

Table of Contents

List of Tables	XIII
List of Figures	XV
List of Abbreviations	XIX
List of Symbols	XXI
1 Introduction	1
2 Requirements in Exoskeleton Drives	5
2.1 General Design Goals	8
2.2 State of the Art in Electrical Machine based Exoskeleton Power Units	9
2.3 Load Cycle Analysis	11
2.3.1 Scalable Human Model	12
2.3.2 Human Centered Approach	14
2.3.3 Identification of Relevant Design Points	16
2.4 Topology Comparison of Electrical Machine based Exoskeleton Power Units	22
2.4.1 Electrical Machine Topology Comparison	23
2.4.2 The Influence of Gear Ratio	25
2.4.3 Actuator Concepts and Selection	27
3 Design of the Reference Drive	31
3.1 Axial Flux Machine	31
3.1.1 Topologies	33

Table of Contents

3.2	Axial Flux Machine Design	36
3.2.1	Geometry Definitions	36
3.2.2	Overview of Modeling Approaches	37
3.2.3	Electrical Load	38
3.2.4	Magnetic Load	41
3.2.5	Frequency based Torque Calculation	45
3.2.6	Procedure of Dimensioning	47
3.2.7	Consideration of Harmonics	52
3.2.8	Mechanical Assessment	55
3.3	Rotor Topology Comparison	56
3.4	Thermal Model	58
4	Scalability of Axial Flux Machines	61
4.1	Scaling of Electrical Machines	61
4.2	Scalability Model	63
4.3	Assumptions, Constraints and Limits	70
4.4	Scaling Routine	72
4.5	Dependency Conclusion	74
4.6	Scaled Machines	77
5	Control Strategies	83
5.1	Dynamic Modelling	83
5.1.1	Multiphase Field Oriented Model	83
5.1.2	Phase Model	85
5.2	Control	87
6	Prototype and Measurement	91
6.1	Prototype	91
6.1.1	Power Unit	91
6.1.2	Axial Flux Machine	94
6.1.3	Power and Signal Electronics	96
6.2	Measurement	98
6.2.1	Test Bench	98
6.2.2	Machine Design Validation	99
6.2.3	Scaling Validation	104
6.2.4	Summary	107
7	Conclusion	111

Bibliography	115
A Additional Topics	131
A.1 Dynamic Inverse Model of a Human Arm	132
A.2 Movement Definition	134
A.3 Sinusoidal Fitting	135
A.4 Calculation Winding Function and Factor	136
A.5 Dimensioning Equations	138
A.6 Leakage Factor	140
A.6.1 Commonly known Resistance	143
A.7 Airgap Convection	144
A.8 Scaling	145
A.8.1 General Scaling Laws	145
A.8.2 Model Equations	145
A.8.3 Auxiliary Values	145
A.9 Finite Element Analysis	148
A.10 Further Measurements	150
A.10.1 Material Characterization of 9S20	150
A.10.2 FOC-Parameter Estimation	151
A.10.3 Operating Points	153