

Reliability of Power Electronic Converter Systems

Edited by Henry Shu-hung Chung,
Huai Wang, Frede Blaabjerg
and Michael Pecht

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Contents

1	Reliability engineering in power electronic converter systems	1
1.1	Performance 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	Reliability 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	DFR of power electronic converter systems	17
1.2.5	Accelerated testing concepts in reliability engineering	20
1.2.6	Strategies to improve the reliability of power electronic converter systems	23
1.3	Challenges and opportunities in research on power electronics reliability	24
1.3.1	Challenges in power electronics reliability research	25
1.3.2	Opportunities in power electronics reliability research	25
	References	26
2	Anomaly detection and remaining life prediction for power electronics	31
2.1	Introduction	31
2.2	Failure 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	FMMEA 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 electronic circuits	51
2.4.6	Canary methods for anomaly detection and prognostics for electronic circuits	52
2.5	Summary	53
	Acknowledgements	53
	References	53
3	Reliability of DC-link capacitors in power electronic converters	59
3.1	Capacitors for DC-links in power electronic converters	59
3.1.1	The type of capacitors used for DC-links	59
3.1.2	Comparison of different types of capacitors for DC-links	60
3.1.3	Reliability challenges for capacitors in power electronic converters	63
3.2	Failure mechanisms and lifetime models of capacitors	64
3.2.1	Failure modes, failure mechanisms, and critical stressors of DC-link capacitors	64
3.2.2	Lifetime models of DC-link capacitors	66
3.2.3	Accelerated lifetime testing of DC-link capacitors under humidity conditions	68
3.3	Reliability-oriented design for DC links	69
3.3.1	Six types of capacitive DC-link design solutions	70
3.3.2	A reliability-oriented design procedure of capacitive DC-links	72
3.4	Condition monitoring of DC-link capacitors	75
	References	77
4	Reliability of power electronic packaging	83
4.1	Introduction	83
4.2	Reliability concepts for power electronic packaging	84
4.3	Reliability testing for power electronic packaging	85
4.3.1	Thermal shock testing	86
4.3.2	Temperature cycling	86
4.3.3	Power cycling test	87
4.3.4	Autoclave	88
4.3.5	Gate dielectric reliability test	88
4.3.6	Highly accelerated stress test	89
4.3.7	High-temperature storage life (HSTL) test	89
4.3.8	Burn-in test	89
4.3.9	Other tests	90
4.4	Power semiconductor package or module reliability	90
4.4.1	Solder joint reliability	91
4.4.2	Bond wire reliability	91
4.5	Reliability of high-temperature power electronic modules	94
4.5.1	Power substrate	95

4.5.2	High-temperature die attach reliability	96
4.5.3	Die top surface electrical interconnection	97
4.5.4	Encapsulation	98
4.6	Summary	99
	Acknowledgements	99
	References	99
5	Modelling for the lifetime prediction of power semiconductor modules	103
5.1	Accelerated cycling tests	105
5.2	Dominant failure mechanisms	106
5.3	Lifetime modelling	108
5.3.1	Thermal modelling	108
5.3.2	Empirical lifetime models	110
5.3.3	Physics-based lifetime models	112
5.3.4	Lifetime prediction based on PC lifetime models	117
5.4	Physics-based lifetime estimation of solder joints within power semiconductor modules	118
5.4.1	Stress–strain (hysteresis) solder behaviour	119
5.4.2	Constitutive solder equations	121
5.4.3	Clech’s algorithm	123
5.4.4	Energy-based lifetime modelling	123
5.5	Example of physics-based lifetime modelling for solder joints	124
5.5.1	Thermal simulation	125
5.5.2	Stress–strain modelling	127
5.5.3	Stress–strain analysis	129
5.5.4	Model verification	130
5.5.5	Lifetime curves extraction	132
5.5.6	Model accuracy and parameter sensitivity	133
5.5.7	Lifetime estimation tool	135
5.6	Conclusions	136
	Acknowledgements	136
	References	137
6	Minimization of DC-link capacitance in power electronic converter systems	141
6.1	Introduction	141
6.2	Performance tradeoff	143
6.3	Passive approach	145
6.3.1	Passive filtering techniques	145
6.3.2	Ripple cancellation techniques	146
6.4	Active approach	147
6.4.1	Power decoupling techniques	147
6.4.2	Ripple cancellation techniques	154

6.4.3	Control and modulation techniques	155
6.4.4	Specialized circuit structures	156
6.5	Conclusions	157
	Acknowledgement	157
	References	157
7	Wind turbine systems	165
7.1	Introduction	165
7.2	Review of main WT power electronic architectures	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	Root causes of failure	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
7.7	Conclusions	188
7.8	Recommendations	189
	Acknowledgements	189
	Terminology	189
	Abbreviations	192
	Variables	192
	References	193
8	Active thermal control for improved reliability of power electronics systems	195
8.1	Introduction	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 power	204

8.3.2	Case study on the DFIG-based wind turbine system	206
8.3.3	Study case in the paralleled converters	210
8.4	Thermal control strategies utilizing active power	212
8.4.1	Impacts of active power to the thermal stress	212
8.4.2	Energy storage in large-scale wind power converters	214
8.5	Conclusions	217
	Acknowledgements	217
	References	218
9	Lifetime modeling and prediction of power devices	223
9.1	Introduction	223
9.2	Failure mechanisms of power modules	225
9.2.1	Package-related mechanisms	225
9.2.2	Burnout failures	227
9.3	Lifetime metrology	229
9.3.1	Lifetime and availability	229
9.3.2	Exponential distribution	230
9.3.3	Weibull distribution	231
9.3.4	Redundancy	232
9.4	Lifetime 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	Summary and conclusions	241
	Acknowledgements	242
	References	242
10	Power module lifetime test and state monitoring	245
10.1	Overview of power cycling methods	245
10.2	AC current PC	246
10.2.1	Introduction	246
10.2.2	Stressors in AC PC	247
10.3	Wear-out status of PMs	249
10.3.1	On-state voltage measurement method	250
10.3.2	Current measurement	253
10.3.3	Cooling temperature measurement	254
10.4	Voltage evolution in IGBT and diode	256
10.4.1	Application of $v_{ce,on}$ monitoring	259
10.4.2	Degradation and failure mechanisms	260
10.4.3	Post-mortem investigation	262
10.5	Chip temperature estimation	262
10.5.1	Introduction	262
10.5.2	Overview of junction temperature estimation methods	264

x	<i>Reliability of power electronic converter systems</i>	
	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	Conclusion	283
	Acknowledgement	283
	References	283
11	Stochastic hybrid systems models for performance and reliability analysis of power electronic systems	287
11.1	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
11.4	Concluding remarks	299
	Acknowledgements	299
	References	299
12	Fault-tolerant adjustable speed drive systems	303
12.1	Introduction	303
12.2	Factors affecting ASD reliability	304
	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	Converter fault isolation stage in fault-tolerant system design	307
12.5	Control or hardware reconfiguration stage in fault-tolerant 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
	Acknowledgements	348
	References	348

13 Mission profile-oriented reliability design in wind turbine and photovoltaic 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 Reliability assessment of PV system	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	385
Acknowledgements	386
References	386
14 Reliability of power conversion systems in photovoltaic applications	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
Acknowledgements	414
References	414
15 Reliability of power supplies for computers	423
15.1 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

15.5	Fan life	435
15.6	High accelerated life test	438
15.6.1	Low temperature stress	440
15.6.2	High temperature stress	441
15.6.3	Vibration stress	441
15.6.4	Combined temperature–vibration stress	443
15.7	Vibration, shock, and drop test	444
15.7.1	Vibration test	444
15.7.2	Shock and drop test	445
15.8	Manufacturing conformance testing	445
15.8.1	The ongoing reliability testing	446
15.9	Conclusions	448
	Acknowledgement	448
	References	448
16	High-power converters	451
16.1	High-power applications	451
16.1.1	General overview	451
16.2	Thyristor-based high-power devices	452
16.2.1	Integrated gate-commutated thyristor (IGCT)	453
16.2.2	Internally-commutated thyristor (ICT)	455
16.2.3	Dual-ICT	455
16.2.4	ETO/IETO	457
16.2.5	Reliability of thyristor-based devices	458
16.3	High-power inverter topologies	459
16.3.1	Two-level converters	459
16.3.2	Multi-level converters	460
16.4	High-power dc–dc converter topologies	464
16.4.1	DAB converter	464
16.4.2	Modular dc–dc converter system	469
	References	471
	Index	475

Chapter 1

Reliability engineering in power electronic converter systems

*Huai Wang¹, Frede Blaabjerg¹, Henry Shu-hung Chung²
and Michael Pecht³*

1.1 Performance factors of power electronic systems

Power electronic systems aim to best serve the needs of highly efficient generation and conversion of electrical energy. This section discusses the basic architecture of a power electronic system and its design objectives and performance factors.

1.1.1 Power electronic converter systems

Electrical energy conversion by power electronic systems can be classified into the following four categories [1]:

1. Voltage conversion and power conversion for both direct current (DC) and alternate current (AC).
2. Frequency conversion.
3. Wave-shape conversion.
4. Poly-phase conversion.

The above four kinds of conversions are used to meet needs in many industry sectors, such as automotive, telecommunications, portable equipment, smart grids, high-voltage DC, flexible AC transmission systems, traction, renewable energy, mining, electrical aircraft, adjustable speed drives, and aerospace. The power-level ranges from sub-W to multi-MW and GW, processed by either a single power converter or multiple power converters.

Figure 1.1 shows the general architecture of a typical power electronic converter system. The electrical energy in the input and output is represented in the form of input voltage v_{in} , input current i_{in} , and input side frequency f_{in} , and output

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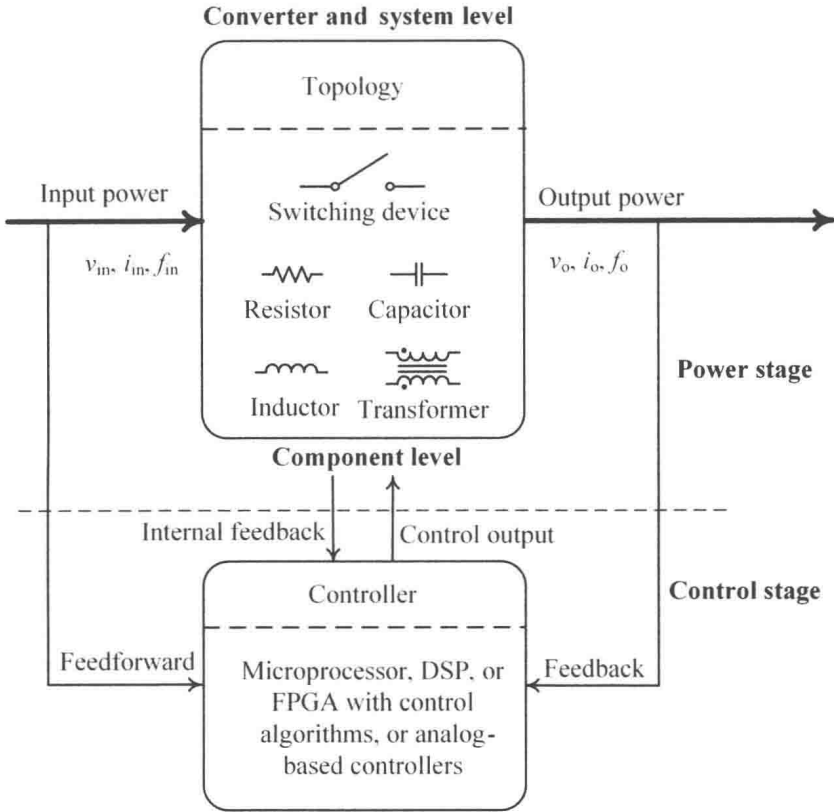


Figure 1.1 The basic architecture of a power electronic converter system. FPGA = field programmable gate arrays

voltage v_o , output current i_o , and output side frequency f_o . The upper and lower blocks in Figure 1.1 show the power stage and control stage, respectively. The power stage is composed of switching devices and one or more kinds of passive components, connected by a specific circuit topology. The switching devices are turned on and off at a frequency in the range of hundreds of Hz to hundreds of MHz, depending on the capability of the devices and the application requirements. The capacitors and inductors are used for energy storage and filtering purposes. The transformers are usually of the high-frequency type and are used for galvanic isolation and step-up/down of voltage. Resistors are in fact not desirable in power electronic systems since they introduce power loss. However, in practical systems, there are parasitic resistances in components and resistors used for circuit snubbers, balancing circuits, filter damping, and so on. The control stage receives conditioned low-voltage signals from the power stage and sends back driven signals to control the on/off of the switching devices, including protection signals at the presence of abnormal operation. It can be implemented either in analog circuits, digital processors, or a hybrid way of both analog and digital parts typically implemented on print circuit boards.

1.1.2 Design objectives for power electronic converters

With the advancements in power switching devices and passive components, circuit topologies, control strategies, sensors, digital signal processors (DSPs), and system integration technologies, there is a large variety of power electronic converter systems and they are still evolving. The converter- or system-level performance is determined by the component-level performance, the applied circuit topology and control strategy, and the practical implementation and usage conditions. Besides the required functionality under specified conditions, power electronic converter design mainly considers the following five performance factors:

1. Cost

Cost is usually the foremost consideration in most consumer and industrial applications, such as lighting systems, photovoltaic plants, and wind turbines. For safety-critical applications, such as in aerospace, railway, and aircraft, other factors may weigh more than cost. A comprehensive cost analysis should include the design cost, manufacturing cost, operational cost, and recycle cost if applicable – that is, the life-cycle cost.

2. Efficiency

One of the distinctive features of power electronic converters is that they can convert and control electrical energy with high efficiency. Therefore, improving the efficiency is always an important design objective to push close to the limit of zero power loss. The widely used efficiency definitions are peak efficiency, rated power efficiency, and weighted efficiency under multiple loading conditions (e.g., European weighted efficiency for PV inverters). For power converters used for renewable energy applications, such as PV and wind power, the long-term total energy production is more useful since the power level could fluctuate frequently with the weather conditions. Therefore, the energy efficiency defined by the annual output energy over the annual input energy of a power converter provides much more insight. It takes into account the long-term environmental and operational conditions, as well as the impact of component degradation.

3. Power density (kW/L or kW/kg)

A general trend in power electronics is towards increased power density in terms of reduced volume or weight for a given power rating. This can be achieved mainly by reducing passive components with the aid of increasing switching frequency of the power devices, and better thermal management and integration solutions.

4. Reliability

The usual engineering definition of reliability is the probability that an item will perform a required function without failure under the stated conditions for a stated period of time [2]. Accordingly, a comprehensive reliability description includes five important aspects: definition of failure criteria, stress condition, reliability numbers (%), confidence level (%), and the time after which the reliability number and confidence level apply. A reliability number will vary by adjusting any one of the other four aspects, indicating the importance

4 *Reliability of power electronic converter systems*

of understanding the background information behind a reliability number. As it is discussed in Section 1.1.3, more stringent reliability requirements and cost constraints are imposed on power electronic converters in both classical applications and emerging applications.

5. *Manufacturability*

With the ever increasing cost of labour involved in the manufacturing process, it is desirable to have power electronic design solutions that can be easily and economically implemented into final products. The manufacturability is largely dependent on the decisions made during the design phase [3]. When it comes to the power electronic converters, the modular design and integration at the component level, power module level, and system level can be accomplished to improve the manufacturability [4]. The emerging additive manufacturing technologies, including 3D printing, will provide new opportunities for power electronic converter design in order to have better manufacturability and thereby to lower the cost [5].

The performance requirements of power electronic products are increasingly demanding in terms of the above five performance factors. Of these, the reliability performance influences the safety, service quality, lifetime, availability, and life-cycle cost of the specific applications.

1.1.3 *Reliability requirements in typical power electronic applications*

While targets concerning the efficiency of power electronic systems are within reach, the increasing reliability requirements create new challenges as discussed in Reference 6:

1. Mission profiles for critical applications (e.g., aerospace, military, avionics, railway traction, automotives, data centres, and medical electronics).
2. Emerging applications under harsh environments and long operation hours (e.g., onshore and offshore wind turbines, photovoltaic systems, air conditioners, and pump systems).
3. More stringent cost constraints, reliability requirements, and safety compliance requirements (e.g., demand for parts per million (ppm) level failure rates in future products).
4. Continuous need for higher power density in power converters and higher level integration of power electronic systems, which may invoke new failure mechanisms and thermal issues.
5. Uncertainty of reliability performance for new materials and packaging technologies (e.g., SiC and GaN devices).
6. Increasing complexity of electronic systems and software architectures in terms of functions, number of components, and control algorithms.
7. Resource constraints (e.g., time, cost) for reliability testing and robustness validation due to time-to-market pressure and financial pressure.