

Contents

Abstract	i
Zusammenfassung	iii
Acknowledgments	v
List of Abbreviations	vii
List of Symbols	vii
1 Introduction	1
1.1 Line Frequency Transformers vs Solid State Transformers	1
1.1.1 Foreword	1
1.1.2 Line Frequency Power Transformers	1
1.1.3 Solid State Transformers	2
1.2 Applications and Requirements	3
1.2.1 Traction	3
1.2.2 Utility Grids	4
1.2.3 MVDC Grids	5
1.3 Challenges	6
1.3.1 Objectives of the Thesis	7
1.3.2 Contributions of the Thesis	7
1.4 Outline of the Thesis	8
1.5 List of publications	9
2 Background and State of the Art	11
2.1 Transformer basics	11
2.2 MFT Scaling Laws: A Qualitative Analysis	13
2.3 Challenges	15
2.3.1 Skin and proximity effect	15
2.3.2 Edge Effect	16
2.3.3 Thermal Coordination	17
2.3.4 Accurate Electric Parameter Design	18
2.3.5 Non-Sinusoidal Excitation	20
2.3.6 Insulation Coordination	21
2.4 State of the Art	21
2.5 Summary	23
3 Design Optimization Process	25
3.1 A High-Level Description	25
3.2 Relevant Features and Specifications	26
3.2.1 MFT Features and Specifications	26
3.2.2 Additional Features	27
3.3 Design Space	28
	ix

3.3.1	Construction Types	28
3.3.2	Design Choices	29
3.3.3	Materials	33
3.4	Summary	36
4	Analytical Modeling	37
4.1	Introduction	37
4.2	Core Losses	38
4.2.1	Literature Review	38
4.2.2	Application of the IGSE	39
4.3	Winding Losses Modelling	41
4.3.1	Literature Review	41
4.3.2	Dowell's Model	41
4.3.3	Practical Application of Dowell's Model	44
4.4	Leakage Inductance Modelling	46
4.4.1	Literature Review	46
4.4.2	Dowell's Model	47
4.4.3	Practical Application of the Dowell's Model	49
4.4.4	FEM Analysis	49
4.4.5	Hybrid Leakage Inductance Model	50
4.5	Magnetizing Inductance	52
4.6	Thermal Modeling	53
4.6.1	Thermal Network Model Based on the 3D Transformer Geometry	53
4.6.2	Thermal FEM Analysis	56
4.7	Conclusion	57
5	Statistical Data-Driven Modeling	59
5.1	Introduction	59
5.2	Leakage Inductance Modelling Of Asymmetric Winding Structures	60
5.2.1	Proposed Modeling Method	61
5.2.2	Application of the Model	65
5.2.3	Experimental Verification	66
5.3	Local Electric Field Modeling Within MFT Insulation	67
5.3.1	Proposed Modeling	69
5.3.2	Simulation Results	71
5.4	Geometry Dependent Core Loss Modeling	72
5.4.1	FEM Analysis	73
5.4.2	Proposed Modeling Approach	75
5.4.3	Experimental Verification	80
5.5	Conclusion	81
6	Design Optimization	83
6.1	Literature Review	83
6.2	Design Optimization Algorithm	83
6.3	Optimal Design Selection	86
6.4	Conclusion	89

7	Proof of Concept	91
7.1	MFT Prototype	91
7.2	Experimental Verification	92
7.2.1	Electrical Parameter Measurement	92
7.2.2	Electrical Measurements in a Resonant Test Setup	94
7.2.3	Thermal Measurements	97
7.2.4	Dielectric Withstand Test	98
7.3	Conclusions	99
8	Sensitivity Analysis of MFT Design	101
8.1	Introduction	101
8.2	Converter Design	103
8.2.1	Selection of the number of cells	103
8.2.2	Cell Design	104
8.3	Quantitative Analysis of the MFT Design Trade-Offs	105
8.3.1	Scope Of The Analysis	105
8.3.2	Method of Analysis	107
8.4	MFT Design Analysis	108
8.4.1	Switching Frequency and Efficiency	109
8.4.2	Switching Frequency and Insulation Voltage	109
8.4.3	Optimal Number Of ISOP Connected Cells	110
8.4.4	Optimal Number Of Parallel Connected DC-DC Converters Within a Cell	114
8.5	Conclusion	116
9	Conclusion and Future Work	117
9.1	Summary and Contributions	117
9.2	Overall Conclusions	119
9.3	Future Work	120
Appendices		121
A	Test Setup Instruments	123
A.1	Used Instruments	123