

Contents

Abstract	ix
Kurzfassung	xi
List of Symbols	xv
1 Introduction	1
2 Electric Machines in Vehicle Traction Applications	5
2.1 Required Characteristics	5
2.2 PM Brushless Machines	7
2.2.1 Classification	7
2.2.2 State-of-the-Art Field Weakening Methods	8
2.2.3 PM Brushless Machines with Axially Displaceable Stator/Rotor	14
3 Prototype Electrical Drive System	19
3.1 Design Specifications	19
3.2 ADR-BLDC Machine: Design and Materials	20
3.3 Power Electronic Components	25
3.4 Basic Equations and Modeling	26
4 Numerical Field Calculation	33
4.1 Finite Element Method Analysis	33
4.1.1 2-D Model	34
4.1.2 3-D Model	35
4.2 Comparison of the 2-D and 3-D FEM Models	38
4.3 Influence of the Axial Rotor Displacement on the Magnetic Field Distribution	42
5 Machine Parameters	45
5.1 Back EMF	45
5.2 Torque Characteristics	50
5.3 Phase Inductance	57
5.3.1 Base Speed Range	57
5.3.2 Mechanical Field Weakening Range	63
5.4 Measurements and Validation	72
5.4.1 Drag Test Measurement Setup	72
5.4.2 Back EMF	74

5.4.3	No-Load Phase Inductance	76
6	Modeling and Control	79
6.1	Dynamic Simulation Model	79
6.2	Operational Characteristics of the ADR-BLDC Machine	82
6.2.1	Pulse Amplitude Modulation Control	82
6.2.2	Operational Limits	86
6.3	Measurements and Validation	93
6.3.1	Load Test Setup	93
6.3.2	Measurements with Axially Aligned Stator and Rotor	94
6.3.3	Measurements with Axially Displaced Rotor	96
6.4	Conclusion	97
7	Systematic Analysis of Losses	99
7.1	Base Speed Range	99
7.1.1	Copper Losses	100
7.1.2	Core Losses	103
7.1.3	Permanent Magnet Losses	104
7.1.4	Mechanical Losses	105
7.2	Field Weakening Range	106
7.2.1	Overview	106
7.2.2	Additional No-load Losses	109
7.2.3	Additional Losses under Load	119
7.3	Measurements and Validation of No-Load Losses	121
7.3.1	Measurement Setup	121
7.3.2	Measurement Uncertainty	122
7.3.3	Primary Measurement Results	123
7.3.4	Validation of Additional End Winding Losses	124
7.3.5	Determination of Additional Stator Core Losses	125
7.3.6	Validation of Housing Losses	127
7.4	Summary	128
8	Recommendations	131
8.1	Reduction of Additional Losses	131
8.1.1	Additional End Winding Losses	131
8.1.2	Additional Stator Core Losses	133
8.1.3	Additional Losses in Construction Parts	135
8.2	Limits	138
8.3	Design Considerations	142
9	Conclusion and Future Work	145
A	Measuring Instruments	149
	Bibliography	151