Contents

Synopsis iv

Acknowledgements xii

1 Introduction 1

1.1 General 1

1.2 Scope of Work 3

1.3 Thesis Outline 7

2 Background 9

2.1 General 9

2.2 Condition Monitoring and Life Assessment of Transformer 10

2.3 Operating stresses on Transformer 11

2.3.1 Thermal stresses 12

2.3.2 Chemical stresses 12

2.3.3 Electrical stresses 12

2.3.4 Mechanical stresses 13

2.4 Mechanical Mode of Failure due Electromagnetic forces 14

2.4.1 Core Type Transformer 15

2.4.2 Shell Type Transformer 15

2.4.3 Radial forces 16

2.4.4 Axial forces 18

2.5 Techniques for assessment of mechanical condition of transformer 22

2.5.1 Short circuit Impedance or Leakage Reactance 23

2.5.2 Magnetizing or no-load excitation current 25

2.5.3 Winding capacitances 27

2.6 Conclusion 29

3 Digital signal Processing Method applied for Condition Monitoring of Transformer 32

3.1 Introduction 32

3.2 Detection of incipient turn to turn fault by wavelet analysis of impulse neutral current 33

3.2.1 The Discrete Wavelet Transform (DWT) 34

3.2.2 DWT analysis of neutral current waveform 36

3.2.3 Finding from Analysis of waveform 38

3.2.4 Limitation of the method 38

3.3 Impedance measurement in frequency range from 10 kHz. up to 10 MHz. . 38

3.3.1 Impedance measurement During short circuit test of transformer . . 39

3.3.2 Case Studies of faulty transformers after Short circuit test in Laboratory 40

3.3.3 Case studies of Aged Transformer in Feild 41

3.3.4 Limitation of the method 45

3.4 Detection of Multiple faults in Transformer by SFRA 46

3.4.1 Failure of transformer detected by SFRA 47

3.4.2 SFRA History 56

3.5 Conclusion 58

4 Basic of SFRA 59

4.1 Introduction 59

4.2 Circuit Theory of SFRA 59

4.2.1 RLC Networks and Resonant Frequency 61

4.2.2 Time and Frequency Domains 63

4.2.3 Two Port Networks 64

4.2.4 Transfer Function 65

4.3 Application of SFRA in Power Transformers 67

4.3.1 Self Inductance 68

4.3.2 Mutual Inductance 70

4.3.3 Series Capacitance 70

4.3.4 Shunt capacitance 73
4.3.5 Low and High Frequency model 75
4.4 Methods of SFRA Measurement 77
4.4.1 Voltage Transfer Measurement: 77
4.4.1.1 High-Voltage Winding 78
4.4.1.2 Low-Voltage Winding 79
4.4.1.3 Inter-Winding 80
4.4.1.4 Series and Common Winding 80
4.4.2 Impedance Measurement 81

5 Modelling of Transformer winding for Interpretation of SFRA 83
5.1 Introduction 83
5.2 Basic Circuit of Transformer 84
5.2.1 Low frequency model 84
5.2.2 Mid Frequency model 85
5.2.3 High frequency model 90
5.3 Method of Interpretation 92
5.3.1 Phase to Phase Comparison 92
5.3.2 Sister Unit Comparision 96
5.3.2.1 Comparison of SFRA plot of two sister unit 96
5.3.2.2 Comparison of SFRA plot of multiple sister unit 97
5.3.2.3 Auto- Correlation Method for Data Comparison 99
5.4 Conclusion 101

6 Variation in SFRA plot due to design and external parameter 102
6.1 Introduction 102
6.2 Effect of Oil-Comparision of SFRA plot for Sister unit with full and partially filled oil 103
6.3 Variation in SFRA due to Residual Moisture of Winding 104
6.4 Variation in SFRA plot due to Residual Magnetism of the Core 111
6.5 Variation in Contact Resistance and Earth Resistance 116
6.6 Effect on SFRA plot due to Electrical Interfrence in Substation 118

7 Classification of fault by Sweep Frequency Response Analysis 122

7.1 Introduction . . . 122

7.2 Interpretation of SFRA for fault classification . . . 122

7.3 Low frequency response . . . 124

7.3.1 Core Fault: . . . 125

7.3.1.1 Unintentional core ground . . . 126

7.3.1.2 Shorted lamination providing additional eddy current loss 127

7.3.2 Shorted turn Fault . . . 131

7.3.3 Open turn or High impedance Fault . . . 133

7.4 Mid-Frequency Response . . . 137

7.4.1 Hoop Buckling of LV winding . . . 138

7.4.2 Prediction of Incipient Fault by SFRA in mid-frequency . . . 139

7.4.2.1 Analysis of SFRA Data . . . 141

7.4.2.2 Capacitance and excitation current test data . . . 159

7.5 High-Frequency Response . . . 160

7.6 Overall Frequency Variation of SFRA . . . 161

7.7 Conclusion . . . 169

8 Expert System for SFRA Based on ANN 170

8.1 Introduction . . . 170

8.2 Basic of ANN . . . 171

8.2.1 The Artificial Neuron . . . 171

8.2.2 Feed-forward Neural Networks . . . 172

8.2.3 Learning Rules and Training Algorithms . . . 173

8.3 Configuration of ANN for application in SFRA . . . 174

8.3.1 Input -Output Data Series . . . 175

8.3.2 Multi Layer Feedforward Network with Back-propagation Training Algorithm . . . 175

8.3.3 Feedforward Neural Networks . . . 178

8.4 Field data collection and classification of DATA . . . 179

8.5 Classification of Fault by ANN . . . 179

8.5.1 Shorted turn or Core related Fault (NNET1) . . . 180

8.5.2 High winding Impedance Fault (*NNET2*) . . . 183

8.5.3 Winding deformation in mid frequency range ($NNET3$) 184
8.5.4 Winding deformation in high frequency range(NNET4) 186
8.6 Conclusion 191

9 Conclusion **192**
9.1 General 192
9.2 Summary of Important Findings 194
9.3 Scope for Further Research 195

Bibliography **196**