IN-RUSH CURRENT MITIGATION ON TOROIDAL TRANSFORMERS WITH COMPOSITE CORES

Warnakula Patabendige Thushan Sameera Perera

(149318P)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

March 2018

IN-RUSH CURRENT MITIGATION ON TOROIDAL TRANSFORMERS WITH COMPOSITE CORES

Warnakula Patabendige Thushan Sameera Perera

(149318P)

Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Installation

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

March 2018

DECLARATION OF THE CANDIDATE AND SUPERVISORS

I declare that this is my own work and this dissertation does not incorporate without acknowledgment 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 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 of the candidate Date

(W. P. T. S. Perera)

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

……

Signature of the supervisor Date

(Prof. J.P. Karunadasa)

ACKNOWLEDGEMENT

First of all, the pride, praise and perfection belong to the almighty alone.

Then, I would like to express my sincere gratitude to my supervisor Prof. J. P. Karunadasa for the continuous guidance given me to drive this research to the success, through motivation, enthusiasm and with his immense knowledge.

Further, I would like to pay my gratitude to all the lecturers engaged in the MSc course programme, for making our vision broader and providing us the opportunity to improve our knowledge in various fields.

Then I would like to extend my appreciation to the company I am currently working Noratel International (Pvt) Ltd. for providing the necessary research material and facilities required to complete this study.

Warmest thanks go to the prototype division of the company for the support given to me by sampling, which greatly helped me for the collection of required data.

Moreover, I appreciate the help given by my colleagues Sumith and Suresh in my work place and for the continuous encouragement throughout this post graduate programme and in the research work.

Finally my special thanks go to my wife, my mother, my father and my brother for their love, unwavering and resolute support during this eventful period.

W. P. T. S. Perera

ABSTRACT

Toroidal transformers play an important role in the transformer industry specially in high end applications due to their superior performance, over the conventional laminated transformers. But toroidal transformers lag in performance when comes to high power requirements, specially due to their extremely high inrush currents compared to the laminated transformers.

There are many options that can be used externally to the toroidal transformer to avoid this issue, but due to the reliability concerns, transformer based inrush current mitigation methods are always preferred in the industry. Conventional transformer based inrush current mitigation methods fall short on toroidal transformers, because those methods tend to mitigate their superior performance also, together with the inrush current.

The proposed transformer based inrush current mitigating method with composite cores will reduce the inrush current extensively, while protecting the typical superior performance characteristics of toroidal transformers. Also the proposed method will have better control over the inrush current than the conventional methods, while being competitive in the market.

The proposed method involves two cores; one is lower grade NGOSS (Non Grain Oriented Silicon Steel) core in the centre for the normal operation, and the other is higher grade GOSS (Grain Oriented Silicon Steel) core positioned around the NGOSS core with a controlled air-gap, for inrush current controlling purpose. Due to the uncut NGOSS core in the centre, the composite core retains high performance in the normal operation without compromising.

This dissertation includes practical development of the composite core together with silicon steel types CK37-35H300 and M0H-M103-27P, and then experimental testing on inrush current and finally converge the research findings for developing a new design guideline for the optimized solution, while discussing the cost and the manufacturing aspects.

TABLE OF CONTENTS

DECLARATION OF THE CANDIDATE AND SUPERVISORS…..... i

ACKNOWLEDGEMENT……..... ii

ABSTRACT ……..... iii

LIST OF FIGURES…….. viii

LIST OF TABLES…….. x

LIST OF ABBREVIATIONS…….. xi

LIST OF APPENDICES……. xii

Chapter 1 – INTRODUCTION

1.1 Toroidal transformer construction…….. 2

1.2 Motivation to the research…….. 4

1.3 Objective of the research…… 5

Chapter 2 - INRUSH CURRENT IN TOROIDAL TRANSFORMERS

2.1 Theoretical background of inrush current…… 7

2.2 Toroidal core……. 9

2.2.1 Silicon steel ……..……. 10

2.2.2 Silicon steel on toroidal core ……...……. 10

2.3 Saturation inductance and inrush current…….……..…… 12

Chapter 3 - RESEARCH DESIGN

3.1 Existing inrush current mitigation methods…..……..... 16

3.1.1 NTC thermistor in primary winding …..…….. 16

3.1.2 Use of NGOSS ……. 18

3.1.3 Cut core toroidal transformers …...……... 21

3.2 Proposed composite core concept for inrush current mitigation .. 23

3.2.1 Design flux density……..……. 24

3.2.2 Airgap size in cut core…….. 25

3.2.2.1 Flux distribution in the composite core……. 26

3.2.2.2 Calculation of saturation inductance Ls…… 30

3.2.2.3 Calculation of inrush current……. 32

3.2.3 Uncut – Cut core cross-sectional area ratio……. 35
3.3 Importance Of Source Impedance On Inrush Current ..…….. 35
3.4 Scope of the research……... 37
Chapter 4 - EXPERIMENTAL DATA COLLECTION
4.1 Inrush current measurement on samples……. 38
4.2 Finding the optimum air gap for outer core……. 39
4.3 Summary of inrush current measurements……... 47
4.4 Inrush current measurements for different area ratios……. 48
Chapter 5 - ANALYSIS OF DATA
5.1 Selection of optimum air-gap …….……. 50
5.2 Calculation of relative permeability …….……... 52
5.3 Calculation of inrush current for different core cross-sectional area ratios……. 53
5.4 Development of design tool for composite core…….. 55
5.5 Comparison between measured and calculated inrush current values…… 57
Chapter 6 - RESULTS DISCUSSION AND MOTIVATION
6.1 Comparison of electrical parameters …….. 60
6.1.1 Comparison of inrush current values…… 60
6.1.2 Comparison of no-load current values…….. 62
6.1.3 Comparison of reactive power loss……... 63
6.1.4 Comparison of active power loss…….. 64
6.2 Use of recycle steel cores …….……... 66
6.3 Comparison of manufacturing aspects……. 67
6.3.1 Manufacturing of conventional cut core…… 67
6.3.2 Manufacturing of composite core…….. 68
6.4 Comparison of mechanical parameters……. 69
Chapter 7 - CONCLUSION AND SUGGESTIONS FOR FUTURE RESEARCH
7.1 Conclusion……. 72
7.2 Suggestions for future research……... 73

Reference List……………………………………………………………………. 74
Appendices……………………………………………………………………….. 75

LIST OF FIGURES

Figure No.	Description	Page
Figure 1.1:	Inrush current transient waveform …….....…	2
Figure 1.2:	Toroidal transformer……..	3
Figure 1.3:	EI laminated transformer ……..	4
Figure 2.1:	Graphical interpretation of inrush current with remanence …..	9
Figure 2.2:	Silicon steel mother coils ……..	10
Figure 2.3:	BH characteristics for AISI CK37 (35H300)…..……..	13
Figure 2.4:	BH characteristics for AISI M-0H M103-27P.....……..	14
Figure 2.5:	BH characteristics for AISI M-5…….....……..	15
Figure 3.1:	Typical characteristic curve for NTC ……...……..…..	17
Figure 3.2:	Magnetization characteristics for GOSS-AISI Grade M5....…..	18
Figure 3.3:	Core loss curve for GOSS-AISI Grade M5…….....…..	19
Figure 3.4:	Magnetization characteristics for NGOSS 35H300…….....	19
Figure 3.5:	Core loss curve for NGOSS 35H300……..….....	20
Figure 3.6:	BH loops before and after core cut……...….....	21
Figure 3.7:	Composite core arrangement……...….....	23
Figure 3.8:	Real manufactured composite core …….....	23
Figure 3.9:	Variation of inrush current with outer core airgap……..	26
Figure 3.10:	Flux density distribution between Cut/Uncut cores..……..	27
Figure 3.11:	BH curve for AISI M0H - M103-27P..……...	28
Figure 3.12:	Experimentally calculated µH characteristic curve..……...	28
Figure 3.13:	Extract of calculated µH characteristic……....……...	29
Figure 3.14:	Calculated Bµ characteristic ……...……....……...	30
Figure 3.15:	BH loops at different air-gaps ……...……....…….....	33
Figure 3.16:	BH loop at deep saturation ……...……....…….....	34
Figure 3.17:	Inrush current measured with high source impedance……..	36
Figure 3.18:	Inrush current measured with low source impedance……..	37
Figure 4.1:	Test setup for inrush current measurement……...……..	38
Figure 4.2:	Variation of inrush current with outer core airgap …..……..	40

Figure 4.3: Inrush current wave form TI-173622…….…..…...….. 40
Figure 4.4: Flux density distribution of Cut/Uncut cores.……...…….. 41
Figure 4.5: Variation of inrush current with outer core airgap.…...…….. 42
Figure 4.6: Inrush current wave form TI-173618C……..…...…….. 42
Figure 4.7: Flux density distribution of Cut/Uncut cores ……...…….. 43
Figure 4.8: Variation of inrush current with outer core airgap.…...…….. 44
Figure 4.9: Inrush current wave form TI-173618D……..…...…….. 44
Figure 4.10: Flux density distribution of Cut/Uncut cores...…..…...…….. 45
Figure 4.11: Variation of inrush current with outer core airgap...…..…..…… 46
Figure 4.12: Inrush current wave form TI-173618E……....…..…..…… 46
Figure 4.13: Flux density distribution of Cut/Uncut cores……...…..…..…… 47
Figure 4.14: Inrush Current (x I_{load}) Vs Steel cross-sectional area ratio……. 49
Figure 5.1: Optimum air-gap to the cut core cross sectional area……. 51
Figure 5.2: Relative permeability Vs Cut-core cross-sectional area….…… 53
Figure 5.3: Inrush Current (x I_{load}) Vs Steel cross-sectional area ratio…..… 54
Figure 5.4: Flow chart of Design tool……..…..… 56
Figure 5.5: Design tool……..…… 57
Figure 6.1: Inrush current of composite / conventional designs……... 61
Figure 6.2: No-load current of composite / conventional designs…… 63
Figure 6.3: Reactive power loss of composite / conventional designs……. 64
Figure 6.4: Active power loss of composite / conventional designs…… 65
Figure 6.5: Recycle core including joints in steel strips……... 66
Figure 6.6: Conventional cut core……. 67
Figure 6.7: Composite core……... 68
Figure 6.8: Humming test set up……... 70

LIST OF TABLES

Table No.	Description	Page
Table 3.1:	Flux densities at normal/inrush condition …….....….	27
Table 3.2:	Experimental test data on AISI M0H - M103-27P……	29
Table 4.1:	Design parameters for TI-173622…….	39
Table 4.2:	Design parameters for TI-173618C……..	41
Table 4.3:	Design parameters for TI-173618D……..	43
Table 4.4:	Design parameters for TI-173618E……..	45
Table 4.5:	Summary of inrush current measurements……	48
Table 4.6:	Inrush current measurements for different area ratios……..	48
Table 4.7:	Inrush current measurements for all samples……	49
Table 5.1:	Optimum air-gap to the cut core cross sectional area……...	51
Table 5.2:	Relative permeability to the core cross sectional area……..	52
Table 5.3:	Comparison between measured and calculated inrush current values…….	58
Table 6.1:	Inrush current measurements of composite / conventional designs……...	60
Table 6.2:	No-load current measurements of composite / conventional designs……..	62
Table 6.3:	Reactive power loss measurements of composite/conventional designs……..	63
Table 6.4:	Active power loss measurements of composite / conventional Designs…….	65

LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternative Current
AISI	American Iron and Steel Institute
DC	Direct Current
EMI	Electro Magnetic Interference
GOSS	Grain Oriented Silicon Steel
H	Height
ID	Inner Diameter
IEC	International Electrotechnical Commission
MMF	Magneto Motive Force
MPL	Magnetic Path Length
NC	Nano Crystalline
NGOSS	Non Grain Oriented Silicon Steel
NTC	Negative Temperature Coefficient
OD	Outer Diameter
RMS	Root Mean Square

LIST OF APPENDICES

Appendix	Description	Page
Appendix A:	Design simulations with ToroidEZE programme for designs with steel area ratio Uncut : Cut – 1.0 : 0.7…….....	75
Appendix B:	Design simulations with ToroidEZE programme for designs with different steel area ratios …….....……....	83
Appendix C:	Test equipment details …….……..	91