Contents

1	Reli		engineering in power electronic converter systems	1			
	1.1	Perfor	mance factors of power electronic systems	1			
		1.1.1	Power electronic converter systems	1			
		1.1.2	Design objectives for power electronic converters	3			
		1.1.3	Reliability requirements in typical power				
			electronic applications	4			
	1.2	Reliab	pility engineering in power electronics	6			
		1.2.1	Key terms and metrics in reliability engineering	6			
		1.2.2	Historical development of power electronics and reliability engineering	11			
		1.2.3	Physics of failure of power electronic components	15			
		1.2.4		17			
			Accelerated testing concepts in reliability engineering	20			
		1.2.6					
			electronic converter systems	23			
	1.3	1.3 Challenges and opportunities in research on power electronics					
	reliability						
		1.3.1	Challenges in power electronics reliability research	25			
		1.3.2	Opportunities in power electronics reliability research	25			
	Refe	erences		26			
2	And	maly d	letection and remaining life prediction for				
	pow	er elec	tronics	31			
	2.1	Introd	uction	31			
	2.2	Failur	e models	32			
		2.2.1	Time-dependent dielectric breakdown models	33			
		2.2.2	Energy-based models	34			
		2.2.3	Thermal cycling models	35			
	2.3	FMM	EA to identify failure mechanisms	36			
	2.4	Data-	driven methods for life prediction	39			
		2.4.1	The variable reduction method	40			
		2.4.2	Define failure threshold by Mahalanobis distance	42			
		2.4.3	K-nearest neighbor classification	46			
		2.4.4	Remaining life estimation-based particle filter parameter	48			

		2.4.5	Data-driven anomaly detection and prognostics for	<i>-</i>
		2.4.6	electronic circuits Canary methods for anomaly detection and prognostics for	51
	2.5	Cuman	electronic circuits	52
			gements	53 53
		erences	gements	53
3	Reli		of DC-link capacitors in power electronic converters	59
	3.1	-	itors for DC-links in power electronic converters	59
		3.1.1	The type of capacitors used for DC-links	59
		3.1.2	1 71 1	60
		3.1.3	Reliability challenges for capacitors in power electronic	
	2.2	Esilon	converters	63
	3.2		e mechanisms and lifetime models of capacitors	64
		3.2.1	Failure modes, failure mechanisms, and	64
		2 2 2	critical stressors of DC-link capacitors	
		3.2.2	Lifetime models of DC-link capacitors Accelerated lifetime testing of DC-link capacitors	60
		3.2.3	under humidity conditions	68
	3.3	Reliah	ility-oriented design for DC links	69
	5.5	3.3.1	Six types of capacitive DC-link design solutions	7(
		3.3.2	A reliability-oriented design procedure of	/ (
		3.3.2	capacitive DC-links	72
	3.4	Condi	tion monitoring of DC-link capacitors	75
		erences	tion monitoring of De link capacitors	73
4	Reli	ability	of power electronic packaging	83
	4.1	Introd	uction	83
	4.2	Reliab	ility concepts for power electronic packaging	84
	4.3	Reliab	ility testing for power electronic packaging	85
		4.3.1	Thermal shock testing	86
		4.3.2	Temperature cycling	86
			Power cycling test	87
			Autoclave	88
			Gate dielectric reliability test	88
		4.3.6	Highly accelerated stress test	89
			High-temperature storage life (HSTL) test	89
		4.3.8	Burn-in test	89
		4.3.9	Other tests	90
	4.4		semiconductor package or module reliability	9(
		4.4.1	Solder joint reliability	91
		4.4.2	Bond wire reliability	91
	4.5		ility of high-temperature power electronic modules	94
		451	Power substrate	94

			Co	ontents	vii
		4.5.2	High-temperature die attach reliability		96
			Die top surface electrical interconnection		97
		4.5.4	÷		98
	4.6	Summ	<u>*</u>		99
			gements		99
		rences			99
5	Mod	lelling	for the lifetime prediction of power		
		_	ctor modules		103
	5.1	Accele	erated cycling tests		105
	5.2	Domin	nant failure mechanisms		106
	5.3	Lifetir	me modelling		108
		5.3.1	Thermal modelling		108
			Empirical lifetime models		110
			Physics-based lifetime models		112
			Lifetime prediction based on PC lifetime models		117
	5.4	-	es-based lifetime estimation of solder joints within		
			semiconductor modules		118
		5.4.1			119
			Constitutive solder equations		121
			Clech's algorithm		123
			Energy-based lifetime modelling		123
	5.5	-	ple of physics-based lifetime modelling for solder joint	īS .	124
			Thermal simulation		125 127
			Stress–strain modelling Stress–strain analysis		127
			Model verification		130
			Lifetime curves extraction		130
			Model accuracy and parameter sensitivity		133
			Lifetime estimation tool		135
	5.6	Concl			136
			gements		136
		rences	5••		137
6	Min	imizati	on of DC-link capacitance in power electronic		
			systems		141
	6.1	Introd	uction		141
	6.2	Perfor	mance tradeoff		143
	6.3	Passiv	re approach		145
		6.3.1	e i		145
		6.3.2	Ripple cancellation techniques		146
	6.4		e approach		147
		6.4.1	Power decoupling techniques		147
		6.4.2	Ripple cancellation techniques		154

viii	Reliability	of power	electronic	converter	systems
	-	· ·			

		6.4.3 Control and modulation techniques	155
	(5	6.4.4 Specialized circuit structures Conclusions	156
			157
		nowledgement erences	157 157
	Kere	rences	13/
7		nd turbine systems	165
		Introduction	165
	7.2	r	165
		7.2.1 Onshore and offshore	165
	7.3	Public domain knowledge of power electronic converter	
		reliabilities	171
		7.3.1 Architecture reliability	171
		7.3.2 SCADA data	174
		7.3.3 Converter reliability	176
	7.4	Reliability FMEA for each assembly and comparative	
		prospective reliabilities	180
		7.4.1 Introduction	180
		7.4.2 Assemblies	181
		7.4.3 Summary	181
	7.5		186
	7.6	Methods to improve WT converter reliability and availability	187
		7.6.1 Architecture	187
		7.6.2 Thermal management	187
		7.6.3 Control	187
		7.6.4 Monitoring	188
		Conclusions	188
	7.8	Recommendations	189
	Ack	nowledgements	189
	Terr	minology	189
	Abb	reviations	192
	Vari	ables	192
	Refe	erences	193
8	Act	ive thermal control for improved reliability of power	
		tronics systems	195
	8.1	· ·	195
		8.1.1 Thermal stress and reliability of power electronics	195
		8.1.2 Concept of active thermal control for improved reliability	198
	8.2	Modulation strategies achieving better thermal loading	199
		8.2.1 Impacts of modulation strategies on thermal stress	199
		8.2.2 Modulations under normal conditions	200
		8.2.3 Modulations under fault conditions	202
	8.3	Reactive power control achieving better thermal cycling	204
		8 3 1 Impacts of reactive nower	204

			Conten	ts 1X
		832	Case study on the DFIG-based wind turbine system	206
		8.3.3	· · · · · · · · · · · · · · · · · · ·	210
	8.4		al control strategies utilizing active power	212
	0.1		Impacts of active power to the thermal stress	212
		8.4.2	Energy storage in large-scale wind power converters	214
	8.5	Conclu	2, 2	217
		nowledg		217
		erences	Schients	218
9			deling and prediction of power devices	223
	9.1	Introdu		223
	9.2		e mechanisms of power modules	225
			Package-related mechanisms	225
			Burnout failures	227
	9.3		ne metrology	229
			Lifetime and availability	229
			Exponential distribution	230
			Weibull distribution	231
			Redundancy	232
	9.4		ne modeling and design of components	233
		9.4.1	Lifetime prediction based on mission profiles	233
		9.4.2	Modeling the lifetime of systems with constant	
			failure rate	234
		9.4.3	Modeling the lifetime of systems submitted to	
			low-cycle fatigue	236
	9.5	Summ	ary and conclusions	241
	Ack	nowledg	gements	242
	Refe	erences		242
10	Powe	er modu	ile lifetime test and state monitoring	245
	10.1	Overvi	iew of power cycling methods	245
	10.2	AC cu	rrent PC	246
		10.2.1	Introduction	246
		10.2.2	Stressors in AC PC	247
	10.3	Wear-o	out status of PMs	249
		10.3.1	On-state voltage measurement method	250
		10.3.2	ĕ	253
		10.3.3		254
	10.4		ge evolution in IGBT and diode	256
		10.4.1		259
		10.4.2		260
		10.4.3	· ·	262
	10.5		emperature estimation	262
	10.0	10.5.1		262
		10.5.1		264
		10.5.2	5 (51 (15)) Of junction temperature estimation methods	207

x Reliability of power electronic converter systems	
---	--

		$10.5.3 v_{ce,on}$ -load current method	265
		10.5.4 Estimating temperature in converter operation	267
		10.5.5 Temperature measurement using direct method	270
		10.5.6 Estimated temperature evaluation	274
	10.6	Processing of state monitoring data	277
		10.6.1 Basic types of state data handling	278
		10.6.2 Application of state monitoring	281
	10.7		283
	Ackn	owledgement	283
		rences	283
11	Stock	nastic hybrid systems models for performance and	
		bility analysis of power electronic systems	287
		Introduction	287
	11.2	Fundamentals of SHS	289
		11.2.1 Evolution of continuous and discrete states	289
		11.2.2 Test functions, extended generator, and	
		moment evolution	290
		11.2.3 Evolution of the dynamic-state moments	291
		11.2.4 Leveraging continuous-state moments for dynamic	
		risk assessment	292
		11.2.5 Recovering Markov reliability and reward models	
		from SHS	293
	11.3	Application of SHS to PV system economics	295
		Concluding remarks	299
		owledgements	299
		rences	299
12	Fault	t-tolerant adjustable speed drive systems	303
12		Introduction	303
	12.2		304
	12.2	12.2.1 Power semiconductor devices	305
		12.2.2 Electrolytic capacitors	305
		12.2.3 Other auxiliary factors	305
	12.3	Fault-tolerant ASD system	306
	12.4	•	307
	12.5	Control or hardware reconfiguration stage in fault-tolerant	307
		system design	308
		12.5.1 Topological techniques	311
		12.5.2 Software techniques	318
		12.5.3 Redundant hardware techniques	328
	12.6	Conclusion	340
	Ackn	owledgements	348
	Refer	rences	348

13	Mission profile-oriented reliability design in wind turbine and					
	photo	ovoltaic systems	355			
	13.1	Mission profile for renewable energy systems	355			
		13.1.1 Operational environment	355			
		13.1.2 Grid demands	357			
	13.2	Mission-profile-oriented reliability assessment	362			
		13.2.1 Importance of thermal stress	363			
		13.2.2 Lifetime model of power semiconductor	363			
		13.2.3 Loading translation at various time scales	365			
		13.2.4 Lifetime estimation approach	366			
	13.3	Reliability assessment of wind turbine systems	367			
		13.3.1 Lifetime estimation for wind power converter	368			
		13.3.2 Mission profile effects on lifetime	372			
	13.4	· · · · · · · · · · · · · · · · · · ·	373			
		13.4.1 PV inverter candidates	374			
		13.4.2 Reliability assessment of single-phase PV systems	378			
		13.4.3 Thermal-optimized operation of PV systems	383			
	13.5 Summary					
	Acknowledgements					
	Refer	rences	386			
14	Relia	bility of power conversion systems in photovoltaic				
		cations	391			
	14.1	Introduction to photovoltaic power systems	391			
		14.1.1 DC/DC conversion	391			
		14.1.2 DC/AC conversion	394			
	14.2	Power conversion reliability in PV applications	396			
		14.2.1 Capacitors	397			
		14.2.2 IGBTs/MOSFETs	399			
	14.3	Future reliability concerns	403			
		14.3.1 Advanced inverter functionalities	404			
		14.3.2 Large DC/AC ratios	409			
		14.3.3 Module-level power electronics	411			
	Ackn	owledgements	414			
	Refer	ences	414			
15	Relia	bility of power supplies for computers	423			
		Purpose and requirements	423			
		15.1.1 Design failure modes and effects analysis	424			
	15.2	Thermal profile analysis	428			
	15.3	De-rating analysis	431			
	15.4	Capacitor life analysis	433			
		15.4.1 Aluminum electrolytic capacitors	434			
		15.4.2 Os-con type capacitors	435			

xii	Reliability of	f power	electronic	converter	systems

	15.5	Fan life		435
	15.6	High acce	elerated life test	438
		15.6.1 L	Low temperature stress	440
		15.6.2 F	ligh temperature stress	441
		15.6.3 V	/ibration stress	441
		15.6.4	Combined temperature–vibration stress	443
	15.7	Vibration	, shock, and drop test	444
		15.7.1 V	Vibration test	444
		15.7.2 S	Shock and drop test	445
	15.8	Manufact	uring conformance testing	445
		15.8.1 T	The ongoing reliability testing	446
	15.9	Conclusio		448
	Ackn	owledgeme	ent	448
		ences		448
16	High-power converters			
	16.1	-	ver applications	451
		· ·	General overview	451
	16.2	Thyristor-	-based high-power devices	452
		•	ntegrated gate-commutated thyristor (IGCT)	453
			nternally-commutated thyristor (ICT)	455
		16.2.3 I	• • • • • • • • • • • • • • • • • • • •	455
			ETO/IETO	457
			Reliability of thyristor-based devices	458
	16.3		ver inverter topologies	459
		- 1	Swo-level converters	459
			Multi-level converters	460
	16.4		ver dc–dc converter topologies	464
		· ·	DAB converter	464
			Modular dc–dc converter system	469
	Refer	ences		471
Ind	OV			475
HIIU	CA.			4/3