

**MODELLING SWEEP FREQUENCY RESPONSE OF  
POWER TRANSFORMERS**

Kotagama Lansakara Imiya Mudiyansele Pramod Bandara Jayarathna

(178069V)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

October 2018

# **MODELLING SWEEP FREQUENCY RESPONSE OF POWER TRANSFORMERS**

Kotagama Lansakara Imiya Mudiyansele Pramod Bandara Jayarathna

(178069V)

Dissertation submitted in partial fulfilment of the requirements  
for the degree Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

October 2018

## **DECLARATION**

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)

Signature:

Date:

K.L.I.M.P.B.Jayarathna

The above candidate has carried out research for the Masters Dissertation under my supervision.

Signatures of the supervisors:

Dr.Rasara Samarasinghe

Date:

Prof. Rohan lucas

Date:

## **ABSTRACT**

Condition monitoring of power system components is crucial in order to supply quality and uninterrupted power supply to its consumers. Among other components, the power transformer is considered to be one of the most expensive and vital components in the power network. Therefore condition assessment and fault diagnosis of power transformers have become main features of the power system's maintenance strategy. Sweep frequency response analysis is a widely used condition monitoring technique to assess mechanical integrity of power transformers. SFRA measures the transformer response to a wide frequency input signal and provides a graphical frequency response of the transformer that needs to be analysed and interpreted afterwards. This thesis presents a novel approach to determine lumped parameter equivalent circuit of transformers using transfer functions estimated from measured SFRA response. Firstly, a novel algorithm based on Levy's and Sanathanan-Koerner method is used to convert the graphical SFRA curves into transfer function in Laplace domain. Once transfer functions estimation is derived, the lumped parameter equivalent circuit model is developed using artificial neural network and genetic algorithm integrated approach. In fact, artificial neural network is used to derive the initial approximation of genetic algorithm where artificial neural network results are optimized by genetic algorithm to find the final estimated parameters. The entire approach has been validated by means of error analysis and actual responses. Furthermore, modelled equivalent circuits by the proposed method have been incorporated to develop reference curves for various power transformer fault types which can be used to assess the severity and fault location of failures. This method can be easily implemented in a digital computer and can be used in on-site fault diagnosis of power transformers.

## **ACKNOWLEDGEMENT**

I would like to express my sincere gratitude to my supervisors, Dr. Rasara samarasinghe and Prof. Rohan Lucas for their guidance and tremendous support given throughout this research. Their instructions and comments immensely helped me to complete this work with success.

I would also like to express my sincere gratitude to the course coordinator, progress review chair and members, and all the lecturers of Department of Electrical Engineering for their valuable feedback and assistance throughout the study.

I would like to thank Mr. W.T.D. Samarasinghe and Mr. M.P.M. Fernando, Electrical Engineers of Asset Management Branch - Transmission division of Ceylon Electricity Board (CEB), for helping me to collect SFRA data from the CEB and for sharing their expertise.

I also thank all my colleagues and friends for giving their fullest cooperation throughout my research and for assisting me to clear my doubts.

Last but not least, I would like to express my deepest gratitude for my parents and family for their understanding, motivation and patience.

# TABLE OF CONTENTS

DECLARATION .....	iii
ABSTRACT .....	iv
ACKNOWLEDGEMENT .....	v
TABLE OF CONTENTS .....	vi
LIST OF FIGURES .....	ix
LIST OF TABLES .....	xii
LIST OF APPENDICES .....	xiii
LIST OF ABBREVIATIONS .....	xiv
Chapter 1 INTRODUCTION .....	1
1.1 Background .....	1
1.2 Objectives .....	5
1.3 Scope of work .....	5
1.4 Thesis outline .....	5
1.5 Publications .....	6
Chapter 2 BACKGROUND STUDY AND LITERATURE REVIEW .....	8
2.1 Introduction .....	8
2.2 Sweep frequency response analysis (SFRA) .....	8
2.3 Types of SFRA Measurements .....	13
2.4 Applications of SFRA .....	14
2.4.1 Fault diagnosis-Reference traces used for comparison .....	15
2.4.2 Transformer faults identification using SFRA .....	16
2.5 Existing models of power transformers .....	16
2.6 Proposed method for transformer modelling .....	21
Chapter 3 TRANSFER FUNCTION ESTIMATION USING FREQUENCY RESPONSE ANALYSIS .....	22
3.1 Introduction .....	22
3.2 Analysis of integer order system in frequency domain .....	24
3.2.1 Levy's method of identification of transfer function .....	24
3.2.2 Sanathanan-Koerner iterative method .....	28
3.3 Routh-Hurwitz stability criterion .....	29
3.4 Proposed algorithm to derive transfer function from SFRA data .....	29
3.5 Application of proposed algorithm (Case study for validation of proposed method) .....	33

3.6	Conclusions .....	45
Chapter 4	MODELLING TRANSFORMER EQUIVALENT CIRCUIT .....	47
4.1	Introduction .....	47
4.2	Lumped parameter network.....	47
4.3	Algorithms and methods used for conversion of transfer function to Lumped parameter network model.....	49
4.3.1	Artificial neural network (ANN).....	49
4.3.2	Genetic algorithm (GA) .....	51
4.4	Proposed method of parameter estimation of lumped equivalent circuit ....	53
4.4.1	Initial approximation using ANN (step 1) .....	55
4.4.2	Secondary approximation –DC gain matching (step 2) .....	56
4.4.3	Optimization of responses using Genetic algorithm (step 3).....	57
4.5	Case study and method validation .....	60
4.5.1	Method validation: numerical validation .....	68
4.5.2	Method validation: comparison with a faulty transformer frequency response.....	69
4.6	Results of other phases and different tests .....	71
4.6.1	Modelling of side phases (phase R/B for open circuit test) .....	71
4.6.2	Modelling of windings (phase R, Y & B for short circuit test) .....	74
4.7	Conclusions .....	77
Chapter 5	REFERENCE CURVES OF POWER TRANSFORMER FAULTS ..	79
5.1	Introduction .....	79
5.2	Fault interpreting using frequency ranges of SFRA.....	80
5.2.1	Frequency ranges of SFRA .....	80
5.2.2	Fault interpretation rules .....	83
5.3	Generated reference curves .....	83
5.3.1	Inter-turn faults.....	84
5.3.2	Transformer core faults .....	86
5.3.3	Earth faults .....	87
5.3.4	Conductor tilting/ winding buckling .....	89
5.3.5	Insulation ageing .....	91
5.4	Conclusions .....	93
Chapter 6	CONCLUSION AND FUTURE WORK .....	94
6.1	Conclusions .....	95
6.2	Future works.....	97

References .....	99
Appendix A: MATLAB code of Levy method estimation .....	107
Appendix B: MATLAB code of constraint function used in GA (" <i>constraint_fcn</i> ") .....	114
Appendix C: MATLAB code of fitness function used in GA (" <i>fit_fcn</i> ") .....	116
Appendix D: MATLAB code to determine regions.....	119



## LIST OF FIGURES

Figure 1.1: Reported failure rates of power transformer [2].....	1
Figure 1.2: Derivation of Bode plots of a power transformers by SFRA [5].....	3
Figure 1.3 Basic structure of the power transformer [1].....	4
Figure 2.1: Test setup of SFRA.....	9
Figure 2.2: Two port model of SFRA test setup .....	9
Figure 2.3: Simplified SFRA test arrangement.....	10
Figure 2.4: Frequency response of test object.....	12
Figure 2.5: SFRA Signature of Bolawatta TR03 -3phase 31.5MVA, 132/33kV .....	12
Figure 2.6: Types of SFRA measurements .....	14
Figure 2.7: Basic steps of modelling transformer using SFRA .....	21
Figure 3.1: Proposed algorithm to obtain transfer function from SFRA data.....	31
Figure 3.2: Original SFRA of 133/33 kV, 31.5 MVA Pauwels transformer (Phase Y) .....	34
Figure 3.3: Inverse values of RMS errors for the numerator and denominator combinations of region 1.....	35
Figure 3.4: Estimated response (red) with original response (blue) in 20 Hz – 29.2 kHz (125 rad/s – 184 krad/s).....	36
Figure 3.5: Inverse values of RMS errors for the numerator and denominator combinations of region 2.....	37
Figure 3.6: Estimated response (red) with reshaped response (blue) in 20 Hz to 117 kHz.....	37
Figure 3.7: Inverse values of RMS errors for the numerator and denominator combinations of region 3.....	39
Figure 3.8: Estimated response (red) with Reshaped response (blue) in 20 Hz to 188 kHz.....	40
Figure 3.9: Inverse values of RMS errors for the numerator and denominator combinations of region 4.....	41
Figure 3.10: Estimated response (red) with reshaped response (blue) in 20 Hz to 2 MHz .....	42
Figure 3.11: Estimated response (red) with original SFRA data (blue) in 20 Hz.....	43
Figure 3.12: Relative error of estimated response with respect to SFRA.....	44
Figure 4.1: Lumped parameter network model.....	48
Figure 4.2: Basic structure of ANN .....	50

Figure 4.3: Bit-String Crossover followed by bit flipping mutation.....	53
Figure 4.4: Steps of parameter estimation.....	54
Figure 4.5: Pseudo code of constraint function “ <i>constraint_fcn</i> ”.....	58
Figure 4.6: Pseudo code of objective function “ <i>fit_fcn</i> ”.....	58
Figure 4.7: Comparison of responses of order-reduced transfer function (orange) with measured SFRA response (blue).....	62
Figure 4.8: Test setup modelled in Simulink.....	62
Figure 4.9: Six-sectional lumped parameter network used to train ANN.....	63
Figure 4.10: Comparison of bode plots of initial approximation obtained from trained ANN and measured SFRA.....	63
Figure 4.11: Frequency response after DC gain matching.....	65
Figure 4.12: Final Six-sectional lumped parameter network (Used for GA).....	66
Figure 4.13: Frequency response of final synthesized circuit (red) with respect to the response of order reduced transfer function (blue).....	67
Figure 4.14: Magnitude plots of order reduced transfer function and synthesized network with Absolute error graph.....	69
Figure 4.15: pre-fault and post-fault SFRA curves of Biyagama 83.3 MVA 3phase transformer (Phase Y, open circuit response).....	70
Figure 4.16: (a) Altered parameters of lumped parameter network (b) Frequency response before and after alteration.....	71
Figure 4.17: Original open circuit SFRA of 132/33 kV, 31.5 MVA Pauwels transformer (Phase R, Y and B).....	72
Figure 4.18: Frequency response of final synthesized circuit (red) with respect to the response of order reduced transfer function of phase B (blue).....	73
Figure 4.19: Original short circuit SFRA of 132/33kV, 31.5MVA Pauwels transformer (Phase R, Y and B).....	75
Figure 4.20: Frequency response of final synthesized circuit (red) with respect to the response of order reduced transfer function of phase Y (blue).....	76
Figure 5.1: Method of region determination of SFRA.....	82
Figure 5.2: (a) Simulating an inter-turn fault by short circuiting section-3 (b) Pre fault and post fault Frequency response.....	84
Figure 5.3: Frequency response of phase ‘Y’ of the transformers before and after inter-turn fault occurrence on phase ‘Y’ of the HV winding (logarithmic frequency scale from 100 Hz to 1 MHz) [16].....	85
Figure 5.4: Reference frequency responses of inter-turn fault (for each winding section).....	85
Figure 5.5: pre-fault and post-fault (core fault) Frequency response.....	86

Figure 5.6: Comparison of Pre-fault and post-fault, HV, B phase, SFRA [60] .....	87
Figure 5.7: (a) simulating earth fault by adding parallel resistance (b) pre fault and post fault Frequency response .....	88
Figure 5.8: Comparison of Pre-fault and post-fault responses of 5 MVA, .....	89
Figure 5.9: Simulating conductor tilting by increasing the ground capacitances .....	90
Figure 5.10: Frequency response of 230kV transformer before and after conductor tilting [9] .....	90
Figure 5.11: Reference frequency responses of tilting/buckling (for different severity levels) .....	91
Figure 5.12: Simulating insulation ageing by reducing capacitances .....	92
Figure 5.13: Frequency response of 400MVA transformer with and without insulation oil [67] .....	92

## LIST OF TABLES

Table 2.1: Mechanical and electrical faults identified by SFRA .....	16
Table 3.1: Selection of best estimation in Sanathanan-Koerner method of proposed algorithm for region 3 .....	39
Table 3.2: Selection of best estimation in Sanathanan-Koerner method of proposed algorithm for region 4 .....	42
Table 4.1: Ranges of randomly generated data for parameters.....	55
Table 4.2: Input parameters of GA .....	57
Table 4.3: Poles and zeros of the order-reduced transfer function of 132/33kV, 31.5MVA Pauwels transformer (PhaseY).....	61
Table 4.4: Estimated parameter values from ANN (step1).....	64
Table 4.5: Resistance values before and after DC gain matching.....	65
Table 4.6: Final estimated parameter values for lumped parameter network .....	67
Table 4.7: Final estimated parameter values for lumped parameter network of phase B (open circuit test).....	73
Table 4.8: Final estimated parameter values for Lumped parameter network of phase Y (short circuit test) .....	76
Table 5.1: Fault interpretation rules .....	83

## LIST OF APPENDICES

Appendix A: MATLAB code of Levy method estimation .....	107
Appendix B: MATLAB code of constraint function used in GA (“ <i>constraint_fcn</i> ”) .....	114
Appendix C: MATLAB code of fitness function used in GA (“ <i>fit_fcn</i> ”).....	116
Appendix D: MATLAB code to determine regions.....	119

## LIST OF ABBREVIATIONS

DGA	Dissolved gas analysis
DC	Direct current
SFRA	Sweep frequency response analysis
RLC	Resister, inductor and capacitor
ANN	Artificial neural network
GA	Genetic algorithm
Std.	Standard
FRA	Frequency response analysis
R-L-C-M	Resister, inductance, capacitance and mutual inductance
EMTP	Electromagnetic transient program
RMS	Root mean square
H.V	High voltage
L.V	Low voltage
TF	Transfer function
SC	short circuit
freq.	Frequency