

1	Introduction	1
1.1	Mathematical modeling of PMSMs	2
1.2	Fault tolerance in applications with PMSMs	3
1.2.1	Fault identification of inter-turn winding short circuits in PMSMs	3
1.2.2	Fault-tolerant control of PMSMs with inter-turn winding short circuit	4
1.3	Goals and contributions of this work	5
1.3.1	MEC-based modeling framework	6
1.3.2	Model-based fault identification of inter-turn winding short circuits in PMSMs	6
1.3.3	Model-based fault-tolerant control of PMSMs with inter-turn winding short circuit	7
1.4	Overview of this work	7
2	MEC-based modeling framework	9
2.1	Magnetic equivalent circuit	10
2.1.1	Constitutive and balance equations	10
2.1.2	Electromagnetic force	12
2.2	Electric equivalent circuit	14
2.2.1	Capacitors	15
2.2.2	Resistors	15
2.2.3	Inductors	16
	Magnetically coupled inductors	16
	Magnetically uncoupled inductors	17
2.3	Elimination of dependent variables	17
2.3.1	Dependencies due to electric interconnection	17

2.3.2	Dependencies due to magnetic interconnection	19
2.3.3	Overall mathematical model	21
3	MEC model of PMSMs with inter-turn winding short circuit	23
3.1	Magnetic equivalent circuit	24
3.2	Electric equivalent circuit	26
3.2.1	Three-phase PMSM	27
3.2.2	Dual three-phase PMSM	28
3.3	Overall model of the considered PMSMs	29
4	Model calibration and fault identification for PMSMs	33
4.1	Model calibration	33
4.1.1	Problem formulation and reference signals	34
4.1.2	Optimization problem	37
4.1.3	Solution of the optimization problem	38
4.1.4	Validation of the calibrated models	41
	Three-phase PMSM	41
	Dual three-phase PMSM	43
4.2	Model-based fault identification	46
4.2.1	Problem formulation and reference signals	46
4.2.2	Optimization problem	47
4.2.3	Solution of the optimization problem	48
4.2.4	Evaluation of the model-based fault identification	48
	Evaluation based on simulations	49
	Evaluation based on measurements	52
5	Fault-tolerant control of PMSMs	57
5.1	Simplified MEC model	58
5.2	Fault-tolerant control strategy	59
5.2.1	One-step model-predictive control	62
5.2.2	State estimation	64
5.2.3	PI current control	66
5.2.4	Compensation of the VSI nonlinearities	67
5.3	Evaluation of the control strategy	69
5.3.1	Three-phase PMSM	70
	Nominal PMSM	70
	PMSM with inter-turn winding short circuit	71
5.3.2	Dual three-phase PMSM	77
	Nominal PMSM	78
	PMSM with inter-turn winding short circuit	81
5.4	Fault-tolerant control with short-circuit current mitigation	82

<i>Contents</i>	ix
6 Summary and outlook	87
6.1 Summary	87
6.2 Outlook	89
A Fundamentals of MEC modeling	91
A.1 Basic concepts	91
A.2 Permeances	92
A.3 Coils and permanent magnets	93
B Existence and uniqueness of a solution of (2.41)	95
Bibliography	99