## Contents

About t	ha adita	May material notherno vianotials in DSM4 2.c.1	WW
	ne euito	Alternativas to permanent magnificação diotary@bav&&&al	XV
Preface			xvii
Acknow			xxix
Abbrevi	ations a	and terminologies	xxxi
1 Elec	trical s	afety	1
Benjamin Moosburger, Christian Vögerl, Tilo Püschel and Jörg Irzinger			
1.1	Electri	ical safety	1
	1.1.1	Lightning and surge protection for wind turbines	1
1.2	The el	ectrical installation as protection against electrical hazards	21
	1.2.1	General types of power supply systems	23
	1.2.2	Residual-current monitoring (RCM)	26
	1.2.3	Insulation monitoring (IMD - insulation monitoring device)	28
	1.2.4	Protection of the power-supply system and the wind turbine	30
1.3	Conclu	usion	33
Refe	erences	Peleven deministration distribution of allustration belong 2.2.2.	34
		3.3.3 Scaled results for generaldednesdanand-efficients/	
2 Gen	erator	design for geared turbines	37
Hen	ri Arnol	ld	
2.1	Introd	uction and basics	37
	2.1.1	Short history of electrical machines	37
	2.1.2	Introduction to geared concepts	39
	2.1.3	Why do we need speed variability?	40
	2.1.4	The advantage of mid and high-speed generator concepts	42
	2.1.5	Dimensioning and law of growth	43
	2.1.6	Stator connection	45
	2.1.7	Rotating magnetic fields	48
	2.1.8	Complex phasors for time harmonic signals	49
	2.1.9	Complex space vectors (CSV)	51
2.2	Induct	tion generator (IG)	53
	2.2.1	Basics	53
	2.2.2	Grid connected IG in stationary operation (DOL)	57
	2.2.3	Speed variable IG in stationary operation using VFD	65
	2.2.4	Dynamic operation	72
2.3	Doubl	e-fed induction generator (DFIG)	76
	2.3.1	Basics	76

		2.3.2	DFIG in stationary operation	78
		2.3.3	Dynamic operation	84
	2.4	Salien	t pole synchronous generator (SPSG)	85
		2.4.1	Basics	85
		2.4.2	SPSG in stationary operation	88
		2.4.3	Dynamic operation	92
	2.5	Perma	nent magnet synchronous generator (PMSG)	96
		2.5.1	Basics	96
		2.5.2	PMSG in stationary operation	99
			Dynamic operation	101
	Refe	rences		104
3	Gen	erator	design for direct-drive turbines	107
	Tob	ias Mui	k and Stephan Jöckel	
	3.1	Introd	uction	107
	3.2	Basic	aspects for designing direct-drive generators for wind	
		turbin		108
		3.2.1	Basic design requirements	108
			Major aspects for minimizing the levelized cost of	
			energy (LCoE)	113
		3.2.3	Other important aspects for designing direct-drive	
			generators	124
	3.3	Scaling laws of direct-drive generators		134
		3.3.1	Basic assumptions for scaling	135
		3.3.2	Scaled results for generator diameter	135
		3.3.3	Scaled results for generator losses and efficiency	135
		3.3.4	Scaled results for generator masses	137
		3.3.5	Conclusions from the scaling exercise: segmentation	
			as the future of the direct drive?	141
	3.4	Stator	winding topologies for direct-drive generators	142
		3.4.1	Definition of symmetrical m <sub>s</sub> -phase stator windings	142
		3.4.2	Definition of the winding factor and current layer of a	
			stator winding	148
		3.4.3	Stator windings topologies with particular reference to	
			low-speed permanent magnet synchronous generators	149
		3.4.4	Conclusion	159
	3.5	Perma	anent magnet rotor topologies for direct drive generators	159
		3.5.1	Boundary conditions	160
		3.5.2	The spoke magnet rotor	161
		3.5.3		162
		3.5.4	Simple interior magnets	163
		3.5.5	V-shape interior magnets	165
		3.5.6		166
		3.5.7	Comparison of the results	167

	3.6	Optimization strategies on V-shape magnets		
		3.6.1	Deriving an appropriate solution with interior	
			V-shape magnets	171
		3.6.2	Combining a continuous rotor iron yoke with	
			concentrated stator windings	176
	3.7	Summ	ary	180
	3.8	Outloo		180
		3.8.1	Evolution of gearboxes and medium-speed concepts	180
		3.8.2	Raw materials	181
		3.8.3	Alternatives to permanent-magnet excitation – conventiona	.1
			direct-current excitation?	182
		3.8.4	Alternatives to permanent-magnet excitation – high-	
			temperature super-conductivity (HTS)?	182
	Refe	rences		185
ı			Carid emulatora – redilitology Himitados III de Internation I	40#
4			erter design	187
			ke and Norbert Hennchen	107
	4.1		historical background	187
	4.2		ical drive train	189
		4.2.1	General assembly	190
		4.2.2	Generator	190
		4.2.3	Main converter	192
			Filter components	208
		4.2.5	Active- and reactive-power feeding	12-30 (2)
		2 2 2	Relevant standards	
	12		Transformer and switchgear	
	4.3		n example	216
	Refe	rences	trends and developments	225 226
	ICCIC	iclices		220
5	Grid	compl	liance and electrical system characterization	229
		en Jers	ch	
	5.1		of-the-art grid compliance	229
	5.2		of amid d 1: 44:	230
		5.2.1	Power quality	230
			Steady state operation	230
			Capability	231
		5.2.4	Active power control behavior	231
		5.2.5	Power of the active power control with frequency increase	
			Behavior in the event of grid faults	232
			Disconnection from grid	
	5.3		ods for compliance testing – field test	232
		5.3.1	Field test – detailed view of the FRT tests	232
		5.3.2	Classification of the field tests to the overall	202
			development of the WT	233
			Paradan da	

	5.4	Test b	enches for grid compliance testing	234		
		5.4.1	Emulate realistic conditions on test benches	234		
		5.4.2	Design basics of DyNaLab drive unit	235		
		5.4.3	Electrical design	235		
		5.4.4	Evaluation of the DyNaLab tests	237		
	5.5	Methods for compliance testing - HiL-GridCoP		238		
		5.5.1	Drivetrain design of Hil-GridCoP test bench	238		
			Electrical design and impedance emulation	240		
		5.5.3	Superposition by the current of the turbine	240		
		5.5.4	Conclusion	243		
		5.5.5	Resume	244		
	5.6	Where	e is grid compliance testing heading?	244		
	5.7	Testin	g on lower V-levels to reduce costs	245		
	5.8		onic measurement methods	246		
			emulators - technology limits for high frequencies	247		
			onic measurement on test benches – PQ4Wind test bench	248		
			Control the impedances of the test bench	250		
	5.11		requirements for wind farm models	250		
			model requirements	251		
			onent-based units certification	252		
		Outloo		254		
		rences	4.2.3 Main convertes	254		
6	X-Ha	ardwai	re-in-the-loop test methods for validation	257		
	Adan	n Zuga	, Mohsen Neshati, Florian Hans, Nils Johannsen			
	and	Oliver .	Feindt			
	6.1	Introd	uction	257		
	6.2	Mecha	anical hardware-in-the-loop (MHIL)	265		
	6.3	Power hardware-in-the-loop (PHIL)		279		
		6.3.1	Basic structure of a PHIL simulation	279		
		6.3.2	Stability and accuracy of PHIL-systems	285		
			Practical aspects of PHIL testing	288		
	6.4		oller hardware-in-the-loop (CHIL)	289		
			Test concepts	290		
			Software simulation	291		
			Hardwired simulation	294		
			Fieldbus simulation	296		
			Combined simulation	297		
			Farm simulation	298		
	6.5		ok and future developments	300		
		rences		303		
7	Win	d turbi	ine control and automation	309		
		Johann				
	7.1					
			n process	313		
			trial control systems	316		
			Industrial PCs	317		

	7.3.2	I/O modules	319	
	7.3.3	Fieldbus	321	
7.4	Safety	system	325	
7.5	Contro	ol cabinets	328	
7.6	Softwa	are application	332	
	7.6.1	Basic functions	333	
	7.6.2	Supervisory control	339	
	7.6.3	Operational control	346	
7.7	Subsy	stem control	354	
	7.7.1	Control cabinets	355	
	7.7.2	Hydraulic and cooling systems	356	
	7.7.3	Tower, nacelle, and hub	357	
	7.7.4	Pitch and rotor	358	
		Gearbox, generator, and shafts	359	
		Converter, transformer, and switchgear	361	
		Yaw system	362	
		Meteorology	363	
		Monitoring and protection systems	364	
7.8	Monit	toring and maintenance	303	
	7.8.1	Remote access	366	
	7.8.2	Data recording	366	
	7.8.3	Farm communication	300	
		Remote communication	309	
		Predictive maintenance	371	
		Computer security	372	
		usions and outlook	317	
Refe	rences		376	
8 Stru	otuvol	hoolth monitoring	201	
		health monitoring	381	
8.1	Motiv	omer Segura, Carsten Ebert and Peter Kraemer	381	
0.1	8.1.1	ation	381	
	8.1.2		301	
	0.1.2	and structural health monitoring?	382	
	813	Relevant standards and guidelines	384	
8.2		ods and monitoring principles		
8.3		and goals of monitoring		
0.5		Rotor blades and pitch bearings	200	
		Drivetrain and nacelle		
		Additional considerations for offshore foundations	395	
8.4		irements to common monitoring sensors	399	
274	8.4.1	Acceleration sensors	399	
	8.4.2		400	
	8.4.3	Strain sensors	400	
8.5				
		onitoring of offshore foundations	401	
		Definition of valuable KPIs	403	

		8.5.2	Comparing monitoring results to design	404		
	8.6	The li	fecycle of an SHM solution	405		
		8.6.1	Formal requirements for monitoring solution providers	407		
	Refer	rences		408		
9	Advanced concepts for control of wind turbine and wind farm					
	syste	systems				
	Tobic	Tobias Meyer and Niklas Requate				
	9.1 Ecological impact of wind energy			412		
			tial for reduced CO <sub>2</sub> eq. emissions from wind farms	414		
		9.2.1		415		
		9.2.2	Improving kWh: increase the lifetime-energy production	416		
	9.3		m-wide control for an entire wind farm	420		
		9.3.1	Structuring the multiple levels of control	421		
		9.3.2				
			farm system control	421		
		9.3.3	Value optimization	423		
	9.4		nal operational planning as input for wind farm flow			
		-	ol and turbine control	424		
		9.4.1	Optimization	426		
		9.4.2		427		
			Classification of operation-influencing conditions	429		
			Scheduling for long time horizon	429		
			Continuous update of operational planning	433		
			Short-term adaptation and override of planning	434		
	9.5		ating the technical and economic benefit of advanced			
	control concepts					
	References					
1.0				4.40		
10	-		of local energy systems	443		
	Christoph Kaufmann, Carlos Cateriano Yáñez, Aline Luxa,					
			scimento Souza and Georg Pangalos	443		
		0.1 Introduction				
	10.2		inertia systems and future requirements for the			
			ration of wind turbines	444		
		.3 Definition of local energy systems				
			n of local energy systems by optimal sizing	452		
	10.5		ol of local energy systems	461		
			1 System level control of local energy systems	461		
	Eine.		2 Component level control of LES	465		
	10.6		lity of local energy systems	471		
			1 Characteristics of LES	471		
			2 Stability of LES	472		
	W//L		3 Stability analysis methods	475		
		Outlo		478		
	Refe	rences		478		
In	dex			485		
AII	A CA					