

Contents

Abbreviations	VII
Nomenclature	XI
1 Introduction	1
1.1 General Considerations	1
1.2 Objectives of the Dissertation	4
1.3 Methodology and Dissertation Structure	5
2 State of the Art	7
2.1 Mechanical Model	7
2.2 Electromagnetic Model	10
3 Fundamentals	13
3.1 Mechanics	13
3.1.1 Linear Vibrations	13
3.1.2 Orthotropic and Transversely Isotropic Materials	14
3.1.3 Classical Analytical Model of the Stator Core	16
3.1.4 Experimental Modal Analysis	18
3.2 Electromagnetics	18
3.2.1 Flux Density Created by the Field and the Stator Windings	19
3.2.2 Slotting Effect	20
3.2.3 Pole Saliency Effect	21
3.2.4 Damper Winding Effect	22
3.2.5 Radial Forces	23
4 Detailed Mechanical Model – Full 3D FE Calculation	25
4.1 Constructive Aspects of Hydro Generators	25
4.2 FE Model with the Frame	27
4.2.1 General Setup of the Models	27
4.2.2 Influence of the Material Parameters and Contact Conditions	29
4.3 Stator Sector Specimen for Core Material Parameter Determination	33
4.3.1 Specimen Design and Methodology	33
4.3.2 Measurement Results without Ventilation Ducts	37
4.3.3 Calculation Results without Ventilation Ducts	40
4.3.4 Discussion Regarding the Results without Ventilation Ducts	42

4.3.5	Measurement Results with Ventilation Ducts	44
4.3.6	Calculation Results with Ventilation Ducts	46
4.3.7	Homogenised Model with Ventilation Ducts	48
4.4	Validation of the Eigenfrequencies on the Complete Stator	50
4.4.1	EMA on the 55 MVA Hydro Generator	50
4.4.2	Discussion of the Measurement Results	53
4.4.3	Comparison with the FE Calculation	56
4.5	Partial Conclusions	60
5	Semi-analytical Mechanical Model – Fast Calculation	63
5.1	Beam Element Model	63
5.1.1	Discretisation of the Geometry	65
5.1.2	Connection of the Nodes	66
5.2	Shell Element Model	69
5.2.1	Modelling Based on the Shell’s Middle Surface	70
5.2.2	Isometric Parametrisation	71
5.2.3	Mixed Interpolation	73
5.2.4	Curved Shells	75
5.2.5	System Assembly	77
5.3	Example Cases and Validation	78
5.4	Partial Conclusions	81
6	Electromagnetic Model	83
6.1	The Vibration Cause Diagram (VCD)	83
6.1.1	Order-vector Representation and VCD Construction	83
6.1.2	Tangential Forces	86
6.1.3	Example Cases	86
6.2	FE Model	89
6.2.1	General Considerations	89
6.2.2	Magnetostatic Calculation	90
6.2.3	Time-step Calculation	91
6.2.4	Harmonic Calculation	91
6.3	Determination of the Connection Impedances in the Damper Winding	92
6.3.1	Direct Measurement of the Damper Winding Pole-to-Pole Impedance	93
6.3.2	Simplified Calculation Model and Discussion	95
6.4	Results and Validation Measurements	97
6.4.1	Subtransient Reactances	97
6.4.2	Magnetic Forces in the 366kVA Research Hydro Generator	99
6.4.3	Further Investigation of the Effect of Damper Winding Connection Impedance on a Fractional-Slot Winding Machine	101
6.4.4	Magnetic Forces in the 55MVA Hydro Generator	103
6.5	Partial Conclusions	104
7	Resulting Vibration and Validation Measurements in Operation	107
7.1	Forced Vibration Calculation	107

7.2	Load Tests in the 55 MVA Hydro Generator	109
7.2.1	Measurement Setup	109
7.2.2	Vibrations at Different Load Conditions	110
7.2.3	Heat Run Test	113
7.2.4	Relative Vibrations	115
7.3	Comparison of Measured and Calculated Results	117
8	Conclusion and Outlook	123
A	Appendix	127
A.1	Machine Geometries	127
A.2	FE Model Details	128
A.3	Contact Conditions in the Stator Sector Specimen	128
A.4	Timoshenko Beam	129
A.5	Numerical Integration	130
A.6	Simplification of Terms for the Curved Shell Element	132
A.7	VCD for a Fractional-Slot Winding Machine	134
A.8	Measurement Setup with the Bode 100	134
A.9	BH Curves of the Pole End Plate	135
A.10	VCD at Rated Load for the 55 MVA Hydro Generator	136
A.11	Additional Data from the SCADA of the 55 MVA Generator	138
A.12	FFT Analysis of the Measured Vibrations at the Stator Frame of the 55 MVA Generator	139
A.13	Approximate Calculation of Eigenfrequencies for Predefined Eigenmodes with the Shell Element Model	139
	Bibliography	143