
To my grandfather Aníbal and my late grandmother Florinda.  

Much more than two people, two true sources of strength and inspiration.
Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Acknowledgments

Firstly, I would like to acknowledge Prof. Paulo Branco, under whose supervision it was an absolute delight to work. His approach towards his students has been an overriding factor in pushing me to be my best self, academically and otherwise.

I would also like to show my appreciation to Eneida Wireless & Sensors, S.A. and to the team of the “FaultLoc” project, especially Dr. José Oliveira, without whom this thesis would not have been possible in the first place.

To my dear Prof. Silva, also known as my dear friend Chico, who “knows things about stuff”, for the endless patience and all the help he provided throughout my whole master’s degree.

To the team of the Electric machines laboratory at IST for the long hours and treasured moments shared while working there. Specifically, to my friend Ada, with whom I shared many hours working in our experimental setup in the laboratory.

I should also thank our laboratory technician, Duarte Batista, for all the help provided while building the experimental setup.

A huge thank you to all my friends and family, who were always there for me in times of need.

Lastly, the most important acknowledgement of all: to my parents Pedro and Adelina, for the unconditional love and support and for always choosing to give me all the best.
Resumo

Os transformadores são um dos componentes mais fundamentais e dispendiosos das redes de energia elétrica. Dos equipamentos atualmente em funcionamento, uma elevada percentagem encontra-se próximo do fim de vida útil. Nesta fase, as falhas incipientes tornam-se mais comuns e a probabilidade de falha total aumenta, pondo em risco a integridade do equipamento. A falha catastrófica de um transformador acarreta custos elevados, justificando-se a necessidade de detecção de falhas incipientes.

Esta dissertação efetua um estudo computacional e experimental de uma metodologia de monitorização on-line, baseada na medição e cálculo de variáveis, tanto elétricas como magnéticas, e no cruzamento de informações a elas específicas.

O trabalho divide-se em duas partes. Na primeira, um modelo de simulação 2D em elementos finitos de um transformador de distribuição é desenvolvido, validado e usado para simular falhas incipientes em localizações distintas no transformador. Os resultados são analisados e aplicados ao desenvolvimento de uma potencial metodologia de detecção e localização de falhas incipientes em transformadores de distribuição.

Na segunda parte, uma bancada para ensaios experimentais de um transformador trifásico foi desenvolvida, testada e usada para emular falhas incipientes nos enrolamentos do transformador, de forma a fornecer informação adicional acerca do comportamento das variáveis e concluir sobre a escalabilidade dos métodos de monitorização previamente propostos.

As conclusões retiradas indicam que a monitorização das tensões, correntes e respectivas componentes simétricas, efetuando um cruzamento com medidas, diretas ou indiretas, da dispersão de fluxo magnético, constitui uma metodologia viável para detecção e localização de falhas incipientes, dependendo da potência do transformador.

Palavras-chave: Transformador de distribuição, Monitorização on-line, Falhas incipientes, Detecção, Localização
Abstract

Transformers are one of the most essential and expensive components of electric grids. Of those currently in service, a very significant percentage is close to its designated lifetime. At such stage, incipient faults become more common and the failure rate increases, endangering the integrity of the equipment. Catastrophic transformer failures bear high costs, which justifies the need for failure prediction and incipient fault detection.

This dissertation provides a computational and experimental study of an on-line monitoring methodology based on the measurement and computation of several variables, both electrical and magnetic, and the subsequent cross-referencing of variable-specific information.

The study consists of two parts. First, a 2D finite element method (FEM) simulation model of a distribution transformer is developed, validated, and used to simulate the gradual appearance of incipient faults in several locations. Simulation results are analyzed and used to develop a potential detection and localization methodology for incipient faults on distribution transformers.

In the second part of this work, a smaller scale setup for experimental study of a three-phase transformer is built, tested and used to emulate the incipient winding faults in the transformer, in order to provide further information on variable behavior and assess the scalability of the previously proposed methods.

Conclusions arising from this work suggest that monitoring the line voltages and currents, as well as their symmetric component systems, and cross-referencing such information with magnetic flux leakage measurements is a viable fault detection and potential fault localization method, depending on transformer power rating.

Keywords: Distribution transformer, On-line monitoring, Incipient faults, Detection, Localization
# Contents

Acknowledgments ......................................................... v
Resumo ........................................................................ vii
Abstract ....................................................................... ix
List of Tables ................................................................. xv
List of Figures ................................................................. xix
Nomenclature ................................................................. xxvii

1 Introduction ................................................................. 1
  1.1 Motivation ................................................................. 2
  1.2 Objectives ................................................................. 3
  1.3 Outline .................................................................. 4

2 State of the Art ............................................................... 7
  2.1 Transformer failures .................................................. 8
  2.2 Monitoring techniques ............................................... 10
    2.2.1 Off-line monitoring .............................................. 11
      2.2.1.1 Dissolved gas analysis .................................... 11
      2.2.1.2 Furan analysis .............................................. 11
      2.2.1.3 Winding resistance and turn ratio measurements . 12
      2.2.1.4 Dissipation factor test .................................... 12
      2.2.1.5 Leakage reactance measurement ...................... 13
      2.2.1.6 Frequency response analysis .......................... 13
    2.2.2 On-line monitoring .............................................. 13
      2.2.2.1 Electrical monitoring .................................... 13
2.2.2.2 Partial discharge detection .................................................. 14
2.2.2.3 Thermal monitoring ............................................................. 14
2.2.2.4 Vibro-acoustic monitoring .................................................... 15

3 Theoretical Background ............................................................... 17

3.1 Fortescue transformation and symmetrical components .................................. 18
  3.1.1 Symmetrical components for voltages and currents .................................. 18
  3.1.2 Apparent power in terms of symmetrical components .................................. 18
  3.1.3 Symmetrical component impedance matrix .......................................... 19
  3.1.4 Application of the symmetrical components to three-phase transformers ......... 20

3.2 Effective B-H curve ................................................................. 21
  3.2.1 Effective B-H curve approximation and its implications ............................ 21
  3.2.2 Example: application of the effective curve approximation to the 35PN300 Silicon
Steel (NGO) .................................................................................... 23

4 Analytical model ............................................................................. 27

4.1 Single-phase equivalent circuit of a three-phase transformer ............................... 28

4.2 Open-circuit test ........................................................................ 28

4.3 Short-circuit test ......................................................................... 30

4.4 Inductance matrix computation through core geometry analysis ....................... 31

5 Finite Element Simulation Model ..................................................... 35

5.1 Geometry ................................................................................... 36

5.2 Materials ................................................................................... 36

5.3 Meshing ..................................................................................... 37

5.4 Electrical circuits ....................................................................... 38

5.5 Frequency domain analysis .......................................................... 39
  5.5.1 Effective curve approximation ....................................................... 39
  5.5.2 Frequency domain equations ....................................................... 39
List of Tables

2.1 Summary of the failure location and cause identification published by Jan, Afzal and Khan in [9]. ............................................................... 8

2.2 Severity classification categories for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]). ............................................................... 9

2.3 Occurrence classification levels for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]). $P$ is the probability of occurrence. ............... 9

2.4 Detection and identification capability classification categories for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]). .................. 9

2.5 Dissolved gases and their main sources, adapted from [11]. ........................................ 11

2.6 Dissolved gas ratio references for fault diagnosis according to IEC 60599, adapted from [11]. ............................................................... 11

6.1 Voltages and currents (in p.u.) obtained in each phase with the transformer operating in open-circuit condition. ............................................................... 42

6.2 Voltages and currents (in p.u.) obtained in each phase with the transformer operating in short-circuit condition. ............................................................... 44

6.3 Comparison between the coil self-inductances obtained from the analytical model and from the simulation model. ............................................................... 47

7.1 Line voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side (1st turn). ............................................................... 55

7.2 Line voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn). ............................................................... 55

7.3 Line voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn). ............................................................... 55

7.4 Line voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1st turn) - variations with respect to reference (initial step). ............... 55
7.5 Line voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn) - variations with respect to reference (initial step). .................................................. 56

7.6 Line voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn) - variations with respect to reference (initial step). .................................................. 56

7.7 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1st turn). ................................................................. 60

7.8 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn). ................................................................. 60

7.9 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn). ................................................................. 61

7.10 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1st turn) - normalized to rated values. .................. 61

7.11 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn) - normalized to rated values. .................. 61

7.12 Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn) - normalized to rated values. .................. 61

7.13 Harmonic amplitude factors for the odd voltage harmonics injected in the primary side. .................. 76

7.14 Main function of each set of variables regarding the localization of a fault occurring in phase X .................................................................................................................. 79

8.1 Rated voltages, currents and apparent power for the transformer of fig. 8.1 .................. 82

8.2 Line voltages and currents obtained from the preliminary open-circuit test. .................. 86

8.3 Line voltages and currents obtained from the preliminary short-circuit test. .................. 86

8.4 Load values per phase and line voltages and currents obtained from the preliminary rated load test. .............................................................................................................. 87

8.5 Line voltages and currents taken from open-circuit (OC), short-circuit (SC) and rated load (RL) tests, before and after experimental setup adaptation. ................................. 90

8.6 Comparison of line voltages and currents taken from open-circuit (OC), short-circuit (SC) and rated load (RL) tests, before and after experimental setup adaptation. .................. 91

8.7 Identification and description of experimental tests to be carried out concerning the emulation of incipient winding faults. ................................................................. 91

8.8 Experimental results for line voltages and currents on primary and secondary side. .................. 93
8.9 Experimental results for line voltages and currents on primary and secondary side - vari-
ations with respect to rated load test (reference) ........................................... 93
8.10 Experimental results for voltages and currents on primary and secondary side, in terms
of symmetrical components ................................................................. 94
8.11 Experimental results for voltages and currents on primary and secondary side, in terms
of symmetrical components - variations with respect to rated load test (reference) ........ 94
8.12 Severity rating of each fault test according to different electrical variables ................ 95
8.13 Average severity rating of each fault test according to different electrical variables and
number of lost coil turns ................................................................. 96
8.14 Ambient and core temperature measurements and respective temperature differential di-
rectly above each transformer limb, with and without the presence of an incipient fault .... 100
8.15 Increase in temperature due to the presence of incipient fault in middle limb ............ 100

B.1 Line voltages and currents obtained for a gradual single turn loss in phase B, on the
primary side (1\textsuperscript{st} turn). The rows highlighted in red and green present the only relevant
variations ................................................................. B.1
List of Figures

1.1 Generic bathtub curve representing risk of failure over time in transformers and other electric equipment with similar behavior, as published in [6]. The black line (bathtub curve) incorporates the failure rates due to "infant mortality" (Blue), wear-out (yellow) and constant random failures (red). ................................................................. 2

1.2 Age profile of a population of over 30000 ENW distribution transformers until 2015, published in [7]. ................................................................. 3

1.3 Age profile of a large population of transmission (primary voltages of 220-500kV), subtransmission (primary voltages of 110-132kV) and distribution (primary voltages of 11-66kV and secondary voltages higher than 240V) transformers operating in Australia until 2015, published in [8]. ................................................................. 3

2.1 Transformer failure location statistics for GSU, transmission and distribution transformers, as published by [10]. ................................................................. 10

2.2 (a) Illustration of magnetostriction phenomena, as published in [3]. (b) Transformer vibration transmission chains, adapted from [27]. ................................................................. 15

3.1 Generic B-H curve representation for different types of materials. ................................................................. 22

3.2 DC (a) and effective (b) B-H curves for the 35PN300 Silicon Steel (non-grain oriented) ................................................................. 24

3.3 Magnetic field $H(t)$ (a) and corresponding operating region on the B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 1T$ is imposed. ................................................................. 24

3.4 Approximated magnetic field $H(t)$ (a) and corresponding operating point on the effective B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 1T$ is imposed. ................................................................. 24

3.5 Magnetic field $H(t)$ (a) and corresponding operating region on the B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 2T$ is imposed. ................................................................. 25
3.6 Approximated magnetic field $H(t)$ (a) and corresponding operating point on the effective B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 2T$ is imposed. ................................................................. 25

4.1 Single-phase equivalent circuit for a balanced three-phase transformer. .......................... 28
4.2 Single-phase equivalent circuit for a balanced three-phase transformer with the secondary winding in open circuit. ................................................................. 29
4.3 Simplified single-phase equivalent circuit for a balanced three-phase transformer with the secondary winding in open circuit. ................................. 29
4.4 Single-phase equivalent circuit for a balanced three-phase transformer with the secondary winding in short-circuit. ................................................................. 30
4.5 Simplified single-phase equivalent circuit for a balanced three-phase transformer with the secondary winding in short-circuit. ................................................................. 30
4.6 Three limb transformer core cross section (a) and equivalent circuit considering magnetic reluctances and magnetomotive forces. ................................. 31

5.1 Model geometry (core and windings), with highlighted parts and measurements. Note: domains surrounding core and windings are hidden. ................................. 36
5.2 Finalized model geometry, showing core, windings and surrounding circular 2-layer domain. 37
5.3 Model geometry showing materials used in each domain. ............................................. 37
5.4 Model mesh: (a) global view of mesh; (b) detail of interest region (core and windings). .. 38
5.5 Lumped parameter electrical circuits: (a) primary; (b) secondary. ................................. 39

6.1 Primary (a) and secondary (b) side circuit diagrams corresponding to the open circuit test of the transformer. ................................................................. 42
6.2 Magnetic flux density norm and magnetic potential vector simulation results - open circuit test. ................................................................. 43
6.3 Primary (a) and secondary (b) side circuit diagrams corresponding to the short-circuit test of the transformer. ................................................................. 43
6.4 Magnetic flux density norm and magnetic potential vector simulation results - short-circuit test. ................................................................. 44
6.5 Primary (a) and secondary (b) side circuit diagrams corresponding to the configuration used for determining the self-inductance of phase A of the primary winding. ................................................................. 46
6.6 Primary (a) and secondary (b) side circuit diagrams corresponding to the configuration used for determining the self-inductance of phase A of the secondary winding. ................................................................. 46

xx
7.1 Surface plot of the magnetic flux density distribution (RMS values) at rated voltage and load: (a) frequency domain; (b) time dependent. .................................................. 50

7.2 Surface plot of the magnetic flux density deviation, at rated voltage and load - frequency domain with respect to time domain. .................................................. 51

7.3 Surface plot of the magnetic flux density deviation, at rated voltage and load - frequency domain with respect to time domain - location (a) and detail (b) of outer corner. .......... 52

7.4 Surface plot of the magnetic flux density deviation, at rated voltage and load - frequency domain with respect to time domain - location (a) and detail (b) of inner corner with 10000-point mesh. .................................................. 52

7.5 Generic connection scheme for simulation of a gradual single turn loss. .................. 53

7.6 Single turn loss fault locations (vertical position within coil) - 1st, 4th, 11th, 15th and 20th turns. .................................................. 54

7.7 Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase A) in different fault locations (1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation. .................................................. 57

7.8 Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase B) in different fault locations (1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation. .................................................. 58

7.9 Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase C) in different fault locations (1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation. .................................................. 59

7.10 Schematic representation of the induced current flow on a secondary winding when the 1st turn is (a) healthy; (b) short-circuited. .................................................. 60

7.11 Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase A): (a) general plot; (b) detail of positive and negative sequence components on separate axis. .................................................. 63

7.12 Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase B): (a) general plot; (b) detail of positive and negative sequence components on separate axis. .................................................. 63

7.13 Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase C): (a) general plot; (b) detail of positive and negative sequence components on separate axis. .................................................. 63
7.14 Positive and negative sequence currents obtained for a gradual single turn loss in the secondary winding (phase A) in different fault locations (4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation. ................................. 64

7.15 Positive and negative sequence currents obtained for a gradual single turn loss in the secondary winding (phase B) in different fault locations (4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation. ................................. 65

7.16 Positive and negative sequence currents obtained for a gradual single turn loss in the secondary winding (phase C) in different fault locations (4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation. ................................. 66

7.17 Magnetic flux density distribution at 0% (a) and 100% (b) turn loss for a fault in the 1st turn of phase A, in the secondary winding. ................................................................. 67

7.18 Magnetic flux density distribution at 0% (a) and 100% (b) turn loss for a fault in the 1st turn of phase B, in the secondary winding. ................................................................. 67

7.19 Magnetic flux density distribution at 0% (a) and 100% (b) turn loss for a fault in the 1st turn of phase C, in the secondary winding. ................................................................. 68

7.20 Surfaces defined to measure limb (S₁, S₂ and S₃) and leakage (S₄ - S₉) magnetic fluxes. ................................. 69

7.21 Normalized magnetic leakage flux to the left (black) and right (red) of the faulty limb, for a gradual 1st turn loss fault in the secondary winding, located in: (a) phase A, left limb; (b) phase B, middle limb; (c) phase C, right limb. ................................................................. 69

7.22 Variation of inward flux leakage in phase A according to fault location and severity: (a) 2D representation; (b) 3D representation. ................................................................. 71

7.23 Variation of inward flux leakage in phase B according to fault location and severity: (a) 2D representation; (b) 3D representation. ................................................................. 71

7.24 Comparison of the magnetic flux density distribution for a single turn loss fault in the secondary winding (phase A) in the 1st (a) and 11th (b) turns. ................................................................. 72

7.25 Single turn loss fault locations in primary winding (vertical position within coil) - 1st, 325th, 651st, 975th and 1300th turns. ................................................................. 73

7.26 Imposed primary voltage waveforms, in p.u., without (a) and with (b) odd harmonics up to the 9th order. ................................................................. 76
7.27 Surface plot of the magnetic flux density distribution (RMS values) at rated RMS voltage and load: (a) purely sinusoidal primary voltages; (b) primary voltages injected with odd harmonics. .............................................. 76

7.28 Surface plot of the magnetic flux density deviation, at rated voltage and load - with harmonics vs. purely sinusoidal .................................................. 77

7.29 Phase A limb flux (RMS) for a gradual single turn loss of the 1st turn in the secondary winding (phase A): (a) general plot; (b) detail. .............................................. 78

7.30 Phase A leakage fluxes (RMS) for a gradual single turn loss of the 1st turn in the secondary winding (phase A): (a) RMS values; (b) normalized with respect to rated limb flux. 78

7.31 Flowchart of the proposed fault detection and localization methodology, for a fault in phase X of the secondary winding, based on the conclusions taken from the fault simulations and the functions attributed to the variables of interest. ........................ 80

8.1 Three-phase, three-column, air-cooled transformer selected for the experimental process, as originally acquired. .................................................. 82

8.2 Highlight of the insulating paper sheets placed in the space between the columns of the transformer. .................................................. 83

8.3 Single-phase schematic of the transformer windings. .............................................. 83

8.4 Top (a) and bottom (b) view of the custom connection board (board 2) for the multiple secondary terminals. .............................................. 84

8.5 Secondary connection board (board 2) with desired connections (a) and corresponding single-phase equivalent scheme (b). .............................................. 85

8.6 Main connection board (board 1) of the experimental setup. .............................................. 85

8.7 Connection scheme for the open-circuit test: (a) primary; (b) secondary. AT: autotransformer connected between the low voltage grid and the transformer and feeding the primary winding at rated voltage. .............................................. 86

8.8 Connection scheme for the short-circuit test: (a) primary; (b) secondary. AT: autotransformer connected between the low voltage grid and the transformer and feeding the primary winding at rated current. .............................................. 87

8.9 Connection scheme for the rated load test: (a) primary; (b) secondary. AT: autotransformer connected between the low voltage grid and the transformer and feeding the primary winding at rated voltage. .............................................. 87

8.10 Schematic representation of connection diagram (a), junctions applied to coil turns (b) and rerouting of turn terminals to main connection board (c). .............................................. 88
8.11 Setup with turns connected in series, without fault (a) and corresponding connection diagram (b). ................................................................. 89

8.12 Setup with turns connected as to emulate a fault between turns 2 and 3 (a) and corresponding connection diagram (b). ................................................................. 89

8.13 Final experimental setup obtained after initial condition assessment tests and subsequent alterations performed on secondary winding. ................................. 90

8.14 Connection diagrams for the tests described in tab. 8.7: (a) Reference; (b) 1 - 2; (c) 1 - 3; (d) 1 - 5; (e) 2 - 3; (f) 2 - 5; (g) 3 - 5. ................................................................. 92

8.15 Hall effect probe used for magnetic flux density leakage measurements - global view (a) and detail of sensor (b). ................................................................. 97

8.16 Illustration of Hall effect sensor operation, as published by [33]. ................................................................. 97

8.17 Characteristic magnetic flux density vs. voltage curve of the Hall effect sensor, adapted from [34]. ................................................................. 97

8.18 Measurement setup used with the hall effect probes to measure the magnetic flux density leakage between transformer limbs. ................................................................. 98

8.19 Location of the hall effect probes in the inter-limb space. ................................................................. 98

8.20 RS Pro Dual Thermo/Clock digital thermometer. ................................................................. 99

8.21 Location of thermal sensors on top section of the transformer core. ................................................................. 100

B.1 Magnetic flux density distribution at 100% turn loss for a fault in the 1st turn of phase B, in the primary winding. ......................................................... B.2

B.2 Evolution of the positive and negative sequence components of the primary currents with the gradual loss of the 1st turn of the primary winding, phase B. ......................................................... B.2

B.3 Normalized magnetic leakage flux to the left (black) and right (red) of the middle limb for a gradual 1st turn loss fault in the primary winding, phase B. Both curves (black and red) are coincident. ......................................................... B.3

B.4 Variation of the flux leakage in the middle limb according to fault location and severity, for a single turn loss fault in phase B of the primary winding: (a) 2D representation; (b) 3D representation. ......................................................... B.3

B.5 Line current obtained for a gradual single turn loss in the primary winding (phase B) in different fault locations (1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation. ......................................................... B.4
B.6 Positive and negative sequence currents obtained for a gradual single turn loss in the primary winding (phase B) in different fault locations (1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

C.1 Line current obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation.

C.2 Line current obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation.

C.3 Positive and negative sequence currents obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

C.4 Positive and negative sequence currents obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

C.5 Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

C.6 Variation of the magnetic flux leakage in the middle limb obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

C.7 Line current obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.
C.8 Line current obtained for a gradual three turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.

C.9 Positive and negative sequence currents obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

C.10 Positive and negative sequence currents obtained for a gradual three turn loss in the secondary winding (phase B) in different fault locations (starting at the 4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

C.11 Normalized magnetic leakage flux to the left (black) and right (red) of the middle limb for a gradual turn loss fault in the secondary winding, phase B, starting in the 1st turn: (a) loss of 2 turns; (b) loss of 3 turns. Both curves (black and red) are coincident.

C.12 Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

C.13 Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

C.14 Magnetic flux density distribution at 100% turn loss for a two turn fault in the 1st – 2nd turns of phase B, in the secondary winding: (a) global view; (b) detail of faulty section.

C.15 Magnetic flux density distribution at 100% turn loss for a three turn fault in the 1st – 3rd turns of phase B, in the secondary winding: (a) global view; (b) detail of faulty section.
Nomenclature

Greek symbols

\( \alpha \)  
Complex 120° rotation coefficient.

\( \Delta \)  
Variation.

\( \delta \)  
Dielectric loss angle.

\( \Phi \)  
Limb magnetic flux column vector.

\( \mu \)  
Magnetic permeability.

\( \mu_r \)  
Relative magnetic permeability.

\( \omega \)  
Angular frequency.

\( \phi \)  
Magnetic flux.

\( \psi \)  
Magnetic linkage flux.

\( \rho \)  
Electric resistivity.

\( \sigma \)  
Electric conductivity.

\( \theta \)  
Temperature.

\( \epsilon \)  
Dielectric permittivity

Roman symbols

\( A \)  
Magnetic potential vector.

\( B \)  
Magnetic flux density vector.

\( B \)  
Magnetic flux density.

\( C_F \)  
Auxiliary magnetomotive force coefficient matrix.

\( D \)  
Electric displacement field vector.
$dB$ Differential element of magnetic flux density.

$dl$ Differential element of distance.

$dt$ Differential element of time.

$E$ Electric field vector.

$F$ Magnetomotive force column vector.

$F$ Magnetomotive force.

$f$ Signal frequency.

$H$ Magnetic field vector.

$H$ Magnetic field.

$I$ Current.

$J$ Electric current density vector.

$j$ Imaginary unit.

$L$ Inductance.

$E$ Magnetization vector.

$N$ Number of turns matrix.

$N$ Number of turns.

$P$ Active power.

$Q$ Reactive power.

$R_m$ Magnetic reluctance matrix.

$R$ Electrical resistance.

$R_{v,h}$ Magnetic reluctance of the vertical/horizontal branches.

$S$ Apparent power.

$T_F$ Complex Fortescue transform matrix.

$T$ Signal period.

$t$ Time.
Current phasor.

Voltage phasor.

Instantaneous velocity of the line element $dl$, for moving circuits.

Voltage.

Magnetic energy density.

Reactance.

Cartesian coordinates.

Complex impedance matrix.

Impedance.

Subscripts

0 Relative to free space (vacuum).

A, B, C Relative to transformer electrical phases.

d Positive sequence (or direct) component.

gnd Relative to the transformer grounding.

h Zero sequence (or homopolar) component.

i Negative sequence (or inverse) component.

m Relative to the magnetization branch.

p Relative to the primary winding.

rms Root mean square.

s Relative to the secondary winding.

Superscripts

FD Relative to the frequency domain.

g Global.

ref Relative to the reference.

TD Relative to the time domain.
-1 Inverse.

T Transpose.
Chapter 1

Introduction

This chapter describes the motivation and goals for this thesis. An outline of this document and its structure is also provided.
1.1 Motivation

It is widely established that power transformers are one of the most critical and expensive components in electric grids ([1], [2], [3], [4]). In particular, distribution transformers comprise the ultimate interface between the grid and the consumer. Failure of such equipment can imply high costs, either due to repairs or system unavailability [1].

The risk of failure in transformers, like in other electric machines, follows a "bathtub" curve (fig. 1.1), which consists in three sections: the commissioning or burn-in stage, which accounts for failures that occur in the early service life of the equipment ("infant mortality"); the normal operation or useful life stage, in which the risk of failure is considered to be minimal, and mostly due to random events; and, finally, the end-of-life or wear-out stage [5].

![Generic bathtub curve representing risk of failure over time in transformers and other electric equipment with similar behavior, as published in [6]. The black line (bathtub curve) incorporates the failure rates due to "infant mortality" (Blue), wear-out (yellow) and constant random failures (red).](image)

In this final stage, the effects of the electrical, mechanical and thermal stresses suffered by the transformer during its normal operation start to become more evident. This inevitable ageing process increases failure rate, thus degrading the overall reliability of the transformer.

Electric grids have existed all over the world for decades. Consequently, there is a large number of transformers which have been in service for a significant amount of time. In their PhD thesis (2016), Yuan Gao [7] shows the age statistics for ENW (Electricity North West) distribution transformers (reportedly over 30000 units) up until 2015 - fig. 1.2. The data suggests that over 40% of the distribution transformers managed by ENW were over 40 years old by 2015 which, Gao states, is possibly due to the major network expansion during 1960s and 1970s.

A different study from 2018 [8] has shown similar data for the Australian grid, with a large population of transmission, sub-transmission and distribution transformers having the age profiles depicted in fig. 1.3,
which clearly shows a large amount of units over 40 years old.

**Figure 1.2: Age profile of a population of over 30000 ENW distribution transformers until 2015, published in [7].**

**Figure 1.3: Age profile of a large population of transmission (primary voltages of 220-500kV), sub-transmission (primary voltages of 110-132kV) and distribution (primary voltages of 11-66kV and secondary voltages higher than 240V) transformers operating in Australia until 2015, published in [8].**

With this paradigm comes a growing concern with the health condition of currently servicing transformers. Consequently, transformer monitoring has become a priority for utilities, in an effort to avoid accidental losses.

### 1.2 Objectives

This study aims at providing relevant advances regarding on-line transformer monitoring methodologies, focusing on the electrical and magnetic behavior of distribution transformers with internal incipient faults and decaying service quality. The objectives can be summarized in the following topics:

1. Development of a FEM simulation model for a typical distribution transformer;
2. Use of the aforementioned model to simulate the behavior of a distribution transformer in the presence of internal incipient winding faults of gradually increasing severity and varying location;

3. Analysis of simulation results to identify patterns in the chosen variables of interest and propose a possible methodology for detecting and locating the studied faults;

4. Performance of an experimental procedure on a low-power three-phase transformer to assess the robustness and scalability of the proposed methodology based on the simulation results.

Regarding the second objective, the simulation of faults in the primary and secondary windings was tested, in all three phases. The gradual faults are modelled by 12 simulations for each of the 5 locations studied. Additionally, faults corresponding to the loss of different fractions of the windings were tested. In total, 1080 simulations were performed.

The analysis techniques mentioned in objective 3 are based on electrical (line voltages and currents and their symmetric components) as well as magnetic (magnetic flux density distribution and flux leakages) quantities. The methodology proposed for fault detection and localization is not based on independent analysis of these variables, but rather on behavioral pattern crossing to obtain relevant information and multiple source confirmation.

1.3 Outline

This thesis is divided into a total of nine chapters, which are listed and briefly described below:

1. **Introduction**: this first introductory chapter in which the motivation, objectives and outline for the thesis are described;

2. **State of the Art**: a literature review on the topic is carried out and the most relevant methodologies for transformer monitoring and fault detection are discussed;

3. **Theoretical Background**: the theoretical fundamentals required to understand the modelling and analysis techniques used in this thesis are given in detail;

4. **Analytical Model**: a theoretical transformer model is established, as a base for comparison to use with the simulation model;

5. **Simulation Model**: a detailed description of the developed FEM simulation model is provided, taking into account the geometry, materials, meshing techniques, electrical circuits and mathematical aspects;

6. **Model Validation**: a comparison between the analytical and simulation models is done in three fronts - an open circuit test, a short-circuit test and a computation of the proper coil inductances - in order to validate the simulation model;

7. **Simulation Results**: The FEM model is simulated for a variety of faults and fault locations, and the main conclusions regarding the variables of interest are taken; a possible methodology for fault
detection and localization is proposed;

8. **Experimental Analysis**: a detailed description of the experimental setup and its preparation process is provided; the results of a set of preliminary tests are compared before and after performing alterations on the setup, to validate its operating condition; a set of fault emulation tests are performed and the results are analyzed within the scope of this work.

9. **Conclusions**: a final chapter summarizing the main conclusions and relevant observations of this thesis, as well as providing guidelines for future work.
Chapter 2

State of the Art

In this chapter, a topic overview on transformer failures, incipient faults and state of the art monitoring techniques is provided.
2.1 Transformer failures

As previously mentioned, transformers constitute key elements of electrical grids, and their failure can represent extremely high costs for utilities. Therefore, failure identification and classification have been the focus of many studies.

In 2015, Jan, Afzal and Khan [9] studied a population of 11kV:220V WAPDA (Water and Power Development Authority, Pakistan) distribution transformers, in an effort to identify and classify the main types of failure occurring in that type of transformer. Table 2.1 summarizes the extensive failure distinction made in [9].

Table 2.1: Summary of the failure location and cause identification published by Jan, Afzal and Khan in [9].

<table>
<thead>
<tr>
<th>Failure Location</th>
<th>Fault Type</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windings</td>
<td>Dielectric</td>
<td>Turn-to-turn insulation breakdown, resulting in winding flashover and turn-to-turn short-circuit.</td>
</tr>
<tr>
<td></td>
<td>Hotspots</td>
<td>Joule losses cause temperature increase and formation of hotspots, which decreases winding physical strength.</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>Distortion, loosening or displacement of the windings, resulting in poor performance and tearing of turn ratio.</td>
</tr>
<tr>
<td>Bushings</td>
<td>Overheating</td>
<td>Transformer vibrations cause loosening of conductors, which results in overheating and damage to insulating paper and oil.</td>
</tr>
<tr>
<td></td>
<td>Breakdown</td>
<td>Overvoltages cause partial discharges and damage to the bushes, leading to their breakdown.</td>
</tr>
<tr>
<td></td>
<td>Water ingress</td>
<td>Ageing and water ingress, or excessive dielectric losses can cause bushing seal breaking.</td>
</tr>
<tr>
<td></td>
<td>Aged oil</td>
<td>Lack of oil maintenance can cause internal over-flashing.</td>
</tr>
<tr>
<td>Tap Changer</td>
<td>Run-through</td>
<td>Delay in change of turn ratio caused by flux of residue in tap changer relay, due to polluted oil.</td>
</tr>
<tr>
<td></td>
<td>Motor</td>
<td>Lack of maintenance causes asynchronous connection between motor driver and tap, resulting in erroneous tap positioning. Motor breakdown can also happen due to overvoltages or misuse of tap changer.</td>
</tr>
<tr>
<td></td>
<td>Old capacitors</td>
<td>Old or burnt-out capacitors in the motor cause loss of control over direction of movement.</td>
</tr>
<tr>
<td></td>
<td>Regular use</td>
<td>Over-use of the tap changer degrades its spring, eventually causing it to break.</td>
</tr>
<tr>
<td>Core</td>
<td>Lamination</td>
<td>Lamination breakdown increases eddy currents and causes overheating, which damages the winding and oil.</td>
</tr>
<tr>
<td>Tank</td>
<td>Oil spills</td>
<td>Reduction of oil (cooling fluid), resulting in loss of cooling capability and overheating.</td>
</tr>
<tr>
<td>Protection System</td>
<td>Failure to operate</td>
<td>Failure of Bucholz protection, surge protector, pressure relief valve or sudden pressure relays, causing the transformer to operate under fault stress instead of disconnecting it.</td>
</tr>
<tr>
<td>Cooling System</td>
<td>Overheating and errors</td>
<td>Failure of fans or fluid circulation systems cause overheating. Thermostat failures lead to erroneous temperature measurements, which can disguise thermal stress.</td>
</tr>
</tbody>
</table>

In [9], the authors also mention that fault classification systems should follow a standard, such as USA military standard MIL-STD-1629A, which is the most commonly used standard throughout the world in the past 30 years. Such document defines the procedures for performing failure mode, effect and
criticality analysis (FMECA) in three stages, described in tabs. 2.2, 2.3 and 2.4 (adapted from [9]), in which failures are classified according to their severity, probability of occurrence and detection capability, respectively.

Table 2.2: Severity classification categories for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]).

<table>
<thead>
<tr>
<th>Category</th>
<th>Severity</th>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>Minor</td>
<td>Primary function is possible but urgent repair is required</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td>Marginal</td>
<td>Reduced ability to perform primary function</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>Critical</td>
<td>Loss of primary function</td>
<td>3</td>
</tr>
<tr>
<td>I</td>
<td>Catastrophic</td>
<td>Equipment rendered unfit to operate</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 2.3: Occurrence classification levels for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]). $P$ is the probability of occurrence.

<table>
<thead>
<tr>
<th>Level</th>
<th>Occurrence</th>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Extremely unlikely</td>
<td>$P &lt; 0.1%$</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>Remote</td>
<td>$0.1% &lt; P &lt; 1%$</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td>$1% &lt; P &lt; 10%$</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>Reasonably probable</td>
<td>$10% &lt; P &lt; 20%$</td>
<td>4</td>
</tr>
<tr>
<td>A</td>
<td>Frequent</td>
<td>$P &gt; 20%$</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2.4: Detection and identification capability classification categories for transformer failures, as defined by military standard MIL-STD-1629A (adapted from [9]).

<table>
<thead>
<tr>
<th>Level</th>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Easy identification</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>Fair identification</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>Rough identification but easy detection</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>Fair detection</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>Rough detection</td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>Complementary test required for detection</td>
<td>6</td>
</tr>
</tbody>
</table>

The overall priority number (PRN) is defined according to the classification methodology described in tabs. 2.2 - 2.4 as (2.1), where $1 \leq \text{PRN} \leq 120$ [9]. This metric can then be used together with failure statistics to establish priority rating for the different failures presented in tab. 2.1.

$$\text{PRN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \quad (2.1)$$

A study from 2009 performed by a CIGRÉ working group [10] compiled data from FNN (Germany) and Eskom Research and Innovation (South Africa) to provide a statistical analysis on transformer failures for generator step-up (GSU), transmission and distribution transformers - fig. 2.1.

For distribution transformers, of the classified failures, winding failures are by far the most common, followed by bushing and tap changer failures. Thus, winding failures will potentially have the highest PRN among distribution transformer failures.
Recalling tab. 2.1, one type of winding failure is the dielectric breakdown between turns, causing turn-to-turn short-circuits and, consequently, loss of a certain amount of turns. This kind of fault, being the most common, will be the main focus of this work.

### 2.2 Monitoring techniques

Transformer monitoring techniques can be divided into two main categories, depending on whether they require the transformer to be taken off service.

Most off-line monitoring techniques are well established and have been studied in detail. For that reason, among them are some of the most effective and commonly used transformer monitoring methodologies. However, the transformer is required to be taken aside for inspection (hence off-line), which can represent high costs for utilities due to temporary equipment unavailability. Therefore, focus has been recently shifting towards on-line techniques, which allow the transformer condition to be continuously monitored while it is in service.

In following subsections, a brief summary of the most common off-line and on-line monitoring techniques is presented.
2.2.1 Off-line monitoring

2.2.1.1 Dissolved gas analysis

Dissolved gas analysis (DGA) is one of the most well-established transformer monitoring techniques. The principle of DGA is to associate the presence and concentration of certain gases in the oil tank with their known causes. The measurement of gas concentration ratios immediately allows one to conclude whether a certain fault occurred. Tables 2.5 and 2.6 (adapted from [11]) summarize the relations between dissolved gases and the corresponding faults, and define the concentration ratio references for fault diagnosis, according to IEC 60599 standard.

Table 2.5: Dissolved gases and their main sources, adapted from [11].

<table>
<thead>
<tr>
<th>Gas</th>
<th>Symbol</th>
<th>Main Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>Partial discharge (PD), power discharge, thermal fault, rust, galvanized parts</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>Corona partial discharge, low and medium temperature thermal faults</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>Low and medium temperature thermal faults</td>
</tr>
<tr>
<td>Ethylene</td>
<td>C₂H₄</td>
<td>High temperature thermal faults</td>
</tr>
<tr>
<td>Acetylene</td>
<td>C₂H₂</td>
<td>Hot-spots, low and high energy discharges</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>Thermal fault involving cellulose, oil oxidation</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>Ageing, thermal fault involving cellulose, oil oxidation</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>Exposure to atmosphere; leaky gasket, air breathing conservator or bladder</td>
</tr>
</tbody>
</table>

Table 2.6: Dissolved gas ratio references for fault diagnosis according to IEC 60599, adapted from [11].

<table>
<thead>
<tr>
<th>Fault</th>
<th>Designation</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial discharge</td>
<td>PD</td>
<td>C₂H₂/C₂H₄ &lt; 0.1, DΗ₂/H₂ &lt; 0.2, C₃Η₄/C₂H₆ &lt; 0.2</td>
</tr>
<tr>
<td>Low energy discharge</td>
<td>D1</td>
<td>&gt; 1, 0.1 – 0.5, &gt; 1</td>
</tr>
<tr>
<td>High energy discharge</td>
<td>D2</td>
<td>0.6 – 2.5, 0.1 – 1, &gt; 2</td>
</tr>
<tr>
<td>Thermal fault (T &lt; 300)</td>
<td>T1</td>
<td>- &gt; 1 &lt; 1</td>
</tr>
<tr>
<td>Thermal fault (300 &lt; T &lt; 700)</td>
<td>T2</td>
<td>&lt; 0.1 &gt; 1 1 – 4</td>
</tr>
<tr>
<td>Thermal fault (T &gt; 700)</td>
<td>T3</td>
<td>&lt; 0.2 &gt; 1 &gt; 4</td>
</tr>
</tbody>
</table>

2.2.1.2 Furan analysis

Furan analysis is a powerful tool for assessing the condition of transformer cellulose insulation. The working principle is analogous to that of DGA. However, furan analysis focuses on detecting the presence of furanic compounds. These organic compounds, which are listed below, are specific to the degradation of insulation paper inside transformers and are only generated when insulation paper degrades [12].

- **2FAL**: 2-furaldehyde
- **5M2F**: 5-methyl-2-furaldehyde
• **5H2F**: 5-hydroxymethyl-2-furaldehyde

• **2ACF**: 2-acetyl furan

• **2FOL**: 2-furfurol

### 2.2.1.3 Winding resistance and turn ratio measurements

Turn ratio and winding resistance tests are a part of the routine maintenance operations performed on power transformers [13].

The periodic measurement of the transformer turn ratio allows one to assess the current health condition of the transformer and predict its evolution based on observed trends. Furthermore, it can help determine whether winding damage has occurred [14].

According to IEEE Std 62-1995 (IEEE standard for turn ratio field testing), for the transformer to be considered healthy, the turn ratio measurements should always be within $\pm 0.5\%$ of the rated winding voltage ratio. Higher deviations with respect to nameplate values registered during a field test may indicate [14]:

- Insulation failures, either turn-to-turn insulation breakdown, resulting in winding flashover, or more severe insulation failures (inter-winding or winding-to-ground);

- Tap changer failures.

Transformer winding resistance measurements, on the other hand, are an important tool for [15]:

- Monitoring Joule losses in the windings;

- Calculating and predicting temperature increases;

- Assessing potential damage to the windings.

### 2.2.1.4 Dissipation factor test

Monitoring the condition of solid insulation, either cellulose or bushings, is possible by focusing on the dielectric dissipation factor (DF) [16], which is mathematically defined as the tangent of the dielectric loss angle $\delta$ - eq.(2.2).

$$DF = \tan(\delta)$$

This technique provides information on potential water ingress, which disturbs the normal behavior of the insulation and affects the dissipation factor. Standard on-site tests, made at rated frequency, can only detect faults at an advanced stage, which is why they should be complemented by a frequency response test of the dielectric. Such measurements can be used to detect faults early on and distinguish the cause (either moisture or high oil conductivity) [16].
2.2.1.5 Leakage reactance measurement

The leakage reactance of a transformer winding is directly linked to magnetic dispersion, i.e., magnetic flux leakage. An increase in flux leakage and, consequently, leakage reactance is typically linked to mechanical displacement or deformation of the windings. Therefore, leakage reactance measurements can provide useful information on the condition of the windings [16].

2.2.1.6 Frequency response analysis

Sweep Frequency Response Analysis (SFRA) consists in imposing a sinusoidal voltage of varying frequency to each transformer coil individually. This test can help mechanical or electrical problems in the windings, terminals or core [16].

Frequency Response of Stray Losses (FRSL) is another form of frequency response analysis. It analyzes the behavior of the resistive component of the short-circuit impedance for a range of frequencies. This test provides the only electrical method to identify short-circuits between parallel strands and local overheating due to excessive eddy current losses [16].

Both these methods are not included in routine tests. However, they should be used for advanced diagnostics [16].

2.2.2 On-line monitoring

2.2.2.1 Electrical monitoring

With the concept of smart grids, there is an increasing concern with sensor installation. The measurement of electrical quantities, namely, the line voltages and currents, is one of the least intrusive on-line monitoring methods, and can provide relevant information for incipient fault detection [17]. By placing sensors in the primary or secondary terminals of the transformer, it is possible to obtain not only the line voltages and currents, but also, indirectly, a number of different variables, such as the apparent power per phase, the power factor and the harmonic content.

Over the years, a wide variety of different electrical monitoring methods have been proposed, for example:

- Direct monitoring of voltages and currents [17];

- Space vector methods and transforms, such as the Park transformation [18];

- Time-frequency analysis based discrete transformation methods, such as the Discrete Wavelet Transform [19].

Electrical monitoring methods are very attractive, in the sense that they are low-cost alternatives to the more commonly used transformer monitoring techniques [19].
2.2.2.2 Partial discharge detection

Monitoring of partial discharge (PD) phenomena is a common technique for assessing the condition of transformer insulation, and detect local defects in the insulation that can be initiated and enlarged by the destructive nature of PD [20]. The detection of partial discharges can be done indirectly, through DGA (previously discussed). However, more recent, on-line methodologies have been developed. One of those is the direct electrical discharge measurement, according to IEC 60270. The other technique uses ultra-high frequency (UHF: 300 MHz - 3 GHz) sensors for PD detection through electromagnetic measurement. The latter has been gaining relevance in the near past [20].

2.2.2.3 Thermal monitoring

Thermal ageing and degradation of the insulation affects the transformer lifetime, since cellulose degradation caused by overheating is irreversible. It is widely accepted that the insulation degradation approximately doubles with every 6°C increase of temperature [21]. On-line temperature monitoring, especially in the upper section of the transformer, which typically has higher temperatures [22], is therefore one of the most relevant methodologies for real-time condition assessment.

Transformer lifetime is directly affected by oil temperature, as well as winding hot-spot temperature. Both these parameters are directly influenced by the load, ambient temperature and Joule losses in the windings [23]. The hot-spot temperature is considered to be particularly critical, since exceeding a certain value can lead to insulation faults and premature thermal ageing [24].

Up until recently, distribution transformer hot-spot temperature estimation was done according to the power transformer loading models established by IEEE and IEC [21]. In this kind of model, hot-spot temperature ($\theta_{HS}$) is calculated taking into account the top-oil temperature ($\theta_{TO}$) and the rise in top-oil temperature registered during the heat-run test ($\Delta\theta_{HR}$) [21]. This corresponds to eq. (2.3), where $I_R$ is the rated current, $I$ is the rated current for a different tap changer position and $m$ is an empirical parameter related to load variations and recommended by the loading guides.

$$\theta_{HS} = \theta_{TO} + \Delta\theta_{HR} \left(\frac{I}{I_R}\right)^{2m}$$ (2.3)

However, with the expansion of electric grids and the appearance of increasingly volatile loads, the search for more accurate hot-spot temperature monitoring methods is gaining relevance [25].

Various studies have provided significant advances regarding this topic, suggesting a wide range of methods, of which the following should be highlighted:

- The addition of real-time load information to the mathematical estimation model used for power transformers [24];
- The use of neural-fuzzy networks for hot-spot temperature modeling, together with a statistical fault diagnosis method (Local Statistical Approach to Fault Diagnosis) for early failure detection [26];
• Fiber optics based measurement systems [25] [22].

Of the aforementioned methodologies, the use of fiber optics is considered to be the most relevant, since, unlike the remaining methods, it provides direct measurements of hot-spot temperature, provided sensor positioning is correct. Such method has been gaining relevance over the years [25].

### 2.2.2.4 Vibro-acoustic monitoring

Transformer vibrations typically originate either from the iron core or from the windings [27]. According to [28], core vibrations are the most significant, since the main source of noise and vibration on power transformers is the motion and periodic mechanical deformation of the magnetic core due to magnetostriction phenomenon and to magnetomotive forces, originated by a fluctuating magnetic flux induced by the coils. Figure 2.2(a) (published in [3]) illustrates this process. Winding vibrations, on the other hand, are a consequence of Lorentz forces exerted upon the windings due to the interaction of winding currents with leakage fields [28]. Figure 2.2(b), adapted from [27], summarizes the most significant vibration transmission chains in transformers.

![Vibro-acoustic monitoring diagram](image)

**Figure 2.2:** (a) Illustration of magnetostriction phenomena, as published in [3]. (b) Transformer vibration transmission chains, adapted from [27].

Vibro-acoustic analysis is a powerful tool, which enables the on-line monitoring of the mechanical stresses suffered by transformers.

In a 2014 study [27], the results of FEM simulations indicated that the top center of the transformer cabinet would be most sensitive spot to vibrations, which is a piece of relevant information when considering the positioning of sensors for vibration monitoring. The monitoring method suggested in [27] is based
on data acquired from piezoelectric acceleration sensor placed on the top wall of the oil tank. The study had rather relevant conclusions, which can be summarized as follows:

- Iron core vibrations are directly affected by the voltage level and core slackness. For significant vibrations at the measuring point (top center of oil tank), it was registered that vibration frequencies were mostly odd multiples of 50Hz;

- Winding vibrations are impacted by the current level and winding slackness. Vibrations originated by the windings and measured at the top center of the oil tank are mostly associated with frequencies which are even multiples of 50Hz;

- Slackness of the iron core or windings greatly increases vibration amplitude.
Chapter 3

Theoretical Background

This chapter provides the theoretical background for this thesis. Basic notions will be given regarding the most fundamental aspects of the following chapters.
3.1 Fortescue transformation and symmetrical components

The Fortescue transformation is a mathematical tool for three-phase system analysis. It allows one to simplify analysis by decomposing the three-phase system, may it be balanced or unbalanced, into three independent balanced systems, called the positive (direct), negative (inverse) and zero (homopolar) sequence components - or, more simply, symmetrical components. Thus, the phase quantities can be expressed as linear combinations of the corresponding symmetrical components. In power system analysis, the application of the Fortescue transformation is particularly helpful since it can easily show evidence that a system might be operating under abnormal conditions, i.e., unbalanced or faulty. For example, the existence of a zero sequence current might indicate a phase-to-ground fault.

Mathematically, the Fortescue transformation is a complex linear transformation given by eq. (3.1), where \( \alpha \) is a complex 120° rotation coefficient.

\[
T_F = \begin{bmatrix}
1 & 1 & 1 \\
\alpha^2 & \alpha & 1 \\
\alpha & \alpha^2 & 1
\end{bmatrix} \quad \alpha = e^{j\frac{2\pi}{3}}
\]  

(3.1)

For future reference, let it be established that the notation for the symmetrical components is the following:

- The subscript \( d \) refers to the positive sequence or direct component;
- The subscript \( i \) refers to the negative sequence or inverse component;
- The subscript \( h \) refers to the zero sequence or homopolar component.

Although the symmetrical components are referred to in the text as the positive, negative and zero sequence, which is represented with the subscripts \(+ - 0\), it was decided to adopt the notation \( dih \), which is more in line with the notation used at IST.

3.1.1 Symmetrical components for voltages and currents

Given the phase voltages and currents, the corresponding symmetrical components can be obtained according to eq. (3.2).

\[
V_{dih} = T_F^{-1} \cdot V_{abc} \quad I_{dih} = T_F^{-1} \cdot I_{abc}
\]  

(3.2)

3.1.2 Apparent power in terms of symmetrical components

Sometimes, it may also be useful to determine the apparent power in terms of its symmetrical components. To that end, one must first express the apparent power, \( S \), as a function of the symmetrical component voltage and current vectors defined in eq. (3.2). The starting point for this task must always
be the definition of apparent power in terms of the phase voltages and currents - eq. (3.3) [29].

\[ S = V_{abc}^T I_{abc}^* \]  

(3.3)

By inverting the relations expressed in (3.2), and after some algebraic manipulation, one can write the apparent power in the form of eq. (3.4), where \( T_F^* \) denotes the element-wise conjugate of \( T_F \).

\[ S = V_{dih}^T T_F^T T_F I_{dih} \]  

(3.4)

This expression can then be simplified into eq. (3.5) by noting that the operation \( T_F^T T_F \) results in a diagonal matrix with all elements equal to 3. Note that one can only substitute this resulting matrix by a scalar because the final result is a single complex quantity.

\[ S = 3 V_{dih}^T I_{dih} \]  

(3.5)

The symmetrical components of the apparent power can then be defined by expanding eq. (3.5) and evidencing the terms corresponding to the positive, negative and zero sequence contributions to the total power - eqs. (3.6) and (3.7).

\[ S = 3 (V_d I_d^* + V_i I_i^* + V_h I_h^*) = S_d + S_i + S_h \]  

(3.6)

\[ S_{dih} = 3 \begin{bmatrix} V_d I_d^* \\ V_i I_i^* \\ V_h I_h^* \end{bmatrix} \]  

(3.7)

Note that the resulting symmetrical components of the apparent power have an associated scaling factor of 3 due to the fact that the conventional Fortescue transformation here used is a voltage invariant transformation. A power invariant transformation could be applied by scaling the transformation matrix \( T_F \) by a factor of \( \frac{1}{\sqrt{3}} \), which would drop the scaling factor in eq. (3.7), but would decrease the symmetrical component values obtained for the voltages and currents by \( \frac{1}{\sqrt{3}} \). Nevertheless, the resulting total apparent power, \( S \), would remain constant, as this operation represents only a switch in mathematical convention (from a voltage invariant to a power invariant transformation).

### 3.1.3 Symmetrical component impedance matrix

When studying a power system under abnormal operating conditions, determining its impedance matrix in terms of symmetrical components is useful, since it allows for a simpler system analysis, especially when it comes to fault conditions.

In order to compute the symmetrical component representation of the impedance matrix, one must first
establish as a starting point the relations expressed in eq. (3.8).

\[ V_{abc} = Z_{abc}I_{abc} \quad V_{dih} = Z_{dih}I_{dih} \] (3.8)

A combination of eqs. (3.2) and (3.8) can be performed, resulting in eq. (3.9).

\[ T_FZ_{dih}I_{dih} = Z_{abc}T_FI_{dih} \] (3.9)

By comparing both sides of the equation and solving with respect to \( Z_{dih} \), one arrives at the general expression for the symmetrical component impedance matrix in terms of the original impedance matrix of the system - eq. (3.10).

\[ Z_{dih} = T_F^{-1}Z_{abc}T_F \] (3.10)

Note that the resulting impedance matrix is strictly diagonal, due to the fact the Fortescue transformation breaks the coupled three-phase system into three decoupled systems. Thus, \( Z_{dih} \) must be of the form described in eq. (3.11).

\[
\begin{bmatrix}
Z_d & 0 & 0 \\
0 & Z_i & 0 \\
0 & 0 & Z_h
\end{bmatrix}
\] (3.11)

### 3.1.4 Application of the symmetrical components to three-phase transformers

Three-phase transformers are characterized by a 6 equation system, since there are, in total, six coils (2 in each of the 3 core legs). Although the Fortescue transformation is normally applied to three equation systems, it can be adapted to accommodate the increased dimension of the system in question. Thus, one can define a global Fortescue transformation matrix, \( T^g_F \), that accounts for the primary and secondary windings of the transformer, which is defined in eq. (3.12). Note that \( T^g_F \) is a \( 6 \times 6 \) matrix comprised of four \( 3 \times 3 \) sub-matrices.

\[
T^g_F = \begin{bmatrix}
T_F & 0 \\
0 & T_F
\end{bmatrix}
\] (3.12)

Once the global Fortescue transformation for the three-phase transformer has been defined, it is possible to couple the primary and secondary systems in a single transformation, allowing for the calculation of the symmetrical component systems for any variable in both windings at once. Applying this principle to the variables studied in sections 3.1.1 through 3.1.3, one arrives at eqs. (3.13), (3.14) and (3.15), which give the global expressions for the symmetrical components of the voltages, currents and impedance for
a three-phase transformer [29].

\[
V_{\text{dih}}^g = (T_F^g)^{-1} V_{\text{abc}}^g = \begin{bmatrix} V_p^d \\ V_p^i \\ V_s^d \\ V_s^i \end{bmatrix}, \quad I_{\text{dih}}^g = (T_F^g)^{-1} I_{\text{abc}}^g = \begin{bmatrix} I_p^d \\ I_p^i \\ I_s^d \\ I_s^i \end{bmatrix} \tag{3.13}
\]

\[
S_{\text{dih}}^g = \begin{bmatrix} S_p^d \\ S_p^i \\ S_s^d \\ S_s^i \end{bmatrix} = 3 \begin{bmatrix} V_p^d I_p^d & V_p^d I_p^i & V_p^d I_s^d & V_p^d I_s^i \\ V_p^i I_p^d & V_p^i I_p^i & V_p^i I_s^d & V_p^i I_s^i \\ V_s^d I_p^d & V_s^d I_p^i & V_s^d I_s^d & V_s^d I_s^i \\ V_s^i I_p^d & V_s^i I_p^i & V_s^i I_s^d & V_s^i I_s^i \end{bmatrix} \tag{3.14}
\]

\[
Z_{\text{dih}}^g = (T_F^g)^{-1} Z_{\text{abc}}^g T_F^g = \begin{bmatrix} Z_p^d & 0 & 0 & 0 & 0 \\ 0 & Z_p^i & 0 & 0 & 0 \\ 0 & 0 & Z_s^d & 0 & 0 \\ 0 & 0 & 0 & Z_s^i & 0 \\ 0 & 0 & 0 & 0 & Z_h^s \end{bmatrix} \tag{3.15}
\]

Note that in the case of the apparent power, the usage of a global transformation matrix brings no advantage, since eq. (3.14) is reached by solving the primary and secondary systems separately.

### 3.2 Effective B-H curve

#### 3.2.1 Effective B-H curve approximation and its implications

Typically, the behavior of a ferromagnetic material is represented by its B-H curve, which is generically represented in fig. 3.1 for different materials. This type of curve shows a non-linear behavior for such materials, which is particularly undesirable when modelling them for computational use, since computational time increases in the presence of non-linearities.

However, when the magnetic fields within the material are approximately sinusoidal, i.e., when there is almost no saturation (which generally holds true for materials operating within their rating), the non-linear material can be approximated by a linear one with the same magnetic energy density. This approximation is called the effective B-H curve, and it consists in computing an equivalent curve which depicts a linear relation between B and H. To that end, one must start by defining an equivalent sinusoidal magnetic field \( H_{eq}(t) \) - eq. (3.16) - of amplitude \( H_{eff} \sqrt{2} \) (where \( H_{eff} \) is the RMS of \( H_{eq} \)).
\[ H_{eq}(t) = H_{eff} \sqrt{2} \sin(2\pi ft) \] (3.16)

There are various methods to determine the equivalent magnetic permeability when the imposed variable is \( H(t) \), or, in other words, the magnetization current. However, when one imposes the magnetization voltage instead, and, consequently, the magnetic flux density \( B(t) \), an adaptation is in order. Note that, in either case, the imposed quantity should be sinusoidal, as most methods to compute the equivalent curve rest on this assumption. In this case, the imposed \( B(t) \) should be of the form defined in eq. (3.17), in which \( B_{eff} \) is the RMS value of \( B(t) \).

\[ B(t) = B_{eff} \sqrt{2} \sin(2\pi ft) \] (3.17)

The preferred method to perform the curve transformation is one analogous to the Average Energy Method [30], in which the average value of the magnetic energy density is assumed to remain constant while performing the curve transformation. Thus, for the same amplitude of \( B(t) \), \( H_{eq}(t) \) is a sinusoid with the amplitude required to generate the same magnetic energy as the actual magnetic field \( H(t) \).

From the B-H curve, the average value of the magnetic energy density for a sinusoidal field with period \( T \) can be written as in (3.18), where one has taken advantage of the fact that the \( H(B) \) function from the B-H curve shows quarter-period symmetry.

\[ \langle \hat{w}_m \rangle = \frac{4}{T} \int_0^T \left( \int_{B(0)}^{B(t)} H(B)dB \right) dt \] (3.18)

On the other hand, since the equivalent magnetic field \( H_{eq} \) is perfectly sinusoidal, it yields the average
value for the magnetic energy density given by (3.19).

\[
\langle \hat{w}_m \rangle = \frac{1}{2} \langle H_{eq}(t) \cdot B(t) \rangle = \frac{1}{2} \frac{B_{eff}^2}{\mu_{eq}}\\
\]

(3.19)

By comparing eqs. (3.18) and (3.19), one arrives at the definition of \( \mu_{eq} \) and \( H_{eq} \) required to conserve the average magnetic energy from the B-H curve - eqs. (3.20) and (3.21).

\[
\mu_{eq} = \frac{B_{eff}^2}{\frac{8}{T} \int_0^T \left( \int_{B(0)}^{B(t)} H(B) dB \right) dt}\\
\]

(3.20)

\[
H_{eff} = \frac{B_{eff}}{\mu_{eq}} = \frac{1}{B_{eff}} \frac{8}{T} \int_0^T \left( \int_{B(0)}^{B(t)} H(B) dB \right) dt\\
\]

(3.21)

By applying eq. (3.21) for different values of the magnetic flux density \( B \), one gets the effective B-H curve for the material in question. The horizontal axis contains the values of \( H_{eff} \), which is the RMS amplitude of the equivalent sinusoidal magnetic field \( H_{eq}(t) \), and the vertical axis gives the corresponding RMS amplitude of the magnetic flux density. Note that, as previously mentioned, since the chosen method assumes the imposed flux density \( B(t) \) to be sinusoidal, the values of \( B_{eff} \) in the vertical axis of the effective B-H curve correspond indeed the RMS amplitude of \( B(t) \). This is illustrated in more detail in section 3.2.2, where an application example carried out.

3.2.2 Example: application of the effective curve approximation to the 35PN300 Silicon Steel (NGO)

Distribution transformers generally have a core made out of non-grain-oriented silicon steel, such as the 35PN300. Thus, the application of the above described method to this material is of particular interest.

To that end, a Matlab script (based in the work of [30] and available in appendix A) was developed, which determines, for each point in the B-H curve, the RMS (effective) value of the equivalent magnetic field \( H_{eq} \) through eq. (3.21). Note that the integrals are determined through numerical methods.

Figure 3.2 shows a comparison between the original and effective B-H curves for the 35PN300 Silicon Steel.

Note that the values of \( B \) and \( H \) present in the effective curve do not correspond to those of the original DC B-H curve. This is due to the fact that while the B-H curve is in the time domain, the effective curve represents a set of RMS values corresponding to purely sinusoidal quantities. Thus, while a given pair of sinusoidal waveforms \( B(t) \) and \( H(t) \) represent an operating region in a conventional B-H curve, they correspond to a single operating point in the effective B-H curve.

To illustrate this approximation, two different situations were considered, with and without material saturation, and the results yielded by both the original AC B-H curve and the effective curve were compared. In a first instance, a sinusoidal magnetic flux density, \( B(t) \), of amplitude 1T was imposed. Figure 3.3
Figure 3.2: DC (a) and effective (b) B-H curves for the 35PN300 Silicon Steel (non-grain oriented)

Figure 3.3: Magnetic field $H(t)$ (a) and corresponding operating region on the B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 1\, \text{T}$ is imposed.

Figure 3.4: Approximated magnetic field $H(t)$ (a) and corresponding operating point on the effective B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 1\, \text{T}$ is imposed.

shows the corresponding time-harmonic magnetic field, $H(t)$ and the respective operating region in
the AC B-H curve. Analogously, fig. 3.4 presents the reconstructed waveform for $H(t)$, assumed to be sinusoidal, and highlights the operating point on the effective B-H curve. By inspecting figs. 3.3 and 3.4, one readily arrives at the conclusion that the magnetic field waveforms, $H(t)$, yielded by either method are identical. This proves, as expected, that the effective B-H curve is a very accurate approximation when working within the linear region of the B-H curve, i.e., in the absence of saturation.

However, in the presence of heavy saturation, this approximation greatly loses its accuracy. This is shown in figs. 3.5 and 3.6, where both curves are compared when a sinusoidal magnetic flux density, $B(t)$, of amplitude $2T$ is imposed.

![Figure 3.5: Magnetic field $H(t)$ (a) and corresponding operating region on the B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 2T$ is imposed.](image)

![Figure 3.6: Approximated magnetic field $H(t)$ (a) and corresponding operating point on the effective B-H curve (b) when a sinusoidal magnetic flux density $B(t)$ of amplitude $B_{\text{max}} = 2T$ is imposed.](image)

Comparing both figs. 3.5 and 3.6, it quickly becomes evident that, contrary to when saturation is absent, the waveforms for $H(t)$ obtained from the original and effective B-H curves are not at all identical. In fact, the B-H curve yields a typical waveform of a heavily saturated magnetic field, which is non-sinusoidal. On the other hand, while resorting to the effective curve approximation, all quantities are assumed
to be sinusoidal, which leads to a very different $H(t)$ waveform. However, the average magnetic energy density remains constant regardless of the curve transformation, which allows for the results to be energy-invariant between both curves. This leads to the inevitable conclusion that heavy saturation greatly degrades the accuracy of this approximation. Nevertheless, this phenomenon can still be accounted for to some extent while obtaining results that are not exact but can be regarded as accurate to a satisfactory degree.

At this point, it is relevant to introduce the context under which this approximation shall be used in the scope of this work.

Transformers (distribution or otherwise) are generally designed such that, while working within rating, all electrical and magnetic quantities can be seen as nearly sinusoidal. This is particularly favorable when considering the use of the effective B-H curve approximation, since such assumption holds true for most distribution transformers. Thus, this approximation can be used for transformer analysis while keeping results accurate. Furthermore, its application is desirable in the sense that a sinusoidal regime enables the use of frequency domain techniques, such as phasor mathematics, greatly simplifying analytical methods.
Chapter 4

Analytical model

An analytical model of a transformer is developed to establish a base for comparison for the following chapters.
4.1 Single-phase equivalent circuit of a three-phase transformer

When analyzing three phase transformers operating under normal conditions, one usually assumes, for simplicity, that these static electric machines are perfectly balanced, i.e., all electrical quantities are strictly sinusoidal, have the same amplitude and frequency, and are separated by $120^\circ$. Note that this assumption is never true for a real transformer, since they are inherently unbalanced due to asymmetries in the magnetic circuit, for example. However, these unbalances are relatively small, which allows one to take the aforementioned assumption while still getting satisfactorily accurate results.

When all three phases are assumed to be perfectly symmetric, the three phase system can be reduced to an equivalent single phase circuit, which represents the behavior of one phase (usually phase A) and can be easily transposed to the remaining phases by performing a phase-shift on the phasors obtained. Such a circuit is represented in fig. 4.1, where the different branches of the circuit have been highlighted. Note that the parameters corresponding to the secondary winding are represented with an apostrophe (’) since their values are referred to the primary.

![Figure 4.1: Single-phase equivalent circuit for a balanced three-phase transformer.](image)

The circuit of fig. 4.1 allows one to perform a set of simple calculations which indicate the expected results for a balanced transformer.

4.2 Open-circuit test

The open circuit test of a transformer is performed by feeding the primary with a three-phase balanced system, at rated voltage, and keeping the secondary in open circuit. Applying this situation to the equivalent circuit of fig. 4.1, it is possible to note that there will be no current flowing in the secondary, and thus the current measured in the primary winding is the magnetization current, as evidenced in fig. 4.2.

The circuit of fig. 4.2 can be further simplified by noting that, since no current flows in the secondary, the electrical parameters of the secondary winding do not influence the behavior of the transformer while in open circuit. Consequently, the voltage in the secondary is equal to the voltage in the magnetization branch.
branch, i.e., the voltage resulting from the magnetization of the transformer core. Figure 4.3 illustrates this simplification.

By applying KVL and KCL to the circuit, one can easily extract the conditions that define the open-circuit operation of a balanced three-phase transformer - eqs. (4.1) through (4.4)

\[ I_s' = 0 \] (4.1)

\[ I_m = I_p \] (4.2)

\[ V_s' = (R_m \parallel jX_m) I_m \] (4.3)

\[ V_p = (R_p + jX_p) I_m + V_s' = [R_p + jX_p + (R_m \parallel jX_m)] I_m \] (4.4)
4.3 Short-circuit test

A short-circuit test on a transformer can be performed by injecting a balanced three-phase current system into the primary winding, at the corresponding rating, and short-circuiting all three phases on the secondary side. Figure 4.4 shows the equivalent circuit for such configuration.

Since the secondary branch is terminated by a short-circuit, its total impedance will be equal to that of the coil itself. In this situation, noting that the impedance of the magnetization branch is much higher, one can simplify the circuit by stating that the magnetization current is neglectable when compared to the winding currents. Such approximation yields the simplified circuit of fig. 4.5.

A few conclusions can be derived from the analysis of the simplified circuit. The most obvious is that, since the secondary winding is short-circuited, its voltage will be null. On the other hand, the voltage measured on the primary side is equal to the voltage drop in the primary and secondary windings when the primary is fed at rated current. Furthermore, the magnetization branch has been neglected, which implies that the core is expected to be strongly demagnetized when the transformer is operating in short-circuit. Equations (4.5) through (4.7) describe the behavior of the equivalent circuit of fig. 4.5.
\[ I_m \approx 0 \]  \hspace{1cm} (4.5)

\[ I_p \approx I_s' \]  \hspace{1cm} (4.6)

\[ V_p \approx [(R_p + R_s') + j(X_p + X_s')] I_p \]  \hspace{1cm} (4.7)

4.4 Inductance matrix computation through core geometry analysis

When analyzing this kind of system, it is important to start by stating the conditions under which the analytical model is valid, i.e., the assumptions on which it is based. The analytical transformer model is based on three essential assumptions [29], namely:

1. The system is operating in the linear region of the B(H) curve;
2. The magnetic field inside the transformer core is uniform;
3. Magnetic dispersion is neglected, i.e., the magnetic field force lines are assumed to be confined within the core.

Figure 4.6(a) shows a cross section of a generic three limb transformer core. By taking into account the core’s geometric symmetry, one notices that it can be divided into 3 vertical and 4 horizontal chunks. This is especially relevant when considering the magnetic reluctance equivalent model of fig. 4.6(b), since it allows one to reduce the 7 reluctance equivalent circuit to only 2 different values - one for the vertical chunks and another for the horizontal ones.

![Diagram](image)

Figure 4.6: Three limb transformer core cross section (a) and equivalent circuit considering magnetic reluctances and magnetomotive forces.
Note that the magnetic reluctances represented above can be computed from the geometric and physical properties of the iron core, as described in eq. (4.8), where \( l_i \) and \( S_i \) are the length and cross-sectional area of the corresponding path, respectively, and \( \mu(H) \) is the magnetic permeability of the material.

\[
R_i = \frac{l_i}{\mu(H) S_i} \quad (4.8)
\]

One can then apply to the equivalent circuit a logic analogous to that of Kirchhoff’s Current and Voltage laws, yielding the equation system expressed in (4.9), which can be written under matrix form - eq. (4.10) - and where the leg surface fluxes are denoted by \( \phi \), the magnetomotive forces by \( F \) and the magnetic reluctances by \( R \).

\[
\begin{align*}
\phi_A + \phi_B + \phi_C &= 0 \\
(R_v + 2R_h) \phi_A - R_v \phi_B &= F_A - F_B \\
R_v \phi_B - (R_v + 2R_h) \phi_C &= F_B - F_C
\end{align*}
\quad (4.9)
\]

\[
\begin{bmatrix}
1 & 1 & 1 \\
R_v + 2R_h & -R_v & 0 \\
0 & R_v & -R_v - 2R_h
\end{bmatrix}
\begin{bmatrix}
\phi_A \\
\phi_B \\
\phi_C
\end{bmatrix}
= 
\begin{bmatrix}
0 & 0 & 0 \\
1 & -1 & 0 \\
0 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
F_A \\
F_B \\
F_C
\end{bmatrix}
\Leftrightarrow \mathbf{R_m} \Phi = \mathbf{C_F} \mathbf{F} \quad (4.10)
\]

Note that a coefficient matrix \( \mathbf{C_F} \) has been defined in order to express the system in terms of the magnetomotive force vector \( \mathbf{F} \).

On the other hand, one can write the magnetomotive forces associated with each core leg as a function of the currents that flow through the surrounding windings, as well as the number of coil turns in those windings - eq. (4.11). This general equation can also be written under matrix form, as presented in (4.12).

\[
F_i = N_p I_{ip} + N_s I_{is} \quad i = \{A, B, C\} \quad (4.11)
\]

\[
\begin{bmatrix}
F_A \\
F_B \\
F_C
\end{bmatrix}
= 
\begin{bmatrix}
N_p & 0 & 0 & N_s & 0 & 0 \\
0 & N_p & 0 & 0 & N_s & 0 \\
0 & 0 & N_p & 0 & 0 & N_s
\end{bmatrix}
\begin{bmatrix}
I_{Ap} \\
I_{BP} \\
I_{CP} \\
I_{As} \\
I_{Bs} \\
I_{Cs}
\end{bmatrix}
\Leftrightarrow \mathbf{F} = \mathbf{NI} \quad (4.12)
\]

Furthermore, the magnetic linkage flux associated with each coil relates to the leg surface fluxes as described by (4.13). Once again, one can write these relations as a matrix system - (4.14).

\[
\psi_{ik} = N_k \phi_i \quad i = \{A, B, C\} \quad k = \{p, s\} \quad (4.13)
\]
\[
\begin{bmatrix}
\psi_{Ap} \\
\psi_{Bp} \\
\psi_{Cp} \\
\psi_{As} \\
\psi_{Bs} \\
\psi_{Cs}
\end{bmatrix} = \begin{bmatrix}
N_p & 0 & 0 \\
0 & N_p & 0 \\
0 & 0 & N_p \\
N_s & 0 & 0 \\
0 & N_s & 0 \\
0 & 0 & N_s
\end{bmatrix}\begin{bmatrix}
\phi_A \\
\phi_B \\
\phi_C
\end{bmatrix} \Leftrightarrow \Psi = N^T \Phi \tag{4.14}
\]

Lastly, the linkage fluxes relate to the coil currents through an inductance matrix \( L \), as stated in (4.15), where \( \Psi \) and \( I \) are the previously defined linkage flux and winding current vectors.

\[
\Psi = LI \tag{4.15}
\]

Due to the geometric symmetry of the transformer core, the inductance matrix should be of the form defined in (4.16), where the diagonal elements \( A_{ij} \) and \( B_{ij} \) of each sub-matrix represent the phase self-inductances and the off-diagonal \( C_{ij} \) and \( D_{ij} \) are the mutual inductances. Note that the latter have negative value.

\[
L = \begin{bmatrix}
L_{pp} & L_{ps} \\
L_{sp} & L_{ss}
\end{bmatrix}, \quad L_{ij} = \begin{bmatrix}
A_{ij} & C_{ij} & D_{ij} \\
C_{ij} & B_{ij} & C_{ij} \\
D_{ij} & C_{ij} & A_{ij}
\end{bmatrix}, \quad i, j = \{p, s\} \tag{4.16}
\]

By combining the relations described in (4.10), (4.12), (4.14) and (4.15), and after some algebraic manipulation, one can come up with a general expression for \( L \) based on the previously defined matrices - eq. (4.17).

\[
L = N^T R_m^4 C_p N \tag{4.17}
\]

Note that this expression depends solely on the constructive aspect of the transformer core and windings and is independent of coil currents and generated magnetomotive forces.

Taking advantage of eq. (4.17), one can write the inductance matrix \( L \) in terms of the transformer’s properties - number of turns in primary and secondary windings, \( N_p \) and \( N_s \), magnetic permeability \( \mu(H) \), core cross-sectional area \( S \) and path lengths \( l_h \) and \( l_v \), defined in fig. 4.6. For the sake of simplicity, 3 auxiliary coefficients \((x, y \text{ and } z)\) have been defined in eq. (4.18), and the inductance matrix has been redefined in eq. (4.19) as a function of 9 different values, \( \Lambda \) through \( I \), by taking advantage of the symmetry of the problem in question. The expressions for those elements are then given in eq. (4.20).

\[
x = \frac{\mu(H) S}{2l_h + 3l_v}, \quad y = \frac{l_h + l_v}{2l_h + l_v}, \quad z = \frac{l_v}{2l_h + l_v} \tag{4.18}
\]
\[
L = \begin{bmatrix}
A & -\frac{1}{2}B & -C & D & -\frac{1}{2}E & -F \\
-\frac{1}{2}B & B & -\frac{1}{2}B & -\frac{1}{2}E & E & -\frac{1}{2}E \\
-C & -\frac{1}{2}B & A & -F & -\frac{1}{2}B & D \\
D & -\frac{1}{2}E & -F & G & -\frac{1}{2}H & -I \\
-\frac{1}{2}E & E & -\frac{1}{2}E & -\frac{1}{2}H & H & -\frac{1}{2}H \\
-F & -\frac{1}{2}B & D & -I & -\frac{1}{2}H & G \\
\end{bmatrix}
\]

(4.19)

\[
\begin{bmatrix}
A & B & C \\
D & E & F \\
G & H & I \\
\end{bmatrix}
= x
\begin{bmatrix}
2yN^2_p & 2N^2_p & zN^2_p \\
2yN_pN_s & 2N_pN_s & zN_pN_s \\
2yN^2_s & 2N^2_s & zN^2_s \\
\end{bmatrix}
\]

(4.20)
Chapter 5

Finite Element Simulation Model

This chapter describes the development of a distribution transformer simulation model using the finite element method and appropriate simulation software.
5.1 Geometry

In order to perform a detailed analysis on the behavioral aspects related to distribution transformers, a simulation model had to be developed. This model solves the multi-variate problem by resorting to the Finite Element Method (FEM) and a FEM simulation software.

The model takes into account the dimensions of a typical 15kV/400V three-phase distribution transformer, which has been projected to work on the knee region of its B-H magnetization curve while supplying a rated power of 690kVA. The resulting geometry is presented in fig. 5.1, where the various parts of the model have been highlighted in different colors. Note that, although the model is bi-dimensional, it has an associated depth, which was taken to be the depth of the core (175mm).

Figure 5.1: Model geometry (core and windings), with highlighted parts and measurements. Note: domains surrounding core and windings are hidden.

However, the transformer geometry alone is not enough to perform a finite element simulation. Thus, the global model geometry has to take into account a sufficiently wide surrounding area, comprised of an inner and an outer layer for mesh control purposes (see section 5.3). The finalized geometry is shown in fig. 5.2.

Note that, in this geometry solution, each coil is divided into two coils connected in series. This is a constructive choice taken in many three-phase distribution transformers that allows for a minimization of magnetic dispersion phenomena.

5.2 Materials

In this simplified model, transformer oil and iron carpentry are not taken into account, since their presence has little effect on the results of the desired steady-state simulations. Thus, as shown in fig. 5.3, the model is comprised of 3 different materials: one for the core, one for the windings and another for the surrounding area.
5.3 Meshing

In order to perform Finite Element analysis on the developed model, it has to include a mesh grid across all domains, which will allow for the software to solve the equations defined by the model physics. This mesh was optimized for result accuracy, as well as computational speed, by using the following logic:

1. In the region of interest (core and windings), the mesh has to be extremely fine, in order to provide accurate results, and is comprised of triangular elements;

2. In the surrounding area, defined as a circle, the mesh is much coarser, since that has little to no effect on the results and allows for lower computational duration. In these domains, the mesh is also triangular;
3. The outer layer is defined as an infinite element domain, where the field decay is exponential instead of linear, which increases the model accuracy. Here, however, the mesh is mapped as a fixed number of rectangular elements.

The resulting mesh is as shown in fig. 5.4, where the color scale shows the element quality factor across the model geometry.

Figure 5.4: Model mesh: (a) global view of mesh; (b) detail of interest region (core and windings).

5.4 Electrical circuits

Although the finite element part of the model allows one to simulate the machine's magnetic field physics, one still has to take into account the electrical part of the transformer. This is done through an external electrical circuit interface, where two separate lumped parameter circuits have been developed - one for the primary and another for the secondary. The primary circuit is fed by a three-phase system which is meant to simulate the MV grid and the secondary circuit connects to a LV load, as shown in fig. 5.5. Note that each coil is comprised of 2 sub-coils connected in series, and, for functional purposes, each sub-coil has been divided into 3 parts. This choice was made taking into account that the type of simulation to be carried out requires the possibility of connecting external circuit components anywhere within the coils. Thus, numerous variable position terminals have been defined across the windings to ensure versatility for desired simulations. Note that the neutral point in the secondary winding is grounded through a grounding resistor, which was taken to be 1Ω.

The coils represented above are linked to the magnetic field physics of the finite element model, and thus the interface between the primary and secondary circuits is done through the magnetic circuit.
5.5 Frequency domain analysis

5.5.1 Effective curve approximation

There are many kinds of studies that can be performed while working with finite element models. For the intended purposes, a frequency domain study is likely the most suitable.

As stated in section 3.2, when all quantities can be treated as approximately sinusoidal, one can make use of the effective B-H curve approximation, which linearizes the model. Since the goal is to be able to simulate incipient faults within the transformer, rather than catastrophic events (i.e. overvoltages, short-circuits, etc.), one can consider with reasonable level of certainty that all quantities will indeed be nearly sinusoidal.

In this situation, a frequency domain study can be performed, which computes the response of the linear or, in this case, linearized system to a harmonic excitation with a certain frequency. For the system in question, that frequency should be 50Hz.

5.5.2 Frequency domain equations

This kind of analysis inevitably starts with the time-harmonic Maxwell's equations, which are stated in eqs. (5.1) through (5.5). The variables here used are defined in the nomenclature section at the beginning of this document.

\[
\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} = \sigma (\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \mathbf{J}_e + \frac{\partial \mathbf{D}}{\partial t} \tag{5.1}
\n\]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5.2) \]

\[ \nabla \cdot \mathbf{B} = 0 \quad (5.3) \]

\[ \nabla \cdot \mathbf{D} = \rho \quad (5.4) \]

\[ \nabla \cdot \mathbf{J} = 0 \quad (5.5) \]

In particular, one should look at the time-harmonic equation for Ampère’s Law - eq. (5.1).

Assuming time-harmonic fields - eqs. (5.6) and (5.7) - and making use of the constitutive relations described in (5.8) and (5.9), one arrives at the frequency domain equation for Maxwell-Ampère’s law [31], which is solved by the finite element software - eq. (5.10).

\[ \mathbf{B} = \nabla \times \mathbf{A} \quad (5.6) \]

\[ \mathbf{E} = -j\omega \mathbf{A} \quad (5.7) \]

\[ \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \quad (5.8) \]

\[ \mathbf{D} = \varepsilon_0 \mathbf{E} \quad (5.9) \]

\[ (j\omega\sigma - \omega^2\varepsilon_0) \mathbf{A} + \nabla \times \left( \frac{1}{\mu_0} \nabla \times \mathbf{A} - \mathbf{M} \right) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) = \mathbf{J}_e \quad (5.10) \]

For low frequency oscillations, such as 50Hz electrical signals, it is possible to assume a quasi-magnetostatic regime - eq. (5.11) - in which the variations of the displacement currents are neglected. In that case, the frequency domain equation for Maxwell-Ampère’s law can be reduced to (5.12).

\[ \frac{\partial \mathbf{D}}{\partial t} = 0 \quad (5.11) \]

\[ j\omega\sigma \mathbf{A} + \nabla \times \left( \frac{1}{\mu_0} \nabla \times \mathbf{A} - \mathbf{M} \right) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) = \mathbf{J}_e \quad (5.12) \]
Chapter 6

Model Validation

This chapter validates the FEM simulation model of the previous chapter by numerically comparing it to the analytical model. This validation is done in three steps, as defined in the validation process outline.
6.1 Validation process outline

To ensure that the results provided by the developed simulation model are trustworthy, a model validation process has to be carried out. This process was defined as a three-step task, consisting of:

1. Open-circuit testing of the transformer;
2. Short-circuit testing of the transformer;
3. Determination of the coil self-inductances (diagonal of the inductance matrix);

The results obtained from the simulation model are then compared to the ones predicted by the analytical model of chapter 4.

6.2 Open-circuit test

In order to simulate an open circuit test on the transformer, the model was configured according to the connection diagrams of fig. 6.1.

![Diagram of primary and secondary side circuit diagrams corresponding to the open circuit test of the transformer.]

The configuration of fig. 6.1 yields the magnetic flux density norm plot of fig. 6.2, and the electrical quantities (voltages and currents) given in tab. 6.1. As expected, no current flows through the secondary coils, which implies that in the equivalent single-phase circuit, the entire primary current diverts to the magnetization branch (see section 4.2). Thus, the core will be fully magnetized, and the winding voltages sit at around the respective rated level, even though no current flows in the secondary.

Table 6.1: Voltages and currents (in p.u.) obtained in each phase with the transformer operating in open-circuit condition.

<table>
<thead>
<tr>
<th>Phase</th>
<th>V_p [p.u.]</th>
<th>I_p [p.u.]</th>
<th>V_s [p.u.]</th>
<th>I_s [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>0.11</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>1.00</td>
<td>0.09</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>1.00</td>
<td>0.11</td>
<td>1.00</td>
<td>-</td>
</tr>
</tbody>
</table>

By combining the results shown in fig. 6.2 and tab. 6.1, one comes to the conclusion that the relations described in the analytical model are also observed in the simulation results:
Figure 6.2: Magnetic flux density norm and magnetic potential vector simulation results - open circuit test.

- No current flows through the secondary winding \( (I_s = 0) \);
- The voltages across the primary and secondary windings are approximately equal, in p.u. \( (V_p \approx V_s) \);
- The current injected in the primary is equal to the magnetization current, which is very small compared to the primary current rating. \( (I_p \approx I_m) \)

### 6.3 Short-circuit test

For the transformer short-circuit test, the simulation model was revised in order to fit the connections illustrated in fig. 6.3, where the primary is now fed by three current sources (one in each phase), which inject current into the system at rated level.

![Circuit Diagram](image)

Figure 6.3: Primary (a) and secondary (b) side circuit diagrams corresponding to the short-circuit test of the transformer.
The resulting magnetic flux density norm is plotted in fig. 6.4, where one can observe the evident demagnetization of the transformer core predicted by the analytical model.

Table 6.2 shows the phasor systems corresponding to the winding voltages and currents, on both the primary and secondary sides. By combining these results with those of fig. 6.4, one comes to the conclusion that the relations described in the analytical model are also observed in the simulation results:

- The iron core is almost completely demagnetized ($I_m \approx 0$);
- There is no voltage across the secondary winding ($V_s = 0$);
- The primary and secondary currents are approximately equal, in p.u. ($I_p \approx I_s$);
- The voltage across the primary winding is the short-circuit voltage, which rests well below the rated voltage.

Note that the demagnetization of the core happens due to the fact that there is a $180^\circ$ phase shift in the currents from the primary to the secondary winding. When the currents flow in opposite directions, the secondary currents will generate a backward field which will counteract the one induced by the primary currents. Thus, when if the primary and secondary currents have the same amplitude, in p.u., the total field will be nearly zero, and the core will be demagnetized.

Table 6.2: Voltages and currents (in p.u.) obtained in each phase with the transformer operating in short-circuit condition.

<table>
<thead>
<tr>
<th>Phase</th>
<th>$V_p$ [p.u.]</th>
<th>$I_p$ [p.u.]</th>
<th>$V_s$ [p.u.]</th>
<th>$I_s$ [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.02</td>
<td>1.00</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>B</td>
<td>0.02</td>
<td>1.00</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>C</td>
<td>0.02</td>
<td>1.00</td>
<td>-</td>
<td>1.00</td>
</tr>
</tbody>
</table>
6.4 Coil self-inductances

In section 4.4, a general expression for the inductance matrix of a three-phase transformer has been defined (see eqs. (4.18), (4.19) and (4.20)). By solving it for the dimensions chosen for the simulation model (see fig. 5.1, section 5.1), one obtains the numerical result for the inductance matrix of the modelled transformer - eq. (6.1). Note that, since the expressions for all entries of the inductance matrix depend on the magnetic permeability of the core, the result of eq. (6.1) is valid for the value of \( \mu \) used for this calculation. For this reason, the magnetic permeability was taken from a point well within the linear region of the B-H curve, where \( \mu \) is nearly constant, and corresponds to a relative permeability of approximately 6050 times the permeability of free space (\( \mu_r \approx 6050 \)).

\[
L = \begin{bmatrix}
192.1531 & -134.2825 & -57.8706 & 2.9562 & -2.0659 & -0.8903 \\
-134.2825 & 268.5650 & -134.2825 & -2.0659 & 4.1318 & -2.0659 \\
-57.8706 & -134.2825 & 192.1531 & -0.8903 & -2.0659 & 2.9562 \\
2.9562 & -2.0659 & -0.8903 & 0.0455 & -0.0318 & -0.0137 \\
-2.0659 & 4.1318 & -2.0659 & -0.0318 & 0.0636 & -0.0318 \\
-0.8903 & -2.0659 & 2.9562 & -0.0137 & -0.0318 & 0.0455
\end{bmatrix}
\]  \( [H] \)  \( (6.1) \)

For the sake of simplicity, this step of the validation process focuses only on the self-inductances, rather than the whole inductance matrix. Thus, a vector \( L_{\text{self}}^{\text{analytical}} \) was defined according to eq. (6.2).

\[
L_{\text{self}}^{\text{analytical}} = \begin{bmatrix}
L_{\text{pp}}^{ii} \\
L_{\text{ss}}^{ii}
\end{bmatrix} = \begin{bmatrix}
192.15 \\
268.57 \\
192.15 \\
45.5 \times 10^{-3} \\
63.6 \times 10^{-3} \\
45.5 \times 10^{-3}
\end{bmatrix} [H] \quad i = \{A, B, C\}  \quad (6.2)
\]

In order to obtain the diagonal of the inductance matrix given by the simulation model, six simulations were carried out, since the transformer has a total of six coils (3 phases, 2 windings). The process for obtaining the self-inductance of a given coil consists in an individual excitation of said coil at a certain voltage, while keeping the remaining coils in open circuit. In order to obtain accurate results, it is important that the transformer be operating well within the linear region of the B-H curve. For this reason, in each test, the coil under observation was fed at half its rated voltage. The connection diagrams corresponding to the individual excitation of phase A on the primary and secondary sides are shown in figs. 6.5 and 6.6, respectively.
Combining the results of all six simulations, the self-inductance vector of eq. (6.3) is obtained.

\[
L_{self} = \begin{bmatrix}
201.20 \\
272.05 \\
200.93 \\
47.6 \times 10^{-3} \\
64.5 \times 10^{-3} \\
47.6 \times 10^{-3}
\end{bmatrix} [H] \tag{6.3}
\]

One can then analyze these results by taking the deviation \( \Delta L \) with respect to those predicted by the analytical model. Such comparison is carried out in tab. 6.3, according to the definition of deviation given...
by eq. (6.4).

$$\Delta L = \frac{|L_{\text{analytical}} - L_{\text{sim}}|}{L_{\text{analytical}}} < 5\%$$

(6.4)

Table 6.3: Comparison between the coil self-inductances obtained from the analytical model and from the simulation model.

<table>
<thead>
<tr>
<th>Primary Inductances [H]</th>
<th>Secondary Inductances [mH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Model</td>
<td>192.15, 268.57, 192.15</td>
</tr>
<tr>
<td>Simulation</td>
<td>201.20, 272.05, 200.93</td>
</tr>
<tr>
<td>Deviation</td>
<td>4.71%, 1.30%, 4.57%</td>
</tr>
</tbody>
</table>

At this point, a few remarks should be made in order to give due insight regarding these values.

Firstly, regarding the numerical values themselves, two conclusions can immediately be taken:

- In the secondary winding, the values obtained are in the order of mH, which is consistent with the small size of the coils, comprised of a total of 20 turns.

- In the primary, however, the inductance values are quite large. In fact, the primary coils are comprised of 1300 turns each, which contributes to high inductance values. Furthermore, one may regard the inductance as the imaginary part of the coil impedance divided by the angular frequency - eq. (6.5).

$$L_{\text{coil}} = \frac{\text{Im} \{ Z_{\text{coil}} \}}{\omega}$$

(6.5)

In the case of the primary winding, since the rated voltage is high but the current is considerably low, the rated impedance is necessarily high, which, taking into account that transformer coils usually have very low resistance, automatically yields very large values for the coil inductances.

In what concerns the accuracy of the results, it is necessary to acknowledge that the analytical model was developed neglecting both magnetic dispersion and, most importantly, saturation. This provides the main source of deviation with respect the values obtained by finite element simulation, since, here, both these phenomena are taken into account. Thus, one can state that the model is accurate to a satisfactory degree in determining transformer coil self-inductances.

Having completed the three steps of the model validation process, the model is considered to be valid and fit to use for the incipient winding fault simulations described in chapter 7.
Chapter 7

Simulation Results

This chapter provides the main simulation results obtained using the FEM model. Different incipient winding fault locations and levels of severity are studied according to different variables of interest, and possible methodologies for fault detection and localization are discussed. A justification for the choice of simulation method is also provided, along with brief analysis on the effect of harmonics in the simulation results.
7.1 Comparison of different simulation methods

In chapter 5, the method of frequency domain analysis was discussed. This shall be the primary simulation method. However, it presents some limitations due to the use of the effective B-H curve approximation and the assumption that all quantities are purely sinusoidal. Thus, a few preliminary simulations were carried out, to compare the results yielded by the frequency domain method to those obtained in the time domain.

A comparison method based on the magnetic flux density distribution was considered most appropriate. The goal is to compare the point-wise RMS values of \( B(x, y) \) in each element of the mesh. To this end, the model was simulated in the same conditions in the frequency and time domains, with the transformer fed by a balanced three phase system, at both rated voltage and load. Figure 7.1 shows the surface plot of \( B(x, y) \) for the frequency domain (a) and time dependent (b) simulations. Note that frequency domain analysis automatically yields the RMS values for \( B(x, y) \) in each element of the mesh. Time dependent simulations, on the other hand, give the instantaneous value in each time step. Therefore, some additional computation steps were taken to compute the elementwise RMS of \( B(x, y) \).

![Surface plot of magnetic flux density distribution](image)

**Figure 7.1:** Surface plot of the magnetic flux density distribution (RMS values) at rated voltage and load: (a) frequency domain; (b) time dependent.

Note that a mesh reduction was done to produce these figures, since the original mesh is comprised of a total of 80937 points, which made the task of reproducing it in Matlab too memory consuming. With this in mind, the mesh was reduced to 2500 points, which was considered an acceptable value as to not compromise visualization quality to an unsatisfactory state.

Both distributions can be compared by computing their deviation relative to one another. Since time dependent simulations are more exact, it was chosen as reference. Hence, the deviation can be computed through eq. (7.1), and the resulting surface plot is presented in fig.7.2. Note that the operation described in eq. (7.1) is elementwise.

\[
\varepsilon_{B(x, y)} = \left| \frac{B_{TD}^{rms} - B_{FD}^{rms}}{B_{TD}^{rms}} \right|
\]  
(7.1)
To avoid singularities in the mesh elements where $B$ is very low (outside the core), the deviation was only computed for elements with $B \geq 0.1 \, T$. In other words, the magnetic flux density in the air around the core was neglected, since its values are so low that they yield extremely high relative deviations, which, numerically speaking, are insignificant.

From fig. 7.2, one can verify that for the most significant region, i.e., the core not accounting for extremities, which is where most of the magnetic flux is concentrated, deviation is neglectable ($< 10\%$). This immediately points towards the conclusion that frequency domain analysis is sufficiently accurate for the intended purposes. There are, however, two sets of regions of interest from the point of view of $\varepsilon_{B(x,y)}$:

1. The outer corners of the core, where the magnetic flux density is very low. In these regions, even a small numerical deviation will yield a big value in terms of percentage, which is why the outer corners present deviations in the order of 25%-35% (see fig. 7.3);

2. In the inner corners of the transformer, the border effects result in higher values of $B$. For such values, the accuracy of the effective B-H curve approximation used by the frequency domain simulation method is greatly reduced. For this reason, these regions present a very high deviation, in the order of 25%-50% (see fig. 7.4)

At this point, it is important to remark that those regions where the deviation is very high can be safely disregarded since:

1. In the outer corners (fig. 7.3), the magnetic flux density is very low and thus is of little importance when compared to the magnitude of $B$ in the most significant region of the core;

2. In the inner corners (fig. 7.4), the region where border effects arise is very small when compared to
the total size of the core. Furthermore, the higher values obtained in these regions do not greatly affect the results in the regions of interest.

![Surface plot](image)

**Figure 7.3**: Surface plot of the magnetic flux density deviation, at rated voltage and load - frequency domain with respect to time domain - location (a) and detail (b) of outer corner.

![Surface plot](image)

**Figure 7.4**: Surface plot of the magnetic flux density deviation, at rated voltage and load - frequency domain with respect to time domain - location (a) and detail (b) of inner corner with 10000-point mesh.

### 7.2 Gradual single turn loss

In a first approach, it was decided to analyze a situation where a single coil turn is gradually lost due to highly located stress. In the simulation model, this situation was mimicked by, after choosing the fault location, connecting a variable resistor, $R_{stl}$, in parallel with the faulty coil turn, as illustrated by fig. 7.5. Its resistance was then chosen according to eq. (7.2), where $R_{lt}$ is the resistance of a single turn and $p$ is the turn loss ratio. Thus, the equivalent resistance resulting from this parallel connection is $(1-p)R_{lt}$, i.e., the factor $P = 100p$ gives the percentage of the turn which is lost.

$$R_{stl} = \frac{1-p}{p}R_{lt} \tag{7.2}$$
This fault simulation was carried out for each transformer coil (for each phase individually, in both the primary and secondary windings), and is detailed in the following sections.

The analysis is similar regardless of the fault location, and is based in the following variables:

1. The line voltages and the corresponding symmetric components;
2. The line currents and the corresponding symmetric components;
3. The magnetic flux density distribution in the magnetic circuit;
4. The magnetic flux leakage between adjacent limbs.

Note that, while the voltages and currents are normalized with respect to their rated value, the magnetic flux leakage is regarded as a percentage of the pre-fault magnetic flux through the origin limb.

### 7.2.1 Gradual single turn loss in a secondary winding

Each secondary winding has a total of 20 copper wire turns, which means that a single turn comprises 5% of the entire winding. Therefore, the loss of one turn in a secondary winding will have much more drastic effects than in the primary, especially regarding the magnetic flux density distribution in the transformer core and the surrounding medium. For this reason, it was decided to give more emphasis to the analysis of faults in the secondary winding, leaving the analysis of the primary faults for a later phase of this work (section 7.2.2).

As one coil turn is gradually lost, it is possible to witness the partial demagnetization of the iron core around the area where the fault occurs.

To illustrate the effect of gradual turn loss in the secondary winding, a set of simulations was performed in each phase. Additionally, to assess the effect of fault location within each phase, the same fault was applied to the 1\(^{st}\), 4\(^{th}\), 11\(^{th}\), 15\(^{th}\) and 20\(^{th}\) turns. (fig. 7.6). For the sake of simplicity, the effect of this type of fault will first be analyzed, for each phase, with a gradual loss of the 1\(^{st}\) turn, and only then will a comparison be made to account for different fault locations. It was considered appropriate to split the analysis into 3 parts, one for each type of variable:

1. The line voltages and currents;
2. The symmetric components of the line voltages and currents;

3. The magnetic flux density distribution in the magnetic circuit and the flux leakage between adjacent limbs;

![Figure 7.6: Single turn loss fault locations (vertical position within coil) - 1st, 4th, 11th, 15th and 20th turns.](image)

### 7.2.1.1 Line voltages and currents

As a first approach to analyzing this type of fault, it was decided to focus on the line voltages and currents. Of the 3 methods studied in this chapter, this is the most superficial kind of analysis, since it is read directly from the electrical model, with no further treatment. However, it is a powerful tool for understanding how a fault in each phase affects the global state of the transformer and whether there are any mutual effects, i.e., the effect a fault in one phase can have on the remaining two.

After simulating a gradual loss of the 1st turn in each phase of the secondary winding, tabs. 7.1, 7.2 and 7.3, corresponding to a fault in phase A, B and C, respectively. These tables show the values obtained for the line voltages and currents, in each phase, in either side of the transformer. Note that the line voltages and currents on the primary side have been omitted since it is considered that their analysis does not add sufficiently relevant information to the analysis of faults on the secondary side. Additionally, to minimize the amount of information shown, only 6 of the 12 simulation steps that comprise the gradual fault simulation method were included. These 6 steps are considered to be sufficient in terms of identifying and understanding variation trends in the gathered data.

To gain better insight into the way each fault affects the line voltages and currents, the deviations of each simulation step with respect to the reference (a turn loss level of 0%, i.e., a normal operating condition) were taken. This data is shown in tabs. 7.4, 7.5 and 7.6, where the rows corresponding to variation trends which were considered relevant are highlighted.

From tabs. 7.4 to 7.6, regarding the gradual loss of a single turn in the secondary winding, the main conclusion one can state is that the line voltage (red) and current (green) on the secondary side will
Table 7.1: Line voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side (1st turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s [V] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>229.43</td>
<td>228.56</td>
<td>227.19</td>
<td>220.13</td>
<td>213.97</td>
<td>210.83</td>
</tr>
<tr>
<td>B</td>
<td>229.39</td>
<td>229.35</td>
<td>229.30</td>
<td>229.16</td>
<td>229.13</td>
<td>229.20</td>
</tr>
<tr>
<td>C</td>
<td>229.38</td>
<td>229.36</td>
<td>229.34</td>
<td>229.25</td>
<td>229.19</td>
<td>229.19</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>989.40</td>
<td>986.82</td>
<td>982.78</td>
<td>962.09</td>
<td>944.25</td>
<td>935.28</td>
</tr>
<tr>
<td>B</td>
<td>989.27</td>
<td>986.29</td>
<td>982.97</td>
<td>973.78</td>
<td>972.00</td>
<td>975.29</td>
</tr>
<tr>
<td>C</td>
<td>989.22</td>
<td>990.73</td>
<td>991.83</td>
<td>990.22</td>
<td>983.30</td>
<td>975.99</td>
</tr>
</tbody>
</table>

Table 7.2: Line voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s [V] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>229.43</td>
<td>229.47</td>
<td>229.47</td>
<td>229.44</td>
<td>229.33</td>
<td>229.22</td>
</tr>
<tr>
<td>B</td>
<td>229.39</td>
<td>228.49</td>
<td>227.06</td>
<td>219.90</td>
<td>214.28</td>
<td>211.69</td>
</tr>
<tr>
<td>C</td>
<td>229.38</td>
<td>229.33</td>
<td>229.28</td>
<td>229.09</td>
<td>229.05</td>
<td>229.10</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>989.40</td>
<td>991.04</td>
<td>992.20</td>
<td>990.19</td>
<td>983.15</td>
<td>976.21</td>
</tr>
<tr>
<td>B</td>
<td>989.27</td>
<td>986.62</td>
<td>982.38</td>
<td>961.21</td>
<td>944.69</td>
<td>937.06</td>
</tr>
<tr>
<td>C</td>
<td>989.22</td>
<td>986.23</td>
<td>982.91</td>
<td>974.30</td>
<td>973.34</td>
<td>976.67</td>
</tr>
</tbody>
</table>

Table 7.3: Line voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s [V] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>229.43</td>
<td>229.43</td>
<td>229.43</td>
<td>229.49</td>
<td>229.57</td>
<td>229.63</td>
</tr>
<tr>
<td>B</td>
<td>229.39</td>
<td>229.40</td>
<td>229.41</td>
<td>229.35</td>
<td>229.23</td>
<td>229.12</td>
</tr>
<tr>
<td>C</td>
<td>229.38</td>
<td>228.51</td>
<td>227.15</td>
<td>220.09</td>
<td>213.93</td>
<td>210.80</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>989.40</td>
<td>986.60</td>
<td>983.51</td>
<td>975.14</td>
<td>973.78</td>
<td>977.04</td>
</tr>
<tr>
<td>B</td>
<td>989.27</td>
<td>990.93</td>
<td>992.18</td>
<td>990.74</td>
<td>983.56</td>
<td>975.78</td>
</tr>
<tr>
<td>C</td>
<td>989.22</td>
<td>986.64</td>
<td>982.61</td>
<td>981.95</td>
<td>944.16</td>
<td>935.20</td>
</tr>
</tbody>
</table>

suffer a significant drop in the affected phase, while remaining relatively unaltered in the remaining phases.

Having established how a single turn loss fault in the 1st turn of the secondary winding affects the line voltages and currents, a comparison of its effect on those same variables depending on fault location will now be performed.

Table 7.4: Line voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1st turn) - variations with respect to reference (initial step).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s [V] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-0.38%</td>
<td>-0.98%</td>
<td>-4.06%</td>
<td>-6.74%</td>
<td>-8.11%</td>
</tr>
<tr>
<td>B</td>
<td>-0.02%</td>
<td>-0.04%</td>
<td>-0.10%</td>
<td>-0.11%</td>
<td>-0.08%</td>
</tr>
<tr>
<td>C</td>
<td>-0.01%</td>
<td>-0.02%</td>
<td>-0.06%</td>
<td>-0.08%</td>
<td>-0.09%</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>-0.26%</td>
<td>-0.67%</td>
<td>-2.76%</td>
<td>-4.56%</td>
<td>-5.47%</td>
</tr>
<tr>
<td>B</td>
<td>-0.30%</td>
<td>-0.64%</td>
<td>-1.57%</td>
<td>-1.75%</td>
<td>-1.41%</td>
</tr>
<tr>
<td>C</td>
<td>0.15%</td>
<td>0.26%</td>
<td>0.10%</td>
<td>-0.60%</td>
<td>-1.34%</td>
</tr>
</tbody>
</table>
Table 7.5: Line voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn) - variations with respect to reference (initial step).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_s ) A</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.00%</td>
<td>-0.04%</td>
<td>-0.09%</td>
</tr>
<tr>
<td>B</td>
<td>-0.39%</td>
<td>-1.02%</td>
<td>-4.14%</td>
<td>-6.59%</td>
<td>-7.71%</td>
</tr>
<tr>
<td>C</td>
<td>-0.02%</td>
<td>-0.05%</td>
<td>-0.13%</td>
<td>-0.15%</td>
<td>-0.12%</td>
</tr>
<tr>
<td>( I_p ) A</td>
<td>+0.17%</td>
<td>+0.28%</td>
<td>+0.08%</td>
<td>-0.63%</td>
<td>-1.33%</td>
</tr>
<tr>
<td>B</td>
<td>-0.27%</td>
<td>-0.70%</td>
<td>-2.84%</td>
<td>-4.51%</td>
<td>-5.28%</td>
</tr>
<tr>
<td>C</td>
<td>-0.30%</td>
<td>-0.64%</td>
<td>-1.51%</td>
<td>-1.61%</td>
<td>-1.27%</td>
</tr>
</tbody>
</table>

Table 7.6: Line voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn) - variations with respect to reference (initial step).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_s ) A</td>
<td>0%</td>
<td>0%</td>
<td>+0.03%</td>
<td>+0.06%</td>
<td>+0.09%</td>
</tr>
<tr>
<td>B</td>
<td>+0.01%</td>
<td>+0.01%</td>
<td>-0.02%</td>
<td>-0.07%</td>
<td>-0.12%</td>
</tr>
<tr>
<td>C</td>
<td>-0.38%</td>
<td>-0.98%</td>
<td>-4.05%</td>
<td>-6.74%</td>
<td>-8.10%</td>
</tr>
<tr>
<td>( I_p ) A</td>
<td>-0.28%</td>
<td>-0.60%</td>
<td>-1.44%</td>
<td>-1.58%</td>
<td>-1.25%</td>
</tr>
<tr>
<td>B</td>
<td>+0.17%</td>
<td>+0.29%</td>
<td>0.15%</td>
<td>-0.58%</td>
<td>-1.38%</td>
</tr>
<tr>
<td>C</td>
<td>-0.26%</td>
<td>-0.67%</td>
<td>-2.76%</td>
<td>-4.55%</td>
<td>-5.46%</td>
</tr>
</tbody>
</table>

Result comparison for different fault locations

In order assess how fault location affects the results listed above, the simulation method was repeated in each phase for 5 different locations, vertically placed as shown in fig. 7.6.

It was already established that, in the case of a fault in the secondary winding, only the affected phase presents significant variations in line voltage and current. For this reason, the study of the effect of fault location on the line voltages and currents is reduced, only taking into account the phase afflicted by the fault. Thus, both 2D and 3D representations of the relevant voltage and current variations were obtained for single turn loss faults in phase A (fig. 7.7), B (fig. 7.8) and C (fig. 7.8).

Through inspection of figs. 7.7, 7.8 and 7.9, it is possible to state the following conclusions:

1. As expected, similarly to what was verified for a fault in the 1st turn, both the line voltage and current in the faulty phase decrease with respect to the reference values, regardless of fault location;

2. The magnitude of the variations seems to be independent of the phase where the fault occurs;

3. In numerical terms, the decrease is more evident in the voltages than in the currents, regardless of fault location;

4. As the fault evolves, the location dependent voltage and current curves start to take a U-shape. This indicates that the effect of a single turn fault on the line voltage and current of the afflicted phase is more significant when the fault is closer to the middle section of the coil. This is considered to be the most important conclusion one can take from this first analysis method.
Figure 7.7: Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase A) in different fault locations (1\textsuperscript{st}, 4\textsuperscript{th}, 11\textsuperscript{th}, 15\textsuperscript{th} and 20\textsuperscript{th} turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.
Figure 7.8: Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase B) in different fault locations (1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.
Figure 7.9: Line voltage and current obtained for a gradual single turn loss in the secondary winding (phase C) in different fault locations (1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.

7.2.1.2 Symmetric components

The second approach to gradual single turn loss fault analysis takes the results of the previous section one step further, through application of the Fortescue transform. The study of the symmetric components of the line voltages and currents is a powerful tool for fault analysis, since not all components are always present, and their appearance might indicate specific occurrences.

Table 7.7, 7.8 and 7.9 show the symmetric components of the secondary voltages and currents obtained for a gradual single turn fault in the 1st turn of the secondary winding, in phases A, B and C, respectively. Note that the primary voltages and currents have once again been disregarded, since they are not considered relevant for the analysis of faults on the secondary side.

At this point, an important observation should be made. With respect to the symmetric components of the current, a gradual turn loss of the first turn in the secondary winding is a special situation, in the sense that the variations registered in the referred variables are much higher than for any other location. This is a consequence of the grounding scheme of the modeled transformer. By short-circuiting the 1st turn, a direct conduction path to the ground node is created, which leads to the appearance of a zero
sequence current. This component is not present when the fault occurs in any other location within the coil. Since the line current itself does not present such high variations, this zero sequence current is compensated by a more significant drop in positive sequence current, and a consequent, very relevant increase in the negative sequence component. This finding implies that the numerical variations in the symmetric components registered for a loss of the 1\textsuperscript{st} will be much higher than when the fault occurs in another zone of the coil. However, qualitatively speaking, all the conclusions taken for this particular situation hold true every fault location test in the simulation process (with the exception of the appearance of a zero sequence current). Figure 7.10 presents schematically the appearance of the conduction path to the ground node when the first turn is short-circuited. Note that $R_{\text{gnd}}$ is the grounding resistance, $Z_{1t}$ is the impedance of the 1\textsuperscript{st} turn and $Z_{ht}$ is the impedance of the remaining (healthy) turns.

![Schematic representation of the induced current flow on a secondary winding when the 1\textsuperscript{st} turn is (a) healthy; (b) short-circuited.](image)

Table 7.7: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1\textsuperscript{st} turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$ [V] (RMS)</td>
<td>D 229.40</td>
<td>229.09</td>
<td>228.60</td>
<td>226.15</td>
<td>224.09</td>
<td>223.07</td>
</tr>
<tr>
<td>$I_s$ [A] (RMS)</td>
<td>I 0.02</td>
<td>0.65</td>
<td>1.39</td>
<td>3.79</td>
<td>5.36</td>
<td>6.20</td>
</tr>
<tr>
<td>$H_s$</td>
<td>H 0.01</td>
<td>0.64</td>
<td>1.36</td>
<td>3.70</td>
<td>5.23</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Table 7.8: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1\textsuperscript{st} turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$ [V] (RMS)</td>
<td>D 229.40</td>
<td>229.09</td>
<td>228.60</td>
<td>226.12</td>
<td>224.21</td>
<td>223.34</td>
</tr>
<tr>
<td>$I_s$ [A] (RMS)</td>
<td>I 0.02</td>
<td>0.72</td>
<td>1.48</td>
<td>3.89</td>
<td>5.33</td>
<td>6.05</td>
</tr>
<tr>
<td>$H_s$</td>
<td>H 0.01</td>
<td>0.64</td>
<td>1.36</td>
<td>3.59</td>
<td>4.93</td>
<td>5.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_s$ [V] (RMS)</td>
<td>D 229.40</td>
<td>229.09</td>
<td>228.60</td>
<td>226.12</td>
<td>224.21</td>
<td>223.34</td>
</tr>
<tr>
<td>$I_s$ [A] (RMS)</td>
<td>I 0.02</td>
<td>0.72</td>
<td>1.48</td>
<td>3.89</td>
<td>5.33</td>
<td>6.05</td>
</tr>
<tr>
<td>$H_s$</td>
<td>H 0.01</td>
<td>0.64</td>
<td>1.36</td>
<td>3.59</td>
<td>4.93</td>
<td>5.60</td>
</tr>
</tbody>
</table>

60
Table 7.9: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn).

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>V_s [V] (RMS)</th>
<th>I_s [A] (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>0%</td>
<td>229.40</td>
<td>0.02</td>
</tr>
<tr>
<td>10%</td>
<td>229.12</td>
<td>0.67</td>
</tr>
<tr>
<td>20%</td>
<td>228.66</td>
<td>1.42</td>
</tr>
<tr>
<td>50%</td>
<td>226.29</td>
<td>3.86</td>
</tr>
<tr>
<td>75%</td>
<td>224.24</td>
<td>5.47</td>
</tr>
<tr>
<td>100%</td>
<td>223.18</td>
<td>6.33</td>
</tr>
</tbody>
</table>

To better understand how the symmetric components vary with the gradual evolution of the fault, a normalization was performed with respect to the rated values of the voltages and currents at play. The results are presented in tabs. 7.10 through 7.12, where the results considered to be most important were highlighted.

Table 7.10: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase A, on the secondary side, (1st turn) - normalized to rated values.

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>V_s [V]</th>
<th>I_s [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>0%</td>
<td>99.33%</td>
<td>0.01%</td>
</tr>
<tr>
<td>10%</td>
<td>99.20%</td>
<td>0.28%</td>
</tr>
<tr>
<td>20%</td>
<td>98.99%</td>
<td>0.60%</td>
</tr>
<tr>
<td>50%</td>
<td>97.93%</td>
<td>1.64%</td>
</tr>
<tr>
<td>75%</td>
<td>97.03%</td>
<td>2.32%</td>
</tr>
<tr>
<td>100%</td>
<td>96.59%</td>
<td>2.62%</td>
</tr>
</tbody>
</table>

Table 7.11: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase B, on the secondary side, (1st turn) - normalized to rated values.

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>V_s [V]</th>
<th>I_s [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>0%</td>
<td>99.33%</td>
<td>0.01%</td>
</tr>
<tr>
<td>10%</td>
<td>99.20%</td>
<td>0.28%</td>
</tr>
<tr>
<td>20%</td>
<td>98.98%</td>
<td>0.64%</td>
</tr>
<tr>
<td>50%</td>
<td>97.91%</td>
<td>1.68%</td>
</tr>
<tr>
<td>75%</td>
<td>97.09%</td>
<td>2.31%</td>
</tr>
<tr>
<td>100%</td>
<td>96.71%</td>
<td>2.62%</td>
</tr>
</tbody>
</table>

Table 7.12: Symmetric components of the voltages and currents obtained for a gradual single turn loss in phase C, on the secondary side, (1st turn) - normalized to rated values.

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>V_s [V]</th>
<th>I_s [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>I</td>
</tr>
<tr>
<td>0%</td>
<td>99.33%</td>
<td>0.01%</td>
</tr>
<tr>
<td>10%</td>
<td>99.21%</td>
<td>0.29%</td>
</tr>
<tr>
<td>20%</td>
<td>99.01%</td>
<td>0.61%</td>
</tr>
<tr>
<td>50%</td>
<td>97.99%</td>
<td>1.67%</td>
</tr>
<tr>
<td>75%</td>
<td>97.10%</td>
<td>2.37%</td>
</tr>
<tr>
<td>100%</td>
<td>96.64%</td>
<td>2.74%</td>
</tr>
</tbody>
</table>

By inspecting tabs. 7.10, 7.11 and 7.12, it is possible to list a few relevant observations:

1. As the secondary voltage in the afflicted phase drops due to the loss of the 1st turn, so does its
positive sequence component. More importantly, one verifies that the negative and zero sequence components of the secondary voltage, initially non-existent, start to increase, reaching approximately 3% of its rated value.

2. Similarly to the voltage, the secondary current in the faulty coil also decreases. However, while the line currents drop less than 6%, its symmetric components show much more significant variations. The positive sequence component decreases around 17% and the negative and zero sequence currents, which are virtually null at first, display values of up to 38% of the rated current, after the fault is fully settled. These variations are much more significant than those of the secondary voltages. Therefore, the symmetric components of the secondary current are considered to be the most relevant metric from this set of variables. Note that, if the fault was located in a different turn, these variations would be less significant (numerically speaking), but still slightly more significant than those of the voltages.

One very important note regarding the secondary zero sequence current is that normally, even in the presence of a fault, it is virtually nonexistent. In the case of a fault in the 1st turn however, a direct current path to the ground node is created, which enables the appearance of a zero sequence current. This is accompanied by a steeper decrease in positive sequence and increase in negative sequence currents, which is much less significant for faults in lower zones of the coil. However, although the variations are numerically smaller, the qualitative conclusions are valid for all other fault locations, which invariably display a drop in positive sequence current, accompanied by a rise in negative sequence current.

Taking into account those conclusions, it was decided to look at the symmetric components of the secondary currents in more detail. In particular, a special level of importance was given to the negative sequence component, which is inherently connected to the backward magnetic field responsible for the demagnetization of the iron core in the presence of a fault, a phenomenon that will be explained in depth further ahead (section 7.2.1.2). Thus, a graphical analysis of the symmetric components of the secondary currents was considered appropriate, since it provides visual confirmation on how relevant the variations of tabs. 7.10, 7.11 and 7.12 truly are. The results are presented in figs. 7.11 through 7.13.

From figs. 7.11(a), 7.12(a) and 7.13(a), one can verify that the existence of negative sequence current in the secondary can indicate the presence of a single turn loss fault. This information can then be crossed with the line voltage or current drops, to identify the phase in which the fault occurs. Additionally, it is adequate to state that, for the transformer here studied, this type of fault might be possible to detect very early on, given the magnitude of the increase in these variables.

Figures 7.11(b), 7.12(b) and 7.13(b) provide a sort of visual method for single turn loss detection, with a noticeable X-shaped curve. These figures clearly show the decrease in positive sequence current and simultaneous rise in negative sequence current, which, as previously mentioned, is particularly significant when the fault occurs in the 1st turn but is also observable in other fault locations, as will be shown in the next section.
Figure 7.11: Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase A): (a) general plot; (b) detail of positive and negative sequence components on separate axis.

Figure 7.12: Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase B): (a) general plot; (b) detail of positive and negative sequence components on separate axis.

Figure 7.13: Evolution of the symmetric components of the secondary currents with the gradual loss of the 1st turn of the secondary winding (phase C): (a) general plot; (b) detail of positive and negative sequence components on separate axis.
Result comparison for different fault locations

Similarly to what was done for the line voltages and currents, a location dependent comparison was also performed for their symmetric components. In this case, since it has already been observed for a 1st turn loss fault that the most relevant variations occur in the positive and negative sequence currents, these will be taken as the focus variables for this step of the analysis. The 2D and 3D representations of these variables were obtained for phase A (fig. 7.14), B (fig. 7.15) and C (fig. 7.16). Note that, for comparative purposes, the case where the fault occurs in the 1st turn has been omitted, since it consists in an extraordinary situation where the variations of the symmetric components are much more numerically significant than for the remaining fault locations. Nevertheless, let it be established that a loss of the first turn in either phase of the secondary winding presents the most relevant variations for this set of variables.

Figure 7.14: Positive and negative sequence currents obtained for a gradual single turn loss in the secondary winding (phase A) in different fault locations (4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.
Figure 7.15: Positive and negative sequence currents obtained for a gradual single turn loss in the secondary winding (phase B) in different fault locations (4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.
Regarding figs. 7.14, 7.15 and 7.16, one observes the following:

1. The numerical variations concerning the drop in positive sequence and the rise in negative sequence current are much lower when comparing any other location to the loss of the 1st turn, for the aforementioned reasons. However, the qualitative aspect holds true: in the presence of a fault, the positive sequence current, initially close to the rated value, drops; simultaneously, a negative sequence current, initially nonexistent, appears.

2. The effect of a single turn fault on the positive and negative sequence currents seems to become less significant as the fault moves down in the coil. This observation is of great importance, since it allows the distinction of the top and bottom sections of the coil when it comes to fault detection. As previously seen, for the line voltages and currents, the results are symmetric with respect to the middle of the coil. The same can be observed for the magnetic flux leakage, which will be studied in detail ahead. Thus, the analysis of symmetric components of the secondary currents is the only method studied in this document that enables one to distinguish geometrically symmetric parts of the coil.
### 7.2.1.3 Magnetic flux density distribution and flux leakage

The final method used to study gradual turn faults in the simulation model, unlike the previous two, is not based on electrical variables, but rather on the magnetic flux density distribution and magnetic flux leakage between limbs. The reason this type of analysis was considered viable was that, while performing gradual single turn loss simulations, it was possible to observe that when this type of fault starts to appear, the transformer core around the area where the fault occurs is gradually but strongly demagnetized. Once again, to illustrate a fault in one turn in the secondary winding, the gradual loss of 1\textsuperscript{st} turn of each secondary coil was simulated. Figures 7.17, 7.18 and 7.17 show the initial and final magnetic flux density distribution in the core for a gradual 1\textsuperscript{st} turn loss in phases A, B and C, respectively. Note that the starting point is exactly the same for all phases, although phase C might appear to have a different flux density distribution due to the magnetic potential vector lines, which are not completely equal.

![Figure 7.17](image1.png)

**Figure 7.17:** Magnetic flux density distribution at 0\% (a) and 100\% (b) turn loss for a fault in the 1\textsuperscript{st} turn of phase A, in the secondary winding.

![Figure 7.18](image2.png)

**Figure 7.18:** Magnetic flux density distribution at 0\% (a) and 100\% (b) turn loss for a fault in the 1\textsuperscript{st} turn of phase B, in the secondary winding.
Regarding the results of phase C, it is important to note that they are perfectly symmetric to those obtained when causing a single turn loss fault in phase A in terms of flux density distribution, although the magnetic potential vector lines do not completely coincide.

Observing the behavior of the magnetic flux density distribution in the presence of a fault, one readily concludes that:

1. Around the area where the fault occurs, the core is almost fully demagnetized, due to the backward magnetic field generated by the negative sequence current which appears in the presence of a fault;

2. In the lower section of the limb, the magnetic flux density increases, even saturating the iron near the inner borders of the limb;

3. The magnetic potential vector lines avoid the demagnetized areas, and, consequently, find alternative paths outside the core, with lower magnetic reluctance.

Of the three items listed above, the latter is considered to be the most relevant for the purpose of fault analysis, since the appearance of magnetic potential lines outside the core indicates the existence of magnetic flux leakage between limbs. Thus, it was decided to measure the increase in flux leakage to either side of the limb where a fault occurs. To this end, 9 measurement surfaces were defined in the model, as shown in fig. 7.20. Surfaces $S_1$ to $S_3$ measure limb fluxes and the remaining measure flux leakage.

Using the defined measurement surfaces, the plots of fig. 7.21 was obtained. The curves of fig. 7.21(a), 7.21(b) and 7.21(c) show the magnetic flux flowing out to either side of the faulty limb, for a fault in phases A, B and C, respectively. Note that the magnetic flux is normalized as a percentage of the limb flux measured at rated load.
Figure 7.20: Surfaces defined to measure limb (S₁, S₂ and S₃) and leakage (S₄ - S₉) magnetic fluxes.

Figure 7.21: Normalized magnetic leakage flux to the left (black) and right (red) of the faulty limb, for a gradual 1st turn loss fault in the secondary winding, located in: (a) phase A, left limb; (b) phase B, middle limb; (c) phase C, right limb.
The most obvious observation regarding fig. 7.21 is that, while initially, with the transformer operating normally, the magnetic flux leakage is negligible or even nonexistent, it quickly becomes very significant, reaching over 50% of the rated limb flux when the fault is in full effect.

Another less obvious conclusion is that the results are perfectly symmetric with respect to the central line of middle limb \( (x = 0) \). In terms of simulation, this means that the results obtained for phase C can be extrapolated from those of phase A, with minimal error, thus reducing the total computation time by approximately \( \frac{1}{3} \).

Additionally, it is worthy to mention that, in the left and right limbs, the flux leakage toward the outside of the transformer, i.e., the outward flux leakage, presents a smaller value when compared to the inward flux leakage (which flows toward the adjacent limb). This is a consequence of the larger magnetic reluctance of the path followed by the outward flux. In the case of the inward flux leakage, the magnetic reluctance is much smaller, since it is much easier for the magnetic flux to re-enter the core. With this in mind, comparisons made further ahead will only take into account the inward flux leakage, given its bigger importance.

**Result comparison for different fault locations**

As previously mentioned, to assess how the flux leakage varies with the vertical location of the fault within the coil, the simulation process was repeated multiple times, applying the fault to the locations shown in fig. 7.6.

A comparison was then made according to fault location. In order to simplify analysis, the following measures were taken:

1. Since it has been observed that phase C presents results symmetric to those of phase A, only phase A will be further analyzed. The conclusions taken for phase A are also considered valid for phase C.

2. Outward flux leakages will be disregarded, since they are not as significant as inward leakages. In other words, looking at fig. 7.20, surfaces \( S_4 \) and \( S_9 \) are disregarded since they measure outward flux leakages.

3. Since leakages measured to either side of phase B (surfaces \( S_6 \) and \( S_7 \)) are symmetric, an average was taken as to reduce the amount of data to analyze.

Figures 7.22 and 7.23 show, in 2D and 3D view, the location dependent flux leakage curves obtained for a single turn loss fault in phase A (fig. 7.22) and in phase B (7.23).

From fig. 7.22, one can state the following conclusions for a gradual single turn loss fault in phase A (and, by extension, phase C):

1. A fault in the middle section of the coil (11\textsuperscript{th} turn) yields lower flux leakage than a fault in one of the extremities, which might make it harder to detect through this method. This happens due to the fact that when the demagnetized section is located in the middle of the limb, it is easier for the leakage
flux to re-enter the faulty limb due to that path’s lower magnetic reluctance when compared to the path toward the neighboring limb, which results in less severe core demagnetization (see fig. 7.24).

Regarding this observation, it is possible that an alternative, more localized, measurement method would improve the ability to detect faults in the middle section of the coil early on. Such a method is suggested in chapter 9, section 9.2.

2. The effect of a single turn loss fault depends only on the distance relative to the middle of the coil and is independent of direction. In other words, the flux leakage will be the same regardless of whether fault happens on the first or last coil turn, for example, since they both have the same distance to the horizontal symmetry axis of the transformer core.

3. The flux leakage curves are V-shaped, and the steepness of their concavity increases with fault severity. In fig. 7.22(a), it is possible to observe that the curve corresponding to total loss of one coil turn is steeper than the remaining curves.
4. As the severity of the fault increases, the V-curve becomes less linear. This is due to the fact that the flux leakage tends to stabilize if the core region around the fault is already strongly demagnetized. This can be confirmed by observing that that faults in the extremities of the coil (1st and 20th turns) cause stronger demagnetization when compared to a fault which occurs in the middle part of the coil.

![Magnetic flux density - fault in phase A](image)

Figure 7.24: Comparison of the magnetic flux density distribution for a single turn loss fault in the secondary winding (phase A) in the 1st (a) and 11th (b) turns.

By inspecting fig. 7.23, one can verify that the conclusions pointed out for a single turn fault in phase A hold true for phase B as well. However, an additional remark is in order. While phases A and C only show significant inward flux leakages (towards phase B), a fault in phase B results in significant flux leakages in either direction, which indicates it might be easier to detect at an earlier stage.

7.2.2 Gradual single turn loss in primary winding

In order to study how the gradual loss of a single turn affects the primary winding, the same process taken to analyze the secondary winding was used. Since the primary is comprised of a total of 1300 turns per phase, one turn corresponds to less than 0.1% of the coil. Consequently, the effects of a single turn loss fault will, in general, be much less drastic in the primary than in the secondary.

The fault was simulated in all three phases, in 5 different locations per phase - 1st, 325th, 651st, 975th and 1300th turns - which correspond to the same vertical locations studied for the secondary, as shown in fig. 7.25.

Since a detailed analysis has already been performed for the secondary winding, the study of the primary side will be reduced to comparative methods. The most relevant results obtained for the single turn loss fault simulations performed on the primary winding are shown in appendix B (tab. B.1 and figs. B.1 - B.6). For the sake of simplicity, these results will be presented in a comparative basis, i.e., rather than providing the full range of tables and graphs presented in section 7.2.1, the analysis will be reduced to only the most relevant results, which justify the conclusions that will be presented and the differences with respect to section 7.2.1. Phase B will be taken as an example, although the same conclusions
Regarding the results obtained for a single turn loss fault in the primary winding, the most relevant observations are the following:

1. In the primary winding, the voltage is imposed and, consequently, invariant. In presence of a turn loss fault, the drop in winding resistance at constant voltage leads to an increase in the line current in the faulty transformer phase, contrasting with the voltage and current drops registered for faults in the secondary. Additionally, since the primary winding is delta-connected, the line current in the phase which is electrically adjacent (i.e., electrically displaced by $+120^\circ$) to the faulty phase also increases. For example, a fault in phase B of the transformer will lead to an increase in line current in phases B and C in the grid side, since transformer phase B is connected between grid phases B and C. This is visible appendix B, tab. B.1.

2. The increase in primary line current is the most numerically noticeable variation caused by a fault in the primary winding (appendix B, tab. B.1). However, it is worthy to note that if the primary voltages were allowed to vary, rather than being imposed, the increase registered in the currents might be less significant.

3. Regarding the positive and negative sequence currents, the variations are also, inevitably, different form the ones registered in the secondary. Since the line currents increase, so does the positive sequence component. The negative sequence component also increases, originating a backward magnetic field which will cause a slight demagnetization of the core (appendix B, fig. B.1). An example of the evolution of the positive and negative sequence components of the primary currents is shown in appendix B, fig. B.2.

4. Regarding the magnetic flux density distribution, the effect is the same as in the secondary, qualitatively speaking. However, the demagnetization is much weaker, since the negative sequence current associated to the backward magnetic field is in the order of magnitude of the primary cur-
rents (rated at 25.65A), and not the secondary currents (rated at 995.93A). This can be verified by comparing fig. B.1 (appendix B) with fig. 7.18(b) (section 7.2.1).

5. Since the demagnetization is weaker, so is the magnetic flux leakage between adjacent limbs. The maximum magnitude of the flux leakage curves is in the order of 8% (appendix B, fig. B.3), contrasting with the flux leakage of approximately 50% registered for the most critical fault locations in the secondary. The fact that the flux leakage is numerically lower also means that the concavity of the V-shaped location-dependent curves will be perfectly linear (appendix B, fig. B.4). This happens due to the fact that the demagnetization is not strong enough for the flux leakage to start stabilizing regardless of the increase in fault severity. The phenomenon of flux leakage stabilization is explained in more detail in section 7.3.

6. Regarding the variation of the variables of interest with fault location, the only variable that still shows a graphically observable trend is the magnetic flux leakage, which maintains the V-shape of its curve. The remaining variables of interest show only slight variations, which are considered too subtle to indicate the vertical location of a fault within the coil (appendix B, figs. B.5 and B.6).

7.3 Gradual multiple turn loss

As a final step to the simulation process, it was decided to study how an increase in the number of lost coil turns would affect the results obtained for the variables of interest. To that end, the model was simulated following the same process as before, but now with a loss of 2 and 3 consecutive turns, respectively. The most important results obtained from this set of simulations are listed in appendix C (figs. C.1 - C.15). Once again, this analysis has been reduced to only the essential results that justify the following conclusions, and phase B has been taken as an example, with its conclusions being qualitatively valid for phases A and C.

Regarding the primary winding, all the qualitative conclusions taken for a single turn loss fault are also valid for in the case of multiple turn loss. The main difference is that the numerical results registered for the latter are much more significant, to the point that the slight location-dependent variations registered in the line currents (as well as in the positive and negative sequence components) become more evident, and allow for a graphical identification of fault location - appendix C, figs. C.1 - C.4.

For the secondary winding, one comes to an identical conclusion. Qualitatively speaking, all the conclusions stated for a single turn loss hold true when the number of lost turns increases, regardless of the more significant numerical values registered for the variations in the voltages and currents, as well as their respective symmetric components - appendix C, figs. C.7 - C.10.

Regarding the magnetic flux leakage, however, an additional remark is in order. In the case of a single turn loss, the magnetic flux leakage curves, although not completely linear, do not show clear evidence that the flux leakage would stabilize if the fault progressed further. On the other hand, when more than one turn is lost, the flux leakage tends to start stabilizing at around 60% (or 70% in the case of phases
A and C) of the rated limb flux - appendix C, fig. C.11. As a consequence, the location dependent V-shaped curves are less spaced between themselves for high fault severity levels - appendix C, figs. C.12 and C.13. This flux leakage stabilization phenomenon happens due to the strength of the demagnetization caused by the faults. When the fault involves multiple turns, the area of the core around the coil section where the fault occurs is almost fully demagnetized - appendix C, figs. C.14 and C.15. Therefore, an increase in fault severity will no longer contribute to the demagnetization of the core, which leads to the stabilization of the flux leakage.

### 7.4 Influence of harmonics in simulation results

Up until this point, all simulations assumed all electric and magnetic quantities to be perfectly sinusoidal. However, since distribution transformers are surrounded by a vast electric grid, that is never the case. In reality, grid voltages typically have fairly significant odd harmonics.

In the model, the grid is simulated by a three phase voltage system, which is forced upon the primary. To better approximate the reality of a servicing distribution transformer, a set of odd harmonics was injected in the primary, alongside the fundamental harmonic.

To ensure the magnetic energy density in the circuit remained approximately constant, the amplitude of the odd harmonics to apply (3rd, 5th, 7th and 9th) was chosen as a percentage of the rated voltage. The amplitude of the fundamental harmonic was then computed such that the total RMS of the applied voltages was equal to that of the purely sinusoidal voltages used previously - eq. (7.3). Note that it was decided to add harmonics only until the 9th order since higher order harmonics are much less significant, and their effect is neglectable when compared to the most significant harmonics.

\[
V_{\text{rms}}^1 = \sqrt{(V_{\text{rms}})^2 - \sum_{i=3,5,7,9} (V_{\text{rms}}^i)^2}
\]  

(7.3)

For simplicity, one can define for each harmonic order an amplitude factor with respect to the rated voltage - eq. (7.4) - and eq. (7.3) can be further simplified, yielding eq. (7.5).

\[
haf_i = \frac{V_i}{V_{\text{rated}}}, \quad i = \{3,5,7,9\}
\]  

(7.4)

\[
haf_1 = \sqrt{1 - \sum_{i=3,5,7,9} haf_i}
\]  

(7.5)

Table 7.13 shows the amplitude factors considered for each harmonic order. Note that this table describes a slightly pessimistic situation, in which, although the RMS of the applied voltages coincides with its rated value, the voltage waveforms will be highly distorted, as can be observed by comparing figs. 7.26(a) and 7.26(b).
Table 7.13: Harmonic amplitude factors for the odd voltage harmonics injected in the primary side.

<table>
<thead>
<tr>
<th>Harmonic Order (i)</th>
<th>Harmonic Amplitude Factor (haf(_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96.2%</td>
</tr>
<tr>
<td>3</td>
<td>15%</td>
</tr>
<tr>
<td>5</td>
<td>20%</td>
</tr>
<tr>
<td>7</td>
<td>10%</td>
</tr>
<tr>
<td>9</td>
<td>5%</td>
</tr>
</tbody>
</table>

Figure 7.26: Imposed primary voltage waveforms, in p.u., without (a) and with (b) odd harmonics up to the 9\(^{th}\) order.

The comparison with the purely sinusoidal case was done in two fronts. In a first approach, without causing any faults in the transformer, and keeping it at rated load, the magnetic flux density distribution, \(B(x, y)\), was compared before and after the injection of harmonics (in RMS values). By inspecting figs. 7.27(a) and 7.27(b), one can conclude that the distribution of magnetic flux density is not greatly affected by the introduction of harmonics, in terms of RMS values. This is be confirmed by fig. 7.28, which shows the percentual deviation between both \(B(x, y)\) maps.

Figure 7.27: Surface plot of the magnetic flux density distribution (RMS values) at rated RMS voltage and load: (a) purely sinusoidal primary voltages; (b) primary voltages injected with odd harmonics.

The second step of this comparison process takes into account the effect of harmonics in the presence
of faults. For that purpose, the results obtained for the flux leakages with gradual single turn loss faults were compared.

As mentioned previously, the computational cost of simulating the model in the time domain is severely higher than in the frequency domain. This is why mass simulations have to be reduced to the frequency domain, and time domain simulations should be performed only if necessary. Since the goal is merely to illustrate the effect of a fault with and without harmonics, this comparison shall be reduced to the simulation of gradual single turn loss of the 1st turn in the secondary winding, in phase A. Additionally, instead of modeling gradual single turn loss by a set of 12 simulations, one for each resistance value, the time domain simulations were performed in sets of 3 (0%, 50% and 100%) of turn loss, which means the flux leakage curves have been linearized into two sections due to high computation times. This linearization can be observed in figs. 7.29 and 7.30, where the time dependent curves (red, green and yellow) are each comprised of two lines, one from 0% to 50% and another from 50% to 100% turn loss.

Figures 7.29 and 7.30 show how the limb and leakage flux behave when odd harmonics are added to the applied primary voltages. From direct observation of these figures, it is possible to observe that the effect of the presence of harmonics in the simulation results is minimal and therefore, the results and conclusions presented so far should hold true even when the voltage and current waveforms are heavily distorted, as long as the RMS values of the voltages and currents remain close to their respective ratings.
7.5 Methodology for fault detection and localization

As a way to summarize the conclusions taken from the simulation results, it was decided to propose a methodology for fault detection and localization. This methodology is based on the variables studied in this chapter and on the observations made regarding each of them. To reiterate, the variables considered to be the most relevant for this assessment are:

1. The line voltage and current in the faulty phase;
2. The positive and negative sequence components of the current in the faulty phase;
3. The magnetic flux leakage measured between the faulty limb and its adjacent counterpart.

Table 7.14 summarizes the main function of each set of variables. Note that, for example, the line voltage and current in the faulty phase might also provide information on whether the fault occurs in the middle section of the coil or in its extremities. However, that is not considered to be its main function, since that
distinction is much more evident when analyzing the magnetic flux leakage in the corresponding limb.

Table 7.14: Main function of each set of variables regarding the localization of a fault occurring in phase X

<table>
<thead>
<tr>
<th>Variable</th>
<th>Main Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_X, I_X$</td>
<td>Distinguish faulty phase from healthy ones</td>
</tr>
<tr>
<td>$I_d, I_i$</td>
<td>Distinguish faults in the top section from faults in the bottom section of a coil</td>
</tr>
<tr>
<td>$\phi_{\text{leak}}^X$</td>
<td>Distinguish faults in the middle section from faults in the extremities of a coil</td>
</tr>
</tbody>
</table>

Thus, the flowchart of fig. 7.31 was created to illustrate the proposed process for detecting and locating a gradual, increasingly significant fault in a given phase of the secondary winding, by using the qualitative conclusions taken in this chapter. Note that, for a fault in the primary winding, the final step would not be possible, since the variations in positive and negative sequence current are symmetric. Thus, it would only be possible, through this method, to distinguish between a fault in the middle section or extremities. This, however, could potentially be solved by implementing the flux measurement discretization method suggested in chapter 9, section 9.2, which discusses the guidelines for future work.
Figure 7.31: Flowchart of the proposed fault detection and localization methodology, for a fault in phase X of the secondary winding, based on the conclusions taken from the fault simulations and the functions attributed to the variables of interest.
Chapter 8

Experimental Analysis

A description of the experimental procedure is given in this chapter. The preparation and usage of the experimental setup are thoroughly described, and the obtained results are analyzed and compared with those of the simulation model.
8.1 Experimental Setup

In chapter 7, a simulation method was implemented, which allowed for a better understanding of the problem in question and the methodology that can be used for incipient fault detection. However, the results obtained through that simulation process should now be validated experimentally, to verify not only the generality of the conclusions taken so far, but also their scalability regarding transformer geometry and overall size.

To that end, a transformer had to be selected, since it will be the central element of the experimental setup. After a close evaluation of the three-phase transformers available at the Electric Machine Laboratory at IST, the three-phase, three column, air-cooled transformer of fig. 8.1 was chosen. This equipment presented the most viable option for the work at hand, due to the connections of the windings - an internally delta-connected primary and a wye-connected secondary. Furthermore, the secondary coils are easily accessible, which is a significant advantage. Note that, in order to guarantee inter-winding insulation, two sheets of insulating paper were placed in the space between each column, as highlighted in fig. 8.2.

![Figure 8.1: Three-phase, three-column, air-cooled transformer selected for the experimental process, as originally acquired.](image)

Table 8.1 shows the rated values for the selected transformer, which were either directly taken or computed from the nameplate data.

<table>
<thead>
<tr>
<th>( V_p ) [V]</th>
<th>( I_p ) [A]</th>
<th>( V_s ) [V]</th>
<th>( I_s ) [A]</th>
<th>( S ) [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>5.77</td>
<td>5 x 52</td>
<td>8.88</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 8.1: Rated voltages, currents and apparent power for the transformer of fig. 8.1
The three-phase transformer is comprised of one delta connected primary winding and 5 wye connected secondary windings. Additionally, by inspecting the transformer topology, it was possible to conclude that the coils in each column are concentric, with the primary in the inner layer and the multiple secondaries on the outer layer. Figure 8.3 shows a single-phase scheme of the transformer windings.

As per the simulation method, part of the experimental process is to analyze the stress the transformer undergoes when a small percentage of its coil turns is lost due to turn-to-turn insulation failure, which produces a short-circuit. As a way to have a finer control over the percentage of short-circuited turns, it was decided that the 5 secondary windings, each initially wye-connected and independent from the
remaining four, should be connected in series, resulting in a single 260V wye-connected winding. To this end, the wye connections of each secondary had to be broken and rewired.

For the sake of versatility, a custom circuit board (board 2, shown in fig. 8.4) was built to serve as a host for the secondary winding connections. This board is comprised of a total of 27 terminals (12 positive and 15 negative terminals). Note that three of the positive terminals (one per phase), corresponding to the main secondary connection points, are not present, as they will connect directly to the main board (board 1) which will be described in further detail ahead.

![Figure 8.4: Top (a) and bottom (b) view of the custom connection board (board 2) for the multiple secondary terminals.](image)

The connection board of fig. 8.4 was then used to connect the five separate secondaries in the desired manner i.e., as a single, wye connected, 260V winding. The connection scheme and corresponding single-phase equivalent scheme are shown in fig. 8.5.

With the secondary board ready, the transformer was put inside a protective wooden box, with a front lid made of acrylic, which will serve as the main connection board for the experimental setup (fig. 8.6). In this board, there are three terminals for the primary winding, another three for the secondary (the main terminals that were not routed to the secondary board) and 8 fault emulation terminals (not used in this first stage), whose purpose will be explained in further detail ahead (section 8.3).

After rewiring the secondary winding terminals and rerouting them to the main and secondary connection boards as described, preliminary tests were carried out, to assess the condition of the transformer, and whether it is working according to expectations. Such tests are described ahead, in section 8.2.
8.2 Preliminary tests

As an intermediate step, it was considered appropriate to carry out a first set of tests in order to assess the operating condition of the transformer and, eventually, replace it in case prior damage. To that end, it was decided to perform:

1. An open circuit test;
2. A short circuit test;
3. A rated load test.
8.2.1 Open-circuit test

The open circuit test was performed by feeding the primary winding at rated voltage and keeping the secondary terminals open - fig. 8.7. This test allowed to verify whether the magnetization current of the transformer fell within the expected range. The results obtained for the line voltages and currents are presented in tab. 8.2.

![Connection scheme for the open-circuit test](image)

**Figure 8.7: Connection scheme for the open-circuit test: (a) primary; (b) secondary. AT: autotransformer connected between the low voltage grid and the transformer and feeding the primary winding at rated voltage.**

<table>
<thead>
<tr>
<th>Phase</th>
<th>( V_p ) [V]</th>
<th>( I_p ) [A]</th>
<th>( V_s ) [V]</th>
<th>( I_s ) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>227.24</td>
<td>0.19</td>
<td>153.50</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>224.19</td>
<td>0.18</td>
<td>151.92</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>227.36</td>
<td>0.24</td>
<td>152.74</td>
<td>-</td>
</tr>
</tbody>
</table>

By comparing the values of the magnetization current with the rated primary current (see tab. 8.1, it is possible to conclude that it is approximately 4%-5% . Thus, the magnetization current is considered to be within the expected range, which, for transformers with non grain-oriented cores, is in the order of 4%-14% [32].

8.2.2 Short-circuit test

Following the open-circuit test, a short-circuit test was also performed. The primary winding was fed at approximately rated current, with the secondary winding short-circuited - fig. 8.8. Analogously to the magnetization current, it was also considered necessary to assess whether the primary short-circuit voltage presented reasonable values. The line voltages and currents obtained from the short-circuit test are presented in tab. 8.2.

<table>
<thead>
<tr>
<th>Phase</th>
<th>( V_p ) [V]</th>
<th>( I_p ) [A]</th>
<th>( V_s ) [V]</th>
<th>( I_s ) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.86</td>
<td>5.91</td>
<td>-</td>
<td>8.92</td>
</tr>
<tr>
<td>B</td>
<td>8.01</td>
<td>5.75</td>
<td>-</td>
<td>8.39</td>
</tr>
</tbody>
</table>
Similarly to what was verified for the magnetization current, the primary short-circuit voltage is also approximately 4%-5% of the rated value, which is in line with expectation (3%-6% for transformers with rated power lower than 1000 kVA) [32].

8.2.3 Rated load test

Finally, a rated load test was performed, according to the connection scheme of fig. 8.9. Table 8.4 shows the values of the resistive load applied to each phase, on the secondary side, as well as the obtained line voltages and currents. The goal of this test was to verify whether all the line voltages and currents were approximately equal to the corresponding rated values, which is confirmed by tab. 8.4.

Table 8.4: Load values per phase and line voltages and currents obtained from the preliminary rated load test.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Load [Ω]</th>
<th>$V_p$ [V]</th>
<th>$I_p$ [A]</th>
<th>$V_s$ [V]</th>
<th>$I_s$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>18.1</td>
<td>227.54</td>
<td>5.57</td>
<td>147.52</td>
<td>8.17</td>
</tr>
<tr>
<td>B</td>
<td>18.2</td>
<td>226.40</td>
<td>5.54</td>
<td>146.41</td>
<td>8.03</td>
</tr>
<tr>
<td>C</td>
<td>18.0</td>
<td>228.63</td>
<td>5.64</td>
<td>147.11</td>
<td>8.16</td>
</tr>
</tbody>
</table>
Hence, it is possible to state that the transformer is in good operating condition and is considered fit to be altered and used for the intended purposes.

8.3 Experimental setup adaptation for incipient fault emulation

Since the goal of this experimental setup and associated procedure is to study incipient winding faults, some further adjustments had to be made on the transformer. Such adjustments correspond to the interruption and rerouting of 4 coil turns in phase B, on the secondary side, resulting in the situation depicted in the diagram of fig. 8.10(a), in which the altered section of the coil is represented. Four out of the five turns, all belonging to the same secondary winding, were cut open, thus creating 2 new terminals. In the end, a total of 8 connection terminals were created and routed to the right section of the board - figs. 8.10(b) and 8.10(c). Note that the 4th turn was left unaltered. The reason for this is that using the 5th turn instead of the 4th, not only does one gain the ability to emulate more severe faults, but it also moves the last fault terminals further down in the coil, which will be an advantage when attempting to establish potential fault location methodologies for this experimental setup (section 8.6).

![Figure 8.10: Schematic representation of connection diagram (a), junctions applied to coil turns (b) and rerouting of turn terminals to main connection board (c).](image)

The series connection of the positive and negative terminal in each turn, illustrated in fig. 8.11, restores the original connection scheme of the winding. However, one now has the option to remove 1 or more turns, thus emulating a single or multiple turn loss type fault. As an example, fig. 8.12 shows the con-
connection scheme corresponding to the loss of a single turn, by interrupting turns 2 and 3 and connecting the positive terminal of 2 to the negative terminal of 3.

![Connection Diagram](image1)

Figure 8.11: Setup with turns connected in series, without fault (a) and corresponding connection diagram (b).

![Setup Image](image2)

Figure 8.12: Setup with turns connected as to emulate a fault between turns 2 and 3 (a) and corresponding connection diagram (b).

The finalized experimental setup obtained following the aforementioned alterations is represented in fig. 8.13.

8.4 Transformer condition assessment following setup adaptation

After preparing the final instance of the experimental setup, it was necessary to assess whether the alterations made to the transformer greatly affected its operating condition. To that end, the preliminary
tests (open-circuit, short-circuit and rated load test) were repeated, and the results obtained for the voltages and currents in each phase were compared to the ones taken initially - tabs. 8.5 and 8.6.

Table 8.5: Line voltages and currents taken from open-circuit (OC), short-circuit (SC) and rated load (RL) tests, before and after experimental setup adaptation.

<table>
<thead>
<tr>
<th>Test</th>
<th>Before Adaptation</th>
<th>After Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OC</td>
<td>SC</td>
</tr>
<tr>
<td>( V_p ) [V] (RMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>227.24</td>
<td>8.86</td>
</tr>
<tr>
<td>B</td>
<td>224.19</td>
<td>8.01</td>
</tr>
<tr>
<td>C</td>
<td>227.36</td>
<td>9.88</td>
</tr>
<tr>
<td>( I_p ) [A] (RMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.19</td>
<td>5.91</td>
</tr>
<tr>
<td>B</td>
<td>0.18</td>
<td>5.75</td>
</tr>
<tr>
<td>C</td>
<td>0.24</td>
<td>6.26</td>
</tr>
<tr>
<td>( V_s ) [V] (RMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>153.50</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>151.92</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>152.74</td>
<td></td>
</tr>
<tr>
<td>( I_s ) [A] (RMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>8.39</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>9.12</td>
</tr>
</tbody>
</table>

By inspecting tab. 8.6, one concludes that most of the measured quantities display variations of no more than 5% after introducing the aforementioned alterations and can thus be disregarded. However, a few remarks should be made:

1. In the open-circuit test, the primary current, i.e., the magnetization current, is very small. This means that a small numerical variation in its value will translate in a high deviation.
2. In the short-circuit test, a great increase in the primary short-circuit voltage is observed in phase B, as well as a significant decrease of the secondary short-circuit current. Both these variations can be explained by the increase in resistance in the secondary side due to the introduction of multiple
junctions and cables in the process of rerouting the coil turn terminals to the main connection board.

8.5 Experimental emulation of transformer winding faults

With the final installment of the experimental setup and with its operating condition reassessed, it is now ready to perform the desired winding fault emulation tests, which are listed and described in tab. 8.7. Figure 8.14 shows the schematic diagrams for the connections made in the fault emulation terminals for each test mentioned in tab. 8.7. From this point forward, to simplify the task of reading this document, tests shall be referred to as defined in this section.

Table 8.7: Identification and description of experimental tests to be carried out concerning the emulation of incipient winding faults.

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 2</td>
<td>Positive terminal of turn 1 connected to negative terminal of turn 2. Turn 1 is lost, the remaining are connected normally.</td>
</tr>
<tr>
<td>1 - 3</td>
<td>Positive terminal of turn 1 connected to negative terminal of turn 3. Turns 1 and 2 are lost, the remaining are connected normally.</td>
</tr>
<tr>
<td>1 - 5</td>
<td>Positive terminal of turn 1 connected to negative terminal of turn 5. All turns (1 through 5) are lost.</td>
</tr>
<tr>
<td>2 - 3</td>
<td>Positive terminal of turn 2 connected to negative terminal of turn 3. Turn 2 is lost, the remaining are connected normally.</td>
</tr>
<tr>
<td>2 - 5</td>
<td>Positive terminal of turn 1 connected to negative terminal of turn 2. Turn 2 to 5 are lost, turn 1 is connected normally.</td>
</tr>
<tr>
<td>3 - 5</td>
<td>Positive terminal of turn 3 connected to negative terminal of turn 5. Turns 3 and 4 are lost, the remaining are connected normally.</td>
</tr>
</tbody>
</table>

8.6 Experimental results

After performing the tests described in section 8.5 (tab. 8.7), it was decided to separately analyze three types of variables:
Figure 8.14: Connection diagrams for the tests described in tab. 8.7: (a) Reference; (b) 1 - 2; (c) 1 - 3; (d) 1 - 5; (e) 2 - 3; (f) 2 - 5; (g) 3 - 5.

1. Electrical quantities: line voltages and currents and respective symmetric components;

2. Magnetic flux density leakage in the inter-limb space;

3. Core temperature above each limb.

8.6.1 Voltages and currents

As a first approach, the line voltages and currents are analyzed. Table 8.8 shows the measured values in each phase for the line voltages and currents on either side of the transformer.

To facilitate the analysis of such variables, it was decided to compute, for each test, the variations with respect to the reference test. Such variations are shown in tab. 8.9, where the highlighted lines correspond to the variables in which a clear trend can be observed. Note that, for all intended purposes, the word "trend" refers not to the numerical values, but to the direction of variation, i.e., to whether the variable increases or decreases with respect to its reference value. Thus, a variable is considered to
Table 8.8: Experimental results for line voltages and currents on primary and secondary side.

<table>
<thead>
<tr>
<th>Number of Lost Turns</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Reference</td>
<td>1 - 2</td>
<td>2 - 3</td>
<td>1 - 3</td>
<td>3 - 5</td>
</tr>
<tr>
<td>(V_p) [V] (RMS)</td>
<td>A 226.56</td>
<td>226.49</td>
<td>225.93</td>
<td>225.91</td>
<td>225.98</td>
</tr>
<tr>
<td></td>
<td>B 225.64</td>
<td>226.01</td>
<td>224.44</td>
<td>225.18</td>
<td>224.72</td>
</tr>
<tr>
<td></td>
<td>C 227.50</td>
<td>226.91</td>
<td>225.93</td>
<td>226.92</td>
<td>227.63</td>
</tr>
<tr>
<td>(I_p) [A] (RMS)</td>
<td>A 5.64</td>
<td>5.58</td>
<td>5.55</td>
<td>5.51</td>
<td>5.53</td>
</tr>
<tr>
<td></td>
<td>B 5.49</td>
<td>5.46</td>
<td>5.42</td>
<td>5.37</td>
<td>5.41</td>
</tr>
<tr>
<td></td>
<td>C 5.55</td>
<td>5.54</td>
<td>5.46</td>
<td>5.50</td>
<td>5.61</td>
</tr>
<tr>
<td>(V_s) [V] (RMS)</td>
<td>A 146.67</td>
<td>146.21</td>
<td>146.31</td>
<td>146.08</td>
<td>146.20</td>
</tr>
<tr>
<td></td>
<td>B 144.70</td>
<td>143.91</td>
<td>144.03</td>
<td>143.18</td>
<td>142.91</td>
</tr>
<tr>
<td></td>
<td>C 146.49</td>
<td>146.40</td>
<td>146.67</td>
<td>146.11</td>
<td>145.86</td>
</tr>
<tr>
<td>(I_s) [A] (RMS)</td>
<td>A 8.24</td>
<td>8.20</td>
<td>8.18</td>
<td>8.19</td>
<td>8.22</td>
</tr>
<tr>
<td></td>
<td>B 7.90</td>
<td>7.86</td>
<td>7.86</td>
<td>7.80</td>
<td>7.83</td>
</tr>
<tr>
<td></td>
<td>C 7.93</td>
<td>7.91</td>
<td>7.96</td>
<td>7.90</td>
<td>8.01</td>
</tr>
</tbody>
</table>

show a variational trend if its value, in the presence of a fault, is always lower or always higher than the reference.

Table 8.9: Experimental results for line voltages and currents on primary and secondary side - variations with respect to rated load test (reference).

<table>
<thead>
<tr>
<th>Number of Lost Turns</th>
<th>1 - 2</th>
<th>2 - 3</th>
<th>1 - 3</th>
<th>3 - 5</th>
<th>2 - 5</th>
<th>1 - 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_p) [%]</td>
<td>A -0.03</td>
<td>-0.28</td>
<td>-0.29</td>
<td>-0.26</td>
<td>-0.12</td>
<td>-0.26</td>
</tr>
<tr>
<td></td>
<td>B +0.16</td>
<td>-0.53</td>
<td>-0.20</td>
<td>-0.41</td>
<td>-0.39</td>
<td>+0.27</td>
</tr>
<tr>
<td></td>
<td>C -0.26</td>
<td>-0.69</td>
<td>-0.26</td>
<td>+0.15</td>
<td>+0.29</td>
<td>-1.32</td>
</tr>
<tr>
<td>(I_p) [%]</td>
<td>A -1.14</td>
<td>-1.65</td>
<td>-2.25</td>
<td>-2.01</td>
<td>-3.24</td>
<td>-4.06</td>
</tr>
<tr>
<td></td>
<td>B -0.66</td>
<td>-1.28</td>
<td>-2.07</td>
<td>-1.42</td>
<td>-2.87</td>
<td>-3.33</td>
</tr>
<tr>
<td></td>
<td>C -0.22</td>
<td>-1.63</td>
<td>-0.91</td>
<td>+1.10</td>
<td>+0.26</td>
<td>-1.17</td>
</tr>
<tr>
<td>(V_s) [%]</td>
<td>A -0.31</td>
<td>-0.24</td>
<td>-0.40</td>
<td>-0.32</td>
<td>+0.17</td>
<td>-0.86</td>
</tr>
<tr>
<td></td>
<td>B -0.55</td>
<td>-0.46</td>
<td>-1.05</td>
<td>-1.24</td>
<td>-1.41</td>
<td>-2.04</td>
</tr>
<tr>
<td></td>
<td>C -0.06</td>
<td>+0.12</td>
<td>-0.26</td>
<td>-0.43</td>
<td>-0.06</td>
<td>-0.79</td>
</tr>
<tr>
<td>(I_s) [%]</td>
<td>A -0.43</td>
<td>-0.67</td>
<td>-0.55</td>
<td>-0.23</td>
<td>-0.42</td>
<td>-1.49</td>
</tr>
<tr>
<td></td>
<td>B -0.43</td>
<td>-0.48</td>
<td>-1.25</td>
<td>-0.86</td>
<td>-1.24</td>
<td>-2.82</td>
</tr>
<tr>
<td></td>
<td>C -0.24</td>
<td>+0.39</td>
<td>-0.41</td>
<td>+0.92</td>
<td>+0.88</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

From tab. 8.9, one can state the following conclusions:

1. The voltage in the faulty phase (B) of the secondary winding decreases as one removes coil turns, since the total induced voltage is proportional to the number of turns;

2. The current in the faulty phase (B) decreases both in the primary and secondary. This is a consequence of the core demagnetization caused by the fault, which is caused by a backward magnetic field. This in turn induced a small current in the coils which flows in the opposite direction of the injected current, thus lowering the overall current flow towards the load.

To further analyze the influence of the emulated incipient winding faults in the transformer voltages and currents, the symmetrical components systems corresponding to each electrical variable were computed. The obtained results are shown in tab. 8.10. Note that, while the results of tab. 8.8 are shown in terms of RMS values only, the symmetric components depend on the phase angles of the line voltages.
and currents. The measurement of such quantities with the available setup has limited accuracy, which affects the results of tab. 8.10 to some extent. For example, the computation of the symmetric components yielded non-zero values (although small) for the zero sequence current on the primary side, which is delta-connected, and should therefore have null zero sequence current.

Table 8.10: Experimental results for voltages and currents on primary and secondary side, in terms of symmetrical components.

<table>
<thead>
<tr>
<th>Number of Lost Turns</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>Reference</td>
<td>1 - 2</td>
<td>2 - 3</td>
<td>1 - 3</td>
<td>2 - 5</td>
</tr>
<tr>
<td>V_p [V] (RMS)</td>
<td>D</td>
<td>225.78</td>
<td>224.51</td>
<td>219.94</td>
<td>224.57</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>8.16</td>
<td>16.46</td>
<td>33.47</td>
<td>13.47</td>
</tr>
<tr>
<td>I_p [A] (RMS)</td>
<td>D</td>
<td>5.50</td>
<td>5.44</td>
<td>5.33</td>
<td>5.41</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.16</td>
<td>0.33</td>
<td>0.75</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V_s [V] (RMS)</td>
<td>D</td>
<td>145.06</td>
<td>143.74</td>
<td>142.80</td>
<td>143.18</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>9.80</td>
<td>14.73</td>
<td>19.40</td>
<td>14.84</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>10.42</td>
<td>15.57</td>
<td>18.80</td>
<td>16.06</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td>D</td>
<td>7.97</td>
<td>7.88</td>
<td>7.84</td>
<td>7.85</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>0.50</td>
<td>0.80</td>
<td>1.02</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.58</td>
<td>0.84</td>
<td>1.03</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Similarly to what was done for the line voltages and currents, the variations of each quantity with respect to the reference test were taken. The results are summarized in tab. 8.11, where, contrary to tab. 8.9, the highlights were suppressed, since, in this case, most all variables display what was previously defined as a trend, never changing the signal of variation with respect to the reference. This can be explained by the fact that all the symmetric components are affected by phase B, where the fault is located.

Table 8.11: Experimental results for voltages and currents on primary and secondary side, in terms of symmetrical components - variations with respect to rated load test (reference).

<table>
<thead>
<tr>
<th>Number of Lost Turns</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>1 - 2</td>
<td>2 - 3</td>
<td>1 - 3</td>
<td>2 - 5</td>
</tr>
<tr>
<td>V_p [V] (RMS)</td>
<td>D</td>
<td>-0.56%</td>
<td>-2.59%</td>
<td>-0.54%</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>+101.64%</td>
<td>+310.03%</td>
<td>+64.98%</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>+78.69%</td>
<td>+240.85%</td>
<td>+60.95%</td>
</tr>
<tr>
<td>I_p [A] (RMS)</td>
<td>D</td>
<td>-1.09%</td>
<td>-3.10%</td>
<td>-1.67%</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>+110.33%</td>
<td>+370.85%</td>
<td>+74.65%</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>+44.80%</td>
<td>+181.07%</td>
<td>+10.61%</td>
</tr>
<tr>
<td>V_s [V] (RMS)</td>
<td>D</td>
<td>-0.91%</td>
<td>-1.56%</td>
<td>-1.30%</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>+50.27%</td>
<td>+97.86%</td>
<td>+51.42%</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>+49.48%</td>
<td>+80.44%</td>
<td>+54.12%</td>
</tr>
<tr>
<td>I_s [A] (RMS)</td>
<td>D</td>
<td>-1.11%</td>
<td>-1.63%</td>
<td>-1.51%</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>+62.26%</td>
<td>+106.06%</td>
<td>+48.77%</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>+44.78%</td>
<td>+79.34%</td>
<td>+57.63%</td>
</tr>
</tbody>
</table>

From the results presented so far, one can state that, by looking at the line voltages and currents of phase B and by analyzing the symmetric components system of the transformer, it is possible to identify the presence of a fault. However, it is not yet established whether one can identify its level of severity. In
order to do so, a severity ranking had to be created for the 6 fault tests performed. Such ranking should be based on the following criteria:

1. The loss of a greater number of coil turns is always more severe (for example, the loss of 2 turns is more severe than the loss of a single turn, regardless of fault location);

2. For the same number of lost coil turns, the fault becomes more severe as one moves downward in the coil, farther from the middle section and closer to the bottom extremity of the limb. This consideration is based on the simulation results of chapter 7, where it was established that the demagnetization of the iron core is stronger when the fault happens closer to one of the extremities of the limb.

Regarding these criteria, a few remarks should be made. The first is based on the fact that one can look at the line voltage as the sum of all single turn voltages in the coil (which, in theory, are all equal). By losing a higher number of turns, one loses a greater portion of the line voltage.

The second criterion, however, is based on the simulation results presented in chapter 7, where it was established that, by moving the fault closer to either extremity of the limb (top or bottom), the demagnetization of the core caused by the fault is more intense, which results in higher magnetic flux leakage. For example, a fault between turns 1 and 2 is close to the middle of the limb, while a fault between turns 3 and 4 is closer to its bottom extremity.

Table 8.12 shows the severity ratings obtained by looking at the variables of interest. The “Reference” row defines the expected ratings for each test (number and color) according to the aforementioned criteria. By comparing the ratings obtained from a certain variable to the reference row, one can assess how accurate it is in locating the fault. The rightmost column shows the accuracy of each variable regarding the severity ratings, i.e., the percentage of tests that were rated in accordance with the reference.

<table>
<thead>
<tr>
<th>Method</th>
<th>Severity Rating</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_p$</td>
<td>D 2 3 4 5 6</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>I 3 6 2 5 1</td>
<td>16.67%</td>
</tr>
<tr>
<td></td>
<td>H 3 6 2 5 1</td>
<td>16.67%</td>
</tr>
<tr>
<td>$I_p$</td>
<td>B 1 2 3 5 6</td>
<td>66.67%</td>
</tr>
<tr>
<td></td>
<td>D 1 6 2 5 1</td>
<td>16.67%</td>
</tr>
<tr>
<td></td>
<td>I 3 6 2 5 1</td>
<td>16.67%</td>
</tr>
<tr>
<td>$V_s$</td>
<td>B 2 1 3 4 5</td>
<td>66.67%</td>
</tr>
<tr>
<td></td>
<td>D 1 3 2 5 4</td>
<td>33.33%</td>
</tr>
<tr>
<td></td>
<td>I 2 5 3 1 6</td>
<td>16.67%</td>
</tr>
<tr>
<td></td>
<td>H 1 5 2 3 6</td>
<td>16.67%</td>
</tr>
<tr>
<td>$I_s$</td>
<td>B 1 2 3 4 6</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>D 1 2 3 4 6</td>
<td>66.67%</td>
</tr>
<tr>
<td></td>
<td>I 3 5 1 2 6</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>H 1 5 3 2 6</td>
<td>16.67%</td>
</tr>
</tbody>
</table>

As expected, by looking only at electrical variables, it is difficult to accurately locate faults within a given coil, since the effect of fault location is less evident in electrical variables than in magnetic quantities,
as shown by the simulation methods described in chapter 7. Specifically, methods based on analysis of symmetric component variables see their accuracy greatly degraded by the fact that experimental measurement of voltage and current phase angles with the available setup is subjected to great uncertainty.

However, if one is solely concerned with the detectability and severity of the fault in terms of the number lost turns, rather than its location, it is possible to obtain higher levels of accuracy. To illustrate this point, fault tests were grouped according to the number of lost turns and average severity ratings were taken for each group. The results are presented in tab. 8.13, where all variables from tab. 8.12 that showed an accuracy lower than 50% have been discarded.

Table 8.13: Average severity rating of each fault test according to different electrical variables and number of lost coil turns.

<table>
<thead>
<tr>
<th>Number of Lost Turns</th>
<th>Average Severity Rating</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Method 1 - 2</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Method 2 - 3</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Method 1 - 3</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Method 3 - 5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Method 2 - 5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Method 1 - 5</td>
<td>1.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Thus, it is possible to conclude that, for the experimental setup at hand, the fault analysis methods based solely on electrical variables were successful in identifying the presence of incipient faults and, accurately enough, distinguish them according to the number of turns affected by the fault. However, such methods are not as accurate in identifying fault location within the coil, which, as previously stated, is in accordance with the simulation results of chapter 7.

8.6.2 Magnetic flux density and leakage flux measurement

Alongside the line voltages and currents, the magnetic flux density leakage between the transformer limbs was also measured for the same set of tests, resorting to two hall effect probes similar to the one of fig. 8.15.

The working principle of Hall effect sensors is that, if fed at a constant DC current, the interaction between that current and the magnetic flux through the sensor surface results in Lorentz forces which act upon the electric charges in the sensor, generating an electromotive force - the Hall voltage - which is directly proportional to the magnetic flux density. This is illustrated by fig. 8.16 [33].

In the case of the probes used in this setup, they were fed by a DC voltage source set to 5V, which is their rated bias voltage. The signals measured in the oscilloscope are proportional to the magnetic flux density such that: the lower saturation voltage is 0V, which corresponds to a flux density of -80 mT; the point where the flux density is null is located at half the bias voltage (2.5V); finally, the positive saturation voltage is equal to the bias (5V) and corresponds to a magnetic flux density of 80 mT. This characteristic behavior is illustrated in fig. 8.17, adapted from [34]. The magnetic flux density leakage measurement setup is represented in fig. 8.18.
The probe measurements are very sensitive to its position. Therefore, a preliminary test was performed, in which the probes were moved vertically along the limbs, in the inter-limb space, as to find the position where the magnetic flux density measurement was maximal. By trial and error, it was concluded that the probes should be positioned in the lower section of the space between the limbs, as illustrated by fig. 8.19. Note that the second probe, which is invisible in this figure, is placed symmetrically, relative to the middle limb.
Figure 8.18: Measurement setup used with the hall effect probes to measure the magnetic flux density leakage between transformer limbs.

Figure 8.19: Location of the hall effect probes in the inter-limb space.

From the measurements taken during the fault emulation tests resorting to this setup, it was not possible to distinguish significant variations of the magnetic flux density leakage in the presence of faults. This observation goes against the conclusions of chapter 7, which might indicate that such conclusions are not strictly scalable. A few reasons for this could be the following:

1. The magnetic flux density leakage is greatly dependent on the geometry and especially the volume of the magnetic circuit and, hence, has to be analyzed in greater depth, taking into account the geometric aspect of the transformer to be studied;
2. The detection of faults by measurement of magnetic flux density leakage might not be possible at such a small scale. While the simulations of chapter 7 refer to a 690kVA distribution transformer, the available experimental setup uses a small 4kVA transformer, for which the maximum magnetic flux density measured between limbs is very small (in the order of 3 mT).

### 8.6.3 Temperature tests

Although temperature analysis was not within the original scope of this work, it was decided on a later phase that performing some kind of experimental test would be appropriate, to stress the importance of temperature analysis for transformer incipient fault detection.

Due to time constraints, it was not possible to perform an extensive analysis on the variation of temperature with the appearance of faults. Thus, it was decided to first establish a baseline for comparison by performing a rated load test. Then, the fault corresponding to total loss of all rerouted turns (worst incipient fault possible with the current experimental setup) was also tested.

During each test, the transformer was left operating with its case open until temperature stabilization was achieved. Note that, at a certain time range, one reaches a state where the measured temperatures can vary approximately $2^\circ C$ around a fixed average value. Thus, for all intended purposes, the criteria for reaching stabilization was defined as not verifying a variation in the average value of each measured temperature for a period of, at least, 5 minutes.

It was decided to take core temperature measurements in 3 points simultaneously, one above each limb (see fig. 8.21). The reasoning behind this relates to the fact that, although overall core temperature is expected to increase in the presence of incipient faults, that increase should be more significant in the middle limb, since the fault occurs in phase B.

To perform those measurements, three thermo/clock sensors similar to the one of fig. 8.20 were used. The digital thermometer has two distinct temperature displays: the "IN" temperature is measured by a sensor located in the interior of the device; the "OUT" temperature is measured by a second sensor, located outside the device. In this case, the "IN" measurement corresponds to the ambient temperature, while "OUT" refers to the sensors placed on top of the transformer core.

![Figure 8.20: RS Pro Dual Thermo/Clock digital thermometer.](image)

Table 8.14 shows the results obtained for the stabilized temperature measurements in both tests. Note that ambient temperature was also measured, as to establish a baseline for comparison, and temperature variations were computed by removing the ambient temperature offset.
Figure 8.21: Location of thermal sensors on top section of the transformer core.

Table 8.14: Ambient and core temperature measurements and respective temperature differential directly above each transformer limb, with and without the presence of an incipient fault

<table>
<thead>
<tr>
<th>Without Fault</th>
<th>Left Limb</th>
<th>Middle Limb</th>
<th>Right Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient [°C]</td>
<td>26.5</td>
<td>26.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Core [°C]</td>
<td>57.5</td>
<td>58.5</td>
<td>58.0</td>
</tr>
<tr>
<td>Difference [°C]</td>
<td>31.0</td>
<td>32.0</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>With Fault (1-5)</th>
<th>Left Limb</th>
<th>Middle Limb</th>
<th>Right Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient [°C]</td>
<td>26.0</td>
<td>25.5</td>
<td>26.0</td>
</tr>
<tr>
<td>Core [°C]</td>
<td>62.5</td>
<td>63.5</td>
<td>62.5</td>
</tr>
<tr>
<td>Difference [°C]</td>
<td>36.5</td>
<td>38.0</td>
<td>36.5</td>
</tr>
</tbody>
</table>

By inspecting tab. 8.14, one can conclude that the increase in temperature variation due to the presence of an incipient fault is evident. To further illustrate this point, the percentual increase was computed according to (8.1), where \( \theta_G \) denotes temperature variation. This computation yields the temperature variation increases of tab. 8.15.

\[
\Delta \theta_{diff} = \frac{\theta_{fault} - \theta_{ref}}{\theta_{ref}}
\]  

(8.1)

Table 8.15: Increase in temperature due to the presence of incipient fault in middle limb.

<table>
<thead>
<tr>
<th>Temperature Increase</th>
<th>Left Limb</th>
<th>Middle Limb</th>
<th>Right Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17.74%</td>
<td>18.75%</td>
<td>15.87%</td>
</tr>
</tbody>
</table>

These results indicate not only that the presence of an incipient fault might cause core temperature to increase greatly, but also that, as expected, said increase will potentially be more significant in the limb where the fault occurs. This can be explained by the demagnetization of the core and consequent redistribution of magnetic flux density due to the presence of an incipient fault in the middle limb.
However, note that this conclusion should be subjected to further study, since only a limited number of tests were performed.
Chapter 9

Conclusions

This chapter finalizes this work, summarizing the most important conclusions and pointing out aspects to be developed in future work.
9.1 Achievements

This thesis aimed at developing a simulation model which would allow for simulation of a distribution transformer with internal incipient faults, as well as obtain an experimental setup capable of emulating such events. The main goal was to thoroughly study a set of interest variables, and to propose a possible methodology for detecting and locating internal faults.

The achieved FEM model is able to perform quick, 2D, frequency domain simulations, which allowed one to gather massive amounts of simulation data with relatively low computational cost. Furthermore, the accuracy of this model was validated by comparing frequency domain results with time domain studies, which have slightly higher precision but considerably more significant computation times.

With the results of the simulation process, it was possible, by crossing the behaviors of the studied variables, to provide a potential methodology for incipient fault detection and localization for faults in the secondary winding of distribution transformers. A less complete version of said methodology was also suggested for faults on the primary side.

The experimental setup which was built in the laboratory gave a clearer view on the variables of interest, especially regarding their dependence on machine geometry and power scale, which is an important part of the work to be carried out in the future.

9.2 Future Work

In this section, some guidelines for future work are provided:

• Simulation of transformer behavior with typical varying load profiles to approximate the operating conditions of field units;

• Performance of 2D simulations for multiple geometries and rated voltage/current levels in order to assess geometry dependence and scalability of the proposed methodologies;

• Discretization of the magnetic leakage flux measurement method to approximate sensor installation and improve localization capabilities;

• Development of a 3D simulation model, to account for non-uniform distribution of magnetic flux density and enable the simulation of the thermal behavior of the transformer;

• Injection of data gathered from field units by Eneida Wireless & Sensors, S.A., in the aforementioned 3D model and assessment of hot-spot locations, which will be critical points for studying incipient faults;

On a final note, it should be stressed that, although the above list has no particular order of priority, it is believed that a discretization of the magnetic flux leakage measurement method would represent the least time-consuming way of improving the proposed methodology in terms of locating incipient faults. This is considered to be a key aspect, since it has been established in this thesis that the magnetic flux
density distribution is intrinsically linked with incipient fault location. By making the leakage flux measurements discrete, therefore approximating the behavior of a real sensor system, and cross-referencing the measurements of different measurement surfaces, it would potentially be possible to detect a fault, distinguish the phase and locate it vertically within the coil.
Bibliography


[6] *Quantifying the Bathtub Curve: Measuring Your Capex Reduction and Delayed IT Expenditures from Sourcing Hardware from OSI is Easy*. OSI Hardware, 606 Olive Street, Santa Barbara, CA 93101.


Temperature_Distribution_in_Windings_of_Transformers_with_natural_Oil_circulation


Appendix A

Matlab script for effective B-H curve computation

1 % Effective B-H curve computation
2 %
3 % Given a sinusoidal B(t) with amplitude Bmax and frequency f:
4 % 1 - for each Bmax, the corresponding Hmax is computed, along with the
5 % average magnetic energy in a half cycle.
6 % 2 - the equivalent amplitude H\text{eq} is then computed such that the
7 % magnetic energy remains constant.
8 %
9 % INPUTS:
10 % BH - DC B-H Curve of the material
11 % f - electrical frequency
12 % nt - number of sample points per cycle
13 % n\text{BH eff} - number of points to compute for effective BH curve
14 %
15 % OUTPUTS:
16 % B\text{H eff} - Effective B-H curve (RMS values)
17 % t - Single-cycle timestamp vector
18 % B(t) - B(t) applied to obtain each point of the effective B-H curve
19 % H(t) - H(t) corresponding to each B(t)
20 % W(t) - Magnetic energy W(t) computed for a half cycle
21 %
22 % CREATED BY: Pedro Bhagubai (2019)
23 % 1st REVISION: Guilherme Freire (2020)
function [BHeff, t, Bt, Ht, Wt] = computeBHeffective(BH, f, nt, nBHeff)

% mirror DC B-H curve to obtain AC curve (no hysteresis)
BH.B = [-flipud( BH.B(2:end) ); BH.B ];
BH.H = [-flipud( BH.H(2:end) ); BH.H ];

t = linspace( 0, 1/f, nt ); % single-cycle timestamp vector
id = round( nt/2 ); % find index corresponding to half-cycle

Bsat = max( BH.B ); % find maximum point in the B-H curve
Bmax = linspace(0 , Bsat , nBHeff ); % B amplitude vector

% preallocations for computational speed
Bt = zeros( nt, nBHeff );
Ht = zeros( nt, nBHeff );
Wt = zeros( nt, nBHeff );
Wav = zeros( nBHeff, 1 );
Heq = zeros( nBHeff, 1 );

for i = 2 : nBHeff

% impose sinusoidal B(t) with amplitude equal to Bmax(i)
Bt(:,i) = Bmax(i) * sin(2*pi*f*t);

% compute corresponding H(t)
Ht(:,i) = interp1( BH.B, BH.H , Bt(:,i) ); % add 'extrap' if necessary

% compute magnetic energy over time as the integral of H.dB from t=0 to t = T
for j = 2 : nt
    Wt(j,i) = trapz( Bt(1:j,i) , Ht(1:j,i) );
end

% compute average energy over a half-cycle
Wav(i) = (2*f) * trapz( t(1:id), Wt(1:id,i) );
%
% compute equivalent amplitude of H according to Average Energy Method
Heq(i) = 4/Bmax(i) * Wav(i);

end

% export effective B-H curve
BHeff.Brms = Bmax' / sqrt(2);
BHeff.Hrms = Heq / sqrt(2);

end
Appendix B

Gradual single turn loss in primary winding

Table B.1: Line voltages and currents obtained for a gradual single turn loss in phase B, on the primary side (1st turn). The rows highlighted in red and green present the only relevant variations.

<table>
<thead>
<tr>
<th>Level of turn loss</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ip [A]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>26.03</td>
<td>26.35</td>
<td>26.71</td>
<td>28.37</td>
<td>31.08</td>
<td>37.72</td>
</tr>
<tr>
<td>C</td>
<td>26.89</td>
<td>27.23</td>
<td>27.63</td>
<td>29.38</td>
<td>32.09</td>
<td>38.20</td>
</tr>
<tr>
<td>V_s [V]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>229.43</td>
<td>229.43</td>
<td>229.44</td>
<td>229.45</td>
<td>229.46</td>
<td>229.49</td>
</tr>
<tr>
<td>B</td>
<td>229.39</td>
<td>229.38</td>
<td>229.38</td>
<td>229.35</td>
<td>229.29</td>
<td>229.15</td>
</tr>
<tr>
<td>C</td>
<td>229.38</td>
<td>229.38</td>
<td>229.38</td>
<td>229.37</td>
<td>229.34</td>
<td>229.29</td>
</tr>
<tr>
<td>Is [A]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>989.40</td>
<td>989.41</td>
<td>989.43</td>
<td>989.49</td>
<td>989.59</td>
<td>989.76</td>
</tr>
<tr>
<td>B</td>
<td>989.27</td>
<td>989.25</td>
<td>989.23</td>
<td>989.14</td>
<td>988.97</td>
<td>988.50</td>
</tr>
<tr>
<td>C</td>
<td>989.22</td>
<td>989.20</td>
<td>989.17</td>
<td>989.06</td>
<td>988.87</td>
<td>988.45</td>
</tr>
</tbody>
</table>
Figure B.1: Magnetic flux density distribution at 100% turn loss for a fault in the 1st turn of phase B, in the primary winding.

Figure B.2: Evolution of the positive and negative sequence components of the primary currents with the gradual loss of the 1st turn of the primary winding, phase B.
Figure B.3: Normalized magnetic leakage flux to the left (black) and right (red) of the middle limb for a gradual 1st turn loss fault in the primary winding, phase B. Both curves (black and red) are coincident.

Figure B.4: Variation of the flux leakage in the middle limb according to fault location and severity, for a single turn loss fault in phase B of the primary winding: (a) 2D representation; (b) 3D representation.
Figure B.5: Line current obtained for a gradual single turn loss in the primary winding (phase B) in different fault locations (1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation.

Figure B.6: Positive and negative sequence currents obtained for a gradual single turn loss in the primary winding (phase B) in different fault locations (1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.
Appendix C

Gradual multiple turn loss

Figure C.1: Line current obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation.
Figure C.2: Line current obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1\textsuperscript{st}, 325\textsuperscript{th}, 651\textsuperscript{st}, 975\textsuperscript{th} and 1300\textsuperscript{th} turns) and fault severity levels: (a) current, 2D representation; (b) current, 3D representation.

Figure C.3: Positive and negative sequence currents obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1\textsuperscript{st}, 325\textsuperscript{th}, 651\textsuperscript{st}, 975\textsuperscript{th} and 1300\textsuperscript{th} turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.
Figure C.4: Positive and negative sequence currents obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th, and 1300th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

Figure C.5: Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.
Figure C.6: Variation of the magnetic flux leakage in the middle limb obtained for a gradual three turn loss in the primary winding (phase B) in different fault locations (starting at the 1st, 325th, 651st, 975th and 1300th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

Figure C.7: Line current obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.
Figure C.8: Line current obtained for a gradual three turn loss in the secondary winding (phase B) in different fault locations (starting at the 1\textsuperscript{st}, 4\textsuperscript{th}, 11\textsuperscript{th}, 15\textsuperscript{th} and 20\textsuperscript{th} turns) and fault severity levels: (a) voltage, 2D representation; (b) voltage, 3D representation; (c) current, 2D representation; (d) current, 3D representation.
Figure C.9: Positive and negative sequence currents obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.
Figure C.10: Positive and negative sequence currents obtained for a gradual three turn loss in the secondary winding (phase B) in different fault locations (starting at the 4th, 11th, 15th and 20th turns) and fault severity levels: (a) positive sequence, 2D representation; (b) positive sequence, 3D representation; (c) negative sequence, 2D representation; (d) negative sequence, 3D representation.

Figure C.11: Normalized magnetic leakage flux to the left (black) and right (red) of the middle limb for a gradual turn loss fault in the secondary winding, phase B, starting in the 1st turn: (a) loss of 2 turns; (b) loss of 3 turns. Both curves (black and red) are coincident.
Figure C.12: Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.

Figure C.13: Variation of the magnetic flux leakage in the middle limb obtained for a gradual two turn loss in the secondary winding (phase B) in different fault locations (starting at the 1st, 4th, 11th, 15th and 20th turns) and fault severity levels: (a) 2D representation; (b) 3D representation.
Figure C.14: Magnetic flux density distribution at 100% turn loss for a two turn fault in the 1st – 2nd turns of phase B, in the secondary winding: (a) global view; (b) detail of faulty section.

Figure C.15: Magnetic flux density distribution at 100% turn loss for a three turn fault in the 1st – 3rd turns of phase B, in the secondary winding: (a) global view; (b) detail of faulty section.