Reliability of electronic components and systems with WBG technology

4E Power Electronic Conversion Technology Annex (PECTA)

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Abstract:

Power electronics plays a vital role in various applications, from household devices to electric vehicles and renewable energy systems. In Denmark, the power electronics sector is a significant contributor to the economy, particularly in wind, motor, and pump controllers. This report, a result of the 4E annex PECTA project, covers reliability challenges at both component and system levels, discusses the state of the art in design processes, and proposes indicators for policymakers to support WBG adoption in energy applications. Conclusively, while existing reliability standards can partially apply to WBG semiconductors, the report suggests the need for specialized testing procedures and potentially international standards for ensuring their reliability. The PECTA project serves as an ideal platform for the development of such standards, involving industrial partners and research institutions with the necessary expertise.

About the IEA 4E Power Electronic Conversion Technology Annex (PECTA):

Power electronic devices incorporating Wide Band Gap (WBG) technologies are maturing rapidly and offer enormous opportunities for improved energy efficiency. 4E´s PECTA assesses the efficiency benefit of utilizing the emerging WBG technology, keeps participating countries informed as markets for Wide Band Gap technologies devices develop, and engages with research, government and industry stakeholders worldwide to lay the base for suitable policies in this area.

Further information on PECTA is available at:
https://pecta.iea-4e.org.

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E):

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP) has been supporting governments to co-ordinate effective energy efficiency policies since 2008. Fourteen countries and one region have joined together under the 4E TCP platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However, the 4E TCP is more than a forum for sharing information: it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.
Current members of 4E TCP are Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK and USA.

The main collaborative research and development activities under 4E include the

- Electric Motor Systems Annex (EMSA)
- Solid State Lighting (SSL) Annex
- Electronic Devices and Networks Annex (EDNA)
- Power Electronic Conversion Technology Annex (PECTA)

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Executive Summary

Foreword

Power electronics is nowadays known for mobile phone chargers, laptop power supplies, and home appliances. But power electronics is also essential for electric vehicles, ships, aircraft, wind turbines, solar panels, and industrial applications. In Denmark, companies have development and production facilities that employ +3500 people in power electronics and an economic turnover of wind, motor, and pump controllers for 10 billion DKK annually. We are looking into a future with new components that can be used in power electronics with potentially greatly improved properties. However, several challenges must be overcome, efficiency and reliability among them. The so-called "Wide Bandgap" technologies (WBG) are very promising in terms of efficiency but remain still almost unknown in terms of reliability. Aalborg University holds worldwide leadership in terms of the reliability of power electronics, both at the component- and the system level (more info on https://www.energy.aau.dk/research/project-websites/corpe).

Report goal and structure

This report is the main outcome of a project for the 4E annex PECTA (https://www.iea-4e.org/pecta) aimed at mapping the potential and timeline of deployment for the use of new electronic components based on WBG technologies, to provide an informed basis for strategical political measures and decisions, considering the state of the art both on applications and reliability. The report is organized as follows:

1. Introduction
2. Reliability issues from component to system
3. State of the art and prospects in reliable component- and system design process
4. Reliability definitions and methodologies in power electronics
5. Indications to policymakers regarding the reliability of electronics to promote WBG for energy and end-user applications

The report comprises a mapping of the present status in terms of reliability as well as several indications regarding the way forward to adopt WBG semiconductors, especially in terms of reliability. A relevant part of the report is the last section, where indications to policymakers are given to promote the transition to more efficient wide bandgap semiconductors.

Main conclusions

Although reliability standards can be applied to a certain extent to WBG semiconductors, new failure mechanisms require ad-hoc testing procedures that cannot be inherited from the established silicon technology. A concrete implementation in the form, e.g., of international standards for reliability testing of WBG would be a possible next step. PECTA is the natural environment to look at it, as it involves by its nature industrial partners and national research institutions that have an interest and the necessary competencies to initiate new standards.

Contents

1. Introduction

1.1. Overview and Objectives of PECTA

One of the barriers (among others) identified for widespread application of WBG in systems/products is the limited knowledge of the reliability of the new technology, compared for instance, to IGBT technology applied for years with a considerably longer track record.

In this regard, PECTA´s Management Committee thinks that it is critical to better understand reliability of electronics in general, and for WBG technology specifically, from different perspectives. The considerations discussed so far in form of guiding questions are listed below:

- What are the main reliability issues (in general and for WBG), classified by level, from component to system?
- What is the state of the art in designing reliable systems and components with WBG?
- What are the metrics/measures that defines reliability in systems and component? (merged)
- Which methodologies are available for determining reliability of systems and component (general and WBG)? (merged)
- What would be relevant for policy makers to address regarding the reliability of electronics to promote WBG for energy and resource efficient systems and end-use products?

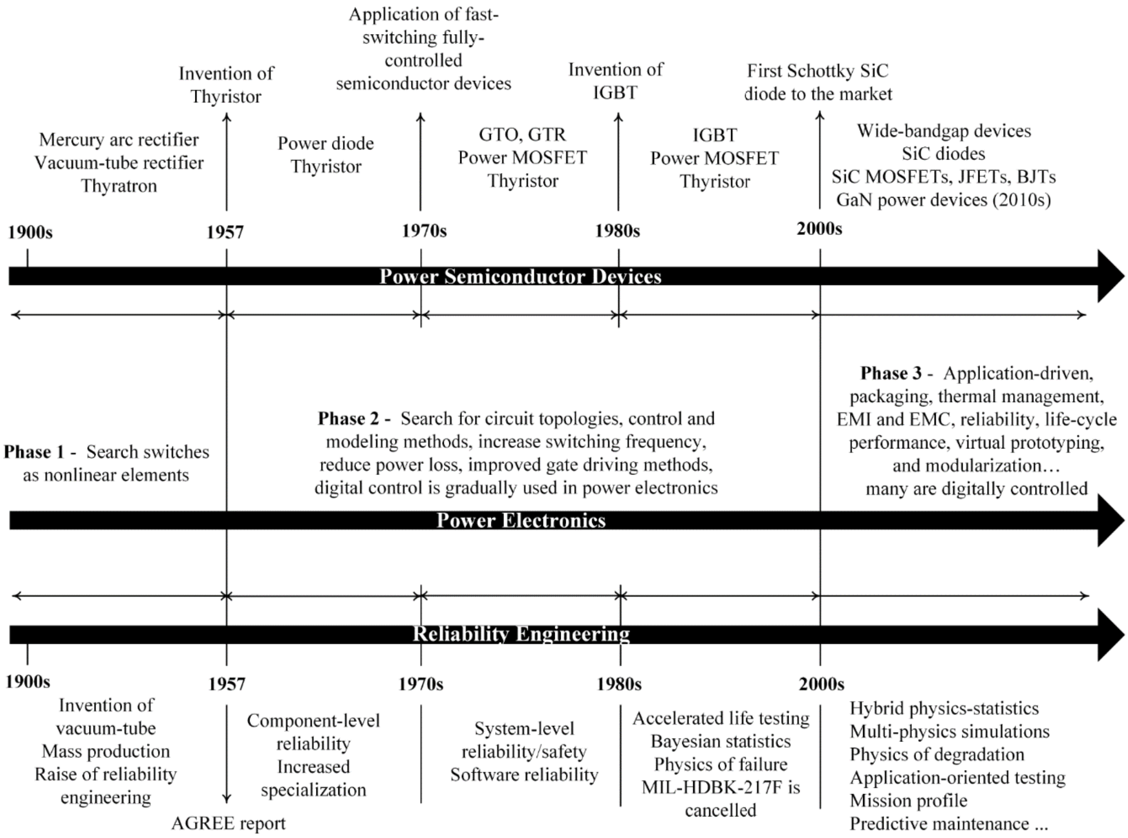


Figure 1. The historical development of power semiconductors, power electronics, and reliability engineering [1].

2. Reliability Issues from Component to System

2.1. Power Semiconductor Devices

Nowadays, strong efforts have been made to improve the reliability of power electronic systems with cost-effective and sustainable solutions. In the meanwhile, Wide Band Gap (WBG) semiconductor devices are capturing increasingly new power applications, as they are quite promising in terms of switching speed, efficiency, thermal management, and high voltage capability, even if the reliability performance of which is still far to be demonstrated. With the increasing demands of application-driven research, reliability has become a considerable practical challenge in power electronics. The historical development of power semiconductors, power electronics, and reliability engineering are listed in Figure 1.

This section focuses on summarizing the power electronic component reliability aspects, in the following order:

- The failure mechanisms of Si IGBT devices.
- The chip-level and packaging-level failure mechanisms, testing, and condition monitoring health precursors of SiC devices.
- The failure mechanisms of GaN devices.

These overviews provide a foundation to understand the state-of-the-art research on power electronics semiconductor devices' reliability.

2.1.1. Si IGBT

In [2], the major failure mechanisms of the IGBT module driven by thermo-mechanical stresses related to the package level are discussed, which mainly include:

- Bond wire fatigue
    - Bond wire lift-off
    - Bond wire heel cracking
- Aluminium reconstruction
- Brittle cracking and fatigue crack propagation
- Corrosion of the interconnections
- Solder fatigue and solder voids
    - Voids
- Burnout failures
    - Latch up
    - Cosmic rays

In [3], the failure mechanisms of the Si IGBT devices are mainly distinguished into two parts:

- Sudden failure, i.e., spontaneous, unpredictable failures.
- Drift failures, i.e., predictable failures, which develop slowly over time.

A more detailed description of different failure mechanisms of the Si IGBT devices is shown in Table 1:

Table 1: Overview of failure mechanisms of IGBT power semiconductors [3].

Modes	Mechanisms		**Failure**
Gate driver failure	Short circuit		
Software failure of control logic			
Wrong selection of IGBT technologies	High losses	Inadmissible high junction temperature	
Overload operation			
High switching frequency			
Low gate voltage			
Large gate resistor			
High load cycle rate, leading of delamination of solder layers	Increased thermal resistance $R_{th(j-c)}$	Inadmissible high junction temperature	
Mounting failure	Increased thermal resistance $R_{th(c-h)}$		
Insufficient cooling			
Low output frequency	High swings of junction temperature		
Strong motor acceleration	High peak currents, lager than $2\times I_{nom}$		
Mechanical vibrations, leading to broken bond wire connections			
High load cycle rate, leading to broken bond wire connections			
Fast switching high di/dt	Inadmissible high collector-emitter voltage		
High stray inductance			
Improper handling	Electrostatic Discharge (ESD)		
In general if $U_{GE} > U_{GES}$			

2.1.2. SiC MOSFET

One critical issue for WBG devices in power electronics relating to reliability is due to their ability to operate at much higher frequencies than their Silicon predecessors [4].

- The intrinsic parasitic inductances can become a significant issue of transients at higher switching speeds, which can negatively impact the reliability of the devices [5].
- Thermal management and lead inductance are crucial factors that deserve attention, and they have been extensively investigated in recent years. Some interesting solutions have been

proposed, such as integrating thermal structures into the package during the assembly process to establish direct thermal links with the device inside the module package [6].

- To comprehend the effect of reliability on individual mechanical elements, it is crucial to break them down and evaluate their impact on reliability accelerators, particularly thermal effects. In this regard, the work conducted in [7] provides a detailed understanding and compares IGBTs and SiC-MOSFETs, demonstrating a potential increase in efficiency and re-liability due to lower losses (and hence less heat) in SiC devices. Lack of planarity and high defect density of SiC wafers complicate fabrication.
- The absence of room temperature implantation leads to an increase in labour costs.
- Low quality gate oxide reduces mobility and can cause threshold instability.
- Short-circuit and overstress failure of SiC MOSFETs.

Table 3: Degradation Mechanism of SiC MOSFET at chip level.

Modes	Mechanisms	Indicators
Instability of threshold voltage	Positive gate bias attracts the electron toward the SiC/SiO$_2$ interface, causing the positive shift of V_{th}; Negative gate bias repels the electron away from the interface, causing negative shift of V_{th}.	Threshold voltage On-state voltage
Gate oxide breakdown	Thinner gate oxide in SiC devices induces gate leakage current when the drain-source voltage is applied, resulting in the breakdown possibility of gate oxide.	Threshold voltage, Leakage current
Body diode degradation	The continuous forward current flowing through SiC MOSFET p-n junction results in accumulated hole–electron recombination energy, which forms the stacking fault extended at the body diode.	Body diode on-state resistance and forward voltage

Table 2: Degradation Mechanism of SiC MOSFET on Package level.

Modes	Mechanisms	Indicators
Bond-wires lift-off	Due to the different coefficient of thermal expansion between SiC and Al, the bond-wires may lift off under long-term temperature swings.	On-state voltage and resistance
Solder layer degradation	Due to the different coefficient of thermal expansion between SiC chip, solder material, and copper substrate, cracks and voids appear in the solder layer under long-term temperature swings, weakening the ability of power losses dissipation.	Thermal resistance, case temperature

Table 4: Failure locations, causes, and typical indicators for SiC MOSFETs.

Failure location	Failure cause	Indicators
Gate oxide	High electric field, high temperature	Gate leakage current I_{gss}
		Threshold voltage shift ΔV_{th}
		Miller Plateau V_{gs_mp}
Body diode	Forward bias	Body diode forward voltage V_F
Bond wires	Thermo-mechanical stresses	On-state drain-source voltage V_{ds_on}
		Drain-source on-state resistance R_{ds_on}
Solder layers		Thermal resistance R_{th_jc}

2.1.3. GaN HEMT

In [8], the most critical degradation processes induced by off-state, on-state, and semi-on-state stress, along with their related failure modes, have been discussed. Additionally, the test methodologies employed for analysing degradation mechanisms have also been presented, as shown in Table 5:

Table 5: Summary of the degradation mechanisms that take place in a GaN power HEMT under off-state, on-state and semi-on state conditions.

Bias point	Degradation mode/process	Physical origin	Test methodology
Off-state	Dynamic-R_{on} increase	Buffer trapping, due to -Ionization of buffer acceptors -Injection of electrons from the substrate	-Pulsed I_D-V_{DS} characterization -“on-the fly“ measurements -Backgating tests -Substrate ramps
	V_{th} shift	Trapping/detrapping of electrons in the gate area	-Pulsed I_D-V_{DS} characterization -“on-the fly“ measurements
	Time-dependent degradation	-Generation of source-drain current paths -Short circuits between gate and channel -Vertical (drain to substrate) breakdown	-HTRB testing -2-terminal (drain to substrate) stress
On-state	V_{th} shift (PBTI, NBTI)	-trapping at the gate insulator (for MIS/MOS structures) -electron/hole trapping in the p-GaN (for transistors with p-GaN gate)	-Pulsed I_D-V_{DS} characterization -“on-the fly“ measurements -capacitance-voltage-frequency analysis -analysis of the correlation between V_{th} shift and gate leakage
	Time-dependent gate breakdown	-TDDB (for MIS/MOS structures) -generation of defects/leakage paths in the p-GaN/AlGaN gate stack	-high temperature gate stress testing -constant voltage gate stress -Pulsed I_D-V_{DS} / Deep Level Transient Spectroscopies (DLTS) to investigate the generation of traps induced by stress -electroluminescence to identify the failed regions
Semi-on-state	V_{th} shift / increase in R_{on} induced by semi-on operation	-trapping of hot electrons under the gate and the gate edge -generation of lattice defects	-constant voltage stress in semi-on conditions -High temperature source current (HTSC) stress -stress in hard switching

Challenges of reliability research on GaN power devices for both normally-on and normally-off types:

- Time dependent breakdown (TDDB) effects in Schottky gate devices were due to different physical mechanisms either related to device design or materials quality:
    - in normally-on power Schottky HEMTs with double field-plate, TDDB was found to be due to the failure of the insulating SiN layer between the two-dimensional electron gas (2DEG) and the first field-plate edge. Increased robustness was achieved by changing the substrate conductivity in order to move the 2DEG edge towards the drain.
    - in AlGaN/GaN power Schottky diodes, breakdown involved first the dielectric at the diode edge and then the AlGaN.
    - drain–source off-state catastrophic breakdown of n-on Schottky gate HEMTs, resulting in device burn-out.
- P-gate devices (either with an ohmic or a Schottky metal contact on top of the p-layer) are currently the most popular choice for n-off devices. A critical mechanism for p-gate HEMTs is the TDDB consequent to the application of a positive gate bias.
- The vertical drain-substrate stack also sustains a high electric field and is prone to time-dependent breakdown.
- The GaN MISHEMT represents an ideal structure for normally-off power GaN electron devices since the dielectric layer significantly reduces the gate leakage; unfortunately, the MIS structure introduces new reliability problems, related with the stability of device threshold voltage. Large positive Vth shifts (positive bias temperature instabilities) have been observed under forward gate bias conditions and attributed to accumulation of electrons at the dielectric/III-N interface where a second electron channel forms in the so-called ‘spill-over’ conditions.
- Negative voltage shift (NBTI) is observed when negative voltage is applied to the gate is usually less severe and becomes relevant only at high temperature.

There are many potential reliability research topics on GaN power devices:

- Schottky-gate and MISHEMT n-on devices for cascode configuration and p-gate n-off devices: time-dependent breakdown effects can be evaluated using standard, well-established testing methods; methods for long-term thermal stability assessment still have to be developed and consolidated into standards. Some issues remain, concerning gate leakage, hot electron degradation, instantaneous breakdown.
- Concerning n-off MISHEMTs, stabilization of threshold voltage remains an open issue, which requires in-depth physical characterization of surface and interface properties and of dielectric materials.
- To increase the operating voltage over 1000V, it is important to focus on the drain-to-substrate stack.

2.2. Power Electronic Converters

- Passive and fast implementation of power electronics in a large variety of applications with all kinds of environmental exposures.
- Cost pressure and physical size requirements for some applications (particularly some commercial products) have not been taken into account.
- Uncertainties in mission profile and variations in strength of components.
- Increasing electrical / electronical content and complexity.
- Lack of understanding in failure mechanisms and failure modes of reliability critical components.

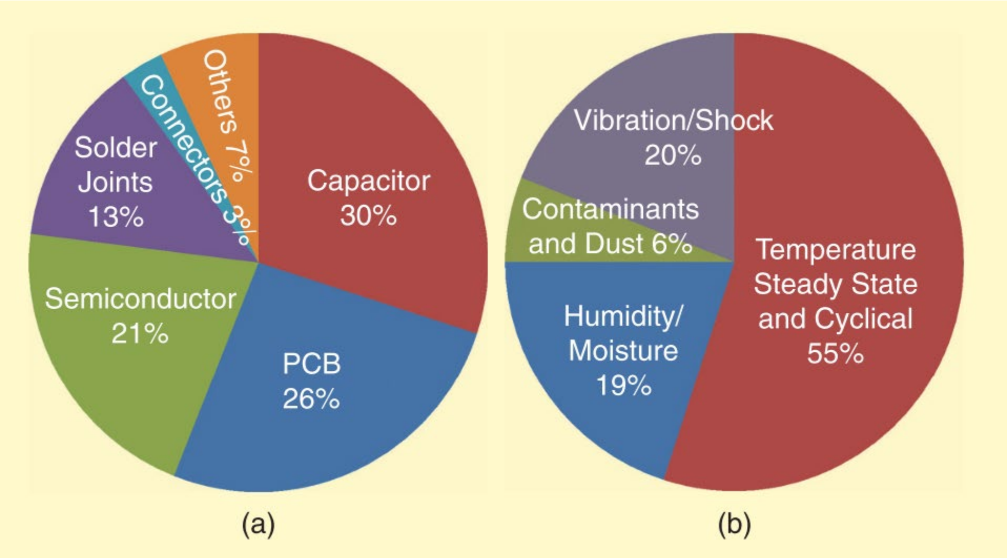


Figure 2. A survey on failure in power electronic converter systems. (a) Failure distribution among major components (b) Source of stress distribution for failures [9].

- Traditional system-level reliability prediction and robustness validation from components to entire systems.
- Higher operating temperature (e.g., with WBG devices), which challenges the overall reliability and lifetime.
- Software reliability becomes an issue as more and more digital controllers are introduced in power electronics systems, which should be treated adequately.

There are many possibilities in power electronics reliability research:

- Research in microelectronics provides an important foundation for the ongoing and future work in power electronics, especially from the methodologies point of view.
- More and more mission profiles and online monitoring data from the field are available and accessible.
- Active thermal control by controlling the power flow in power electronic circuits.
- Component-level and system-level smart de-rating operation.
- Condition monitoring and fault-tolerant design, which allows extend lifetime and reduced failure rate.
- Emerging semiconductor and capacitor technologies enable more reliable power electronic components and systems.
- Computer-aided automated design software to save time and cost in the development process.
- Trends for modular design of power converters and standardized power electronic components and packaging technologies, for example, high-level power integration or hybridization, such as 3D packaging.
- With better understanding of failure mechanisms in power electronics, more failure mechanism-specific accelerated testing could be designed, leading to improved reliability predictions for targeted applications.
- Multi-objective optimization methods can be applied for the trade-off design among the cost, expected service time, and reliability of power electronic systems.

2.3. Power Electronic Based Systems

2.3.1. Power Systems

A power system is a large system with a huge number of sub-systems and components operating together in order to perform its functionality as supplying the costumers for a long period of time regardless of its components lifetime [10].

According to CIGRE [11], the electric system reliability can be addressed by considering two basic and functional aspects of the electric system adequacy and security.

Adequacy: The reliability of the electric system to always supply the aggregate electric power and energy requirements of the customers considering scheduled and unscheduled outages of system facilities.

Security: The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system facilities.

In conventional power systems, the electric power has been generated by large-scale thermal power plants and delivered to the consumers by transmission and distribution systems in a centralized, top-down structure [10]. With the development of power electronics technology, clean energy resources have been increasingly adopted in the electric power generation. More and more small-scale renewable resources such as PV and wind power have been integrated into the distribution systems [12]. Besides the renewable resources, the new technologies such as DC transmission systems and Electric Vehicles (EVs) have also made contributions to form the modern power systems, as shown in Figure 4.

Modernized power system have new challenges in reliable, resilient, and efficient operation, mainly classified into three categories including challenges caused by microgrid operation, challenges associated with proliferation of renewable energies and challenges posed by power electronics [12]. Different aspects and issues raised by these technologies are summarized in Figure 3.

Among all induced challenges with the new power system technologies, the power electronic converters are frequent failure sources in many applications such as wind and PV systems [13-19] in which areas the WBG devices have been broadly used. In [20,21], some package-related reliability design considerations of the medium voltage power modules have been discussed.

In medium voltage power systems, WBG devices enabled solid state transformer (SST) has been promised to replace the traditional distribution transformer, which has existed for more than a century and not being efficient enough for the modern power system [22]. More specifically, the vertical high voltage SiC power devices with high breakdown voltage and switching frequency makes the SST application 40 times to 100 times increase in V*f capability. The reliable medium voltage SST can be developed using simple topologies, also the input voltage can be higher to meet the requirement of the modern power system, especially the distributed system [23, 24].

In high voltage power system, currently there is none available commercial applications of WBG power devices. In the current high voltage applications, such as flexible alternating current transmission system (FACTS) and high-voltage direct current (HVDC), they are served by high power silicon thyristors (SCR, <8kV) and Si IGBTs (<6.5kV) [25]. However, due to WBG such as SiC's extreme capability to support high blocking voltages, transmission applications such as HVDC could benefit tremendously from ultra-high voltage SiC technology [26].

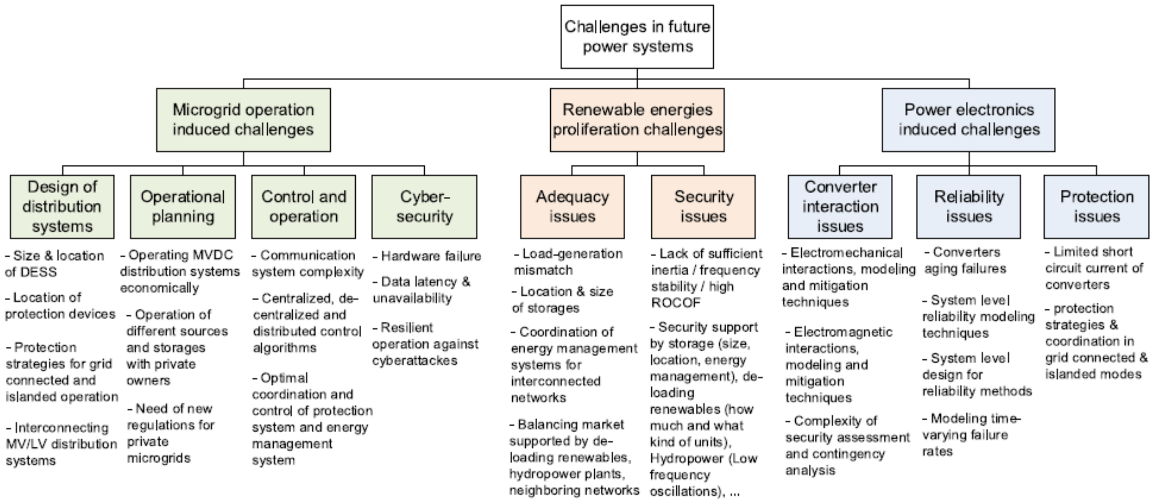


Figure 3. Challenges in future power electronic based power systems [12].

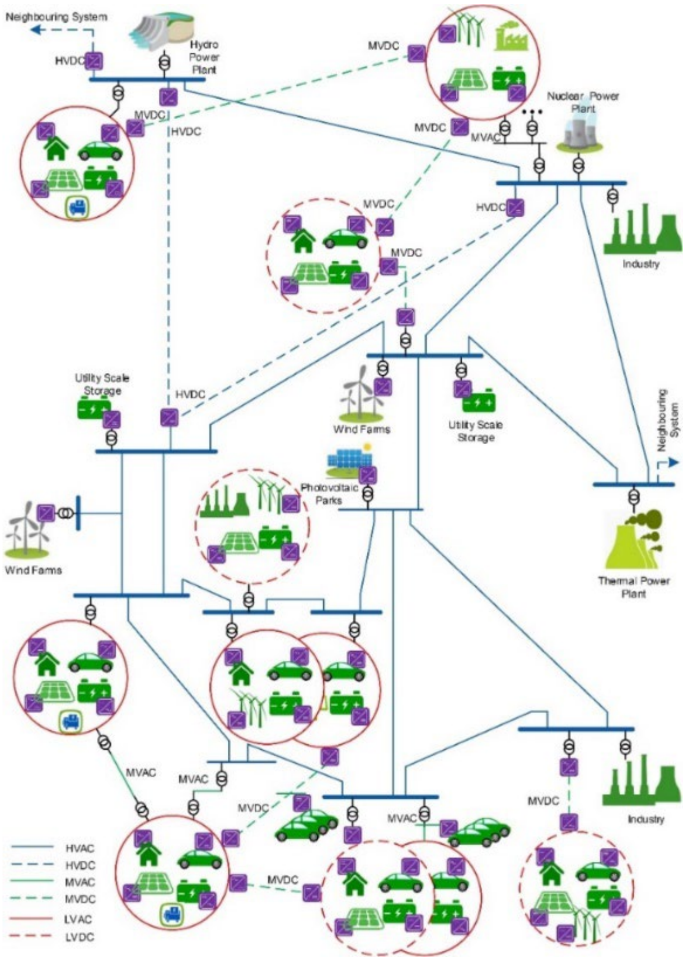


Figure 4. Typical structure of modern power systems with hybrid AC and DC sub-grids [12].

2.3.2. Power Electronic Systems for Photovoltaic

Photovoltaic (PV) power systems are a significant renewable energy source. However, large-scale PV system design faces challenges due to uncertainty and variability in system components and environmental factors. The vulnerability of PV system components is influenced by temperature fluctuations, power losses, and ambient conditions. Solar insolation and power input variability result in increased electrical stress on PV panels, shortening their lifecycles and impacting power electronic interface reliability. Thus, PV power systems exhibit lower reliability compared to conventional generation sources.

In summary, the technical issues listed below either require further investigation or remain unresolved:

- Developing failure rates for power electronic components in PV systems that consider power input, power loss, and temperature dependencies.
- Integrating power input curves and PV voltage regulation schemes into PV reliability assessments.
- Defining PV reliability metrics to accurately measure energy availability and outage time.
- Constructing a multi-state model for PV microgrids using reliability data from PV systems.
- Creating new reliability evaluation algorithms to assess active distribution systems with embedded PV microgrids.

In PV systems, inverters, which are comprised of semiconductor modules, are among the components that are susceptible to vulnerabilities. These inverters consist of switching components (such as IGBTs or diodes) and capacitors. The reliability of a PV inverter relies on the performance of each individual component within it.

In grid-connected PV systems, PV inverters often handle high levels of power flow and operate in high-temperature environments. These conditions can degrade the reliability of the inverter and increase the likelihood of aging-related component failures. After exploring various circuit topologies for single-phase PV inverters, it was revealed that failures predominantly occur in the switching stage, with temperature being the most probable cause of such failures [27].

Further improvements may be possible with WBG devices or better thyristors. WBG devices offer potential cost reduction for PV inverters through two main approaches: material reduction and simpler circuit designs. By utilizing higher frequency switching, the size of passives can be reduced. Furthermore, operating at higher temperatures with SiC technology enables smaller heat sinks. Adopting two-level inverters instead of three-level inverters minimizes the need for auxiliary components. Additionally, the use of monolithic gate drives with GaN technology decreases the parts count.

The inadequacy of existing device testing standards in predicting converter reliability was highlighted in [28]. For instance, concerning the effects of Bias Temperature Stress (HTRB and HTGB) on Threshold Voltage instability in SiC devices, the current AEC-Q101 standard (based on JEDEC JESD-22 A108C method) states that "electrical testing shall be completed as soon as possible and no longer than 96 hours after removal of bias from devices." However, this standard falls short in terms of measurement temperature, measurement time, and measurement speed, necessitating the need for more comprehensive testing protocols.

The application of WBG devices in PV power systems faces several challenges:

- The fast-switching speed of WBG devices can lead to increased electromagnetic interference (EMI) if power converters utilizing WBG devices are not designed properly. This elevated EMI can negatively impact system performance and potentially hinder compliance with industry standards for electromagnetic compatibility (EMC).
- If stray capacitance and inductance in the power circuits are not effectively minimized, the high rate of change in converter output voltages (dV/dt) and currents (di/dt) can result in undesired overvoltage on load terminals.
- While incorporating WBG devices can enhance converter performance, it contradicts the goal of reducing system cost due to the current high market price of WBG devices. Thus, striking a

balance between improved performance and cost-effectiveness becomes a significant challenge in WBG device implementation for PV.

2.3.3. Power Electronic Systems for Wind Turbine

The primary power-converter system in wind turbines (WT) often experiences frequent failures, leading to increased repair costs and downtime. This issue of high converter failure rates is not limited to a particular manufacturer or specific sites but is rather observed globally across various types of wind turbines. Numerous studies and the collective experience of WT operators confirm this widespread problem. To develop effective countermeasures, it is essential to comprehend the underlying mechanisms and causes of converter failures in wind turbines. Gaining a comprehensive under-standing of these factors serves as a foundation for devising efficient strategies to mitigate the issue.

The existing scientific literature on the reliability of (main) converters in WT can be broadly categorized into two main groups:

- Field-data-based failure statistics or reliability studies, which primarily concentrate on system-level analysis.
- Theoretical lifetime calculations based on mission profiles and established lifetime models. However, these calculations often overlook the specific failure modes observed in real-world operational conditions.

In [29], converter-specific failure data has been analysed from maintenance reports, which provided insights into the spare parts utilized, as well as turbine logbooks. Based on this information, failures were categorized according to specific converter components. These categories include the phase module (comprising IGBT modules, corresponding driver boards, DC-link capacitors, and busbars; in electrically excited synchronous generators (EESG)-based WT, it also encompasses the corresponding components in the excitation unit), converter control board, cooling system, main circuit breaker, grid-coupling contactor, and other converter failures.

Figure 5 shows the distribution of failed components over the converter-component categories.

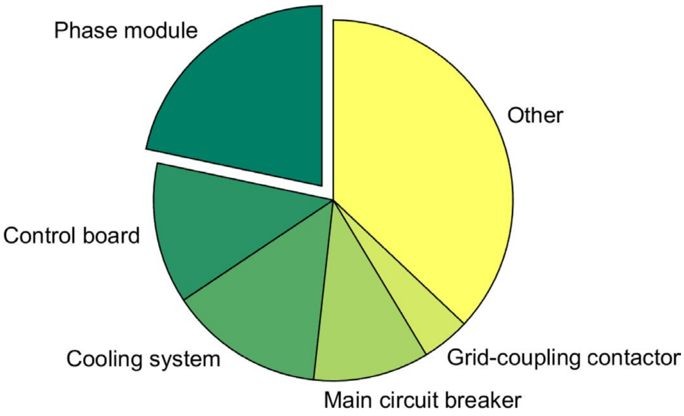


Figure 5. Distribution of failed converter components over categories, based on 3829 operating years of wind turbines of different generator-converter concepts and types [29].

The analysis indicates that the phase-module category accounts for the largest proportion, constituting 22% of failed converter components.

The key conclusion from the analysis of Figure 6. is that the distribution of IGBT-module failures in different wind turbine models suggests that thermal-cycling induced fatigue is unlikely to be a significant cause of converter failures, even in older turbines.

In [29], it was also noted that the months with high failure rates coincide with the periods of highest absolute humidity, suggesting that humidity and/or condensation play an important role in the emergence of phase-module failures.

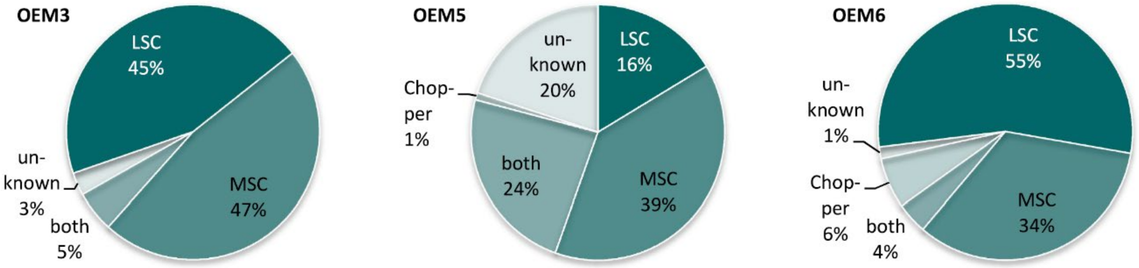


Figure 6. Distribution of IGBT-module failures over machine-side converter (MSC), line-side converter (LSC) and chopper in doubly fed induction generators (DFIG)-based wind turbines [29].

The silicon-based device has long been recognized as a reliable solution in wind power converters. However, recent advancements in WBG devices have unveiled tremendous potential for future high-power converters.

Figure 7 illustrates the power rating-frequency characteristics of power devices utilized in wind power converters. The chart displays the boundaries of commercially available power devices, with the dashed line indicating the limits of silicon-based devices. Additionally, the diagram highlights the potential contributions of WBG devices in high-power applications.

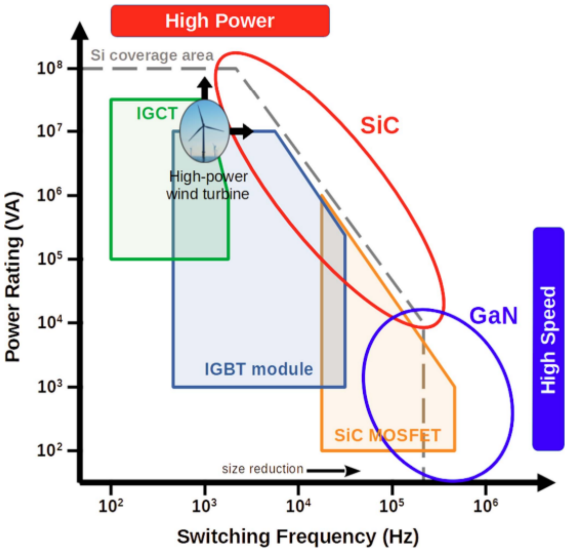


Figure 7. Power rating-frequency characteristics of power devices in wind power converter [30].

The SiC MOSFET exhibits excellent operation capability at high switching frequencies and over a wide temperature range, opening up new possibilities in power converter design with respect to topology, passive components, and cooling systems. Moreover, utilizing SiC MOSFETs allows for a significant increase in power density. To further enhance high-frequency operation, the soft-switching technique is proposed. This technique minimizes the overlap of voltage and current on the power device during the switching transient process, thereby reducing switching losses and enabling the power converter to operate at even higher switching frequencies. This, in turn, leads to improved power density and efficiency.

However, it's important to note that achieving soft-switching operation requires the inclusion of auxiliary devices and passive components, which introduces additional complexity and reduces the overall reliability of the power converter. This drawback must be taken into consideration, particularly in wind power applications.

Although SiC-based wind power converters offer promising advantages, there are still significant challenges to address in practical operation.

In [30], several aspects have been discussed:

- The high cost of SiC-based devices and the manufacturing processes are still a concern.
- The field reliability of the SiC-based converter should be further addressed. Furthermore, the lifetime models and lifetime extension strategies need to be enhanced.
- The novel packaging technologies need to be developed to fully utilize the advantages of SiC. The higher switching frequencies will demand novel interconnection technologies and optimized layout designs to minimize the electrical parasitic of the package. Further, high temperature operation will need to incorporate advanced materials and cooling approaches to lower the thermal resistance and enhance the heat removal capability.
- The gate driving technology should be developed to perform the high-speed switching. Also, overvoltage and overcurrent protection schemes should be considered without decreasing efficiency. Further, the driving circuits should be designed to mitigate electromagnetic interference and support long-term operation at high temperatures.

2.3.4. Power Electronic Systems for Electric Vehicle

Reliability plays a pivotal role as a vital performance metric that necessitates meticulous consideration throughout the stages of design, manufacturing, testing, and field operation of Electric Vehicle (EV)/ Hybrid Electric Vehicle (HEV).

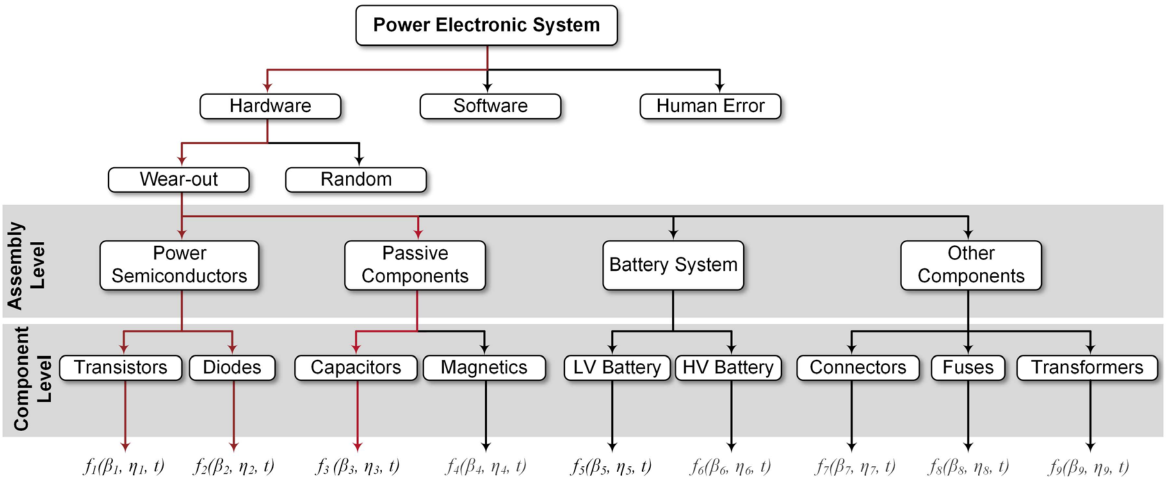
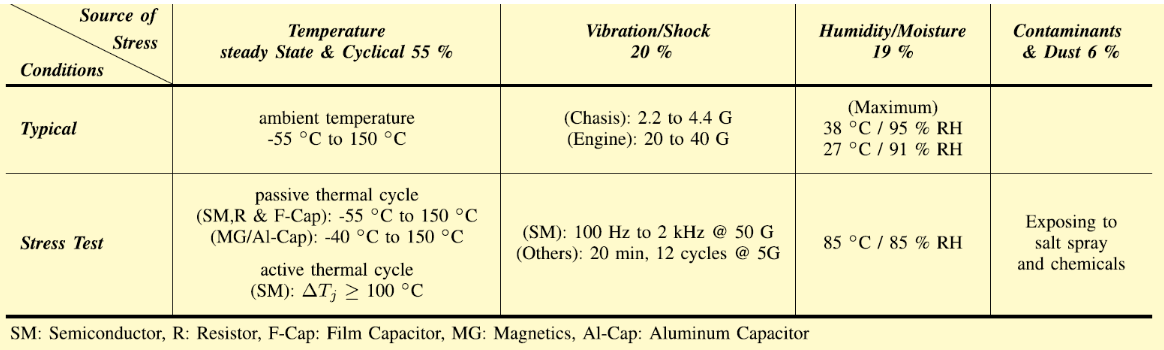


Figure 8. Typical failure modes of the EV/HEV power electronic system [31].

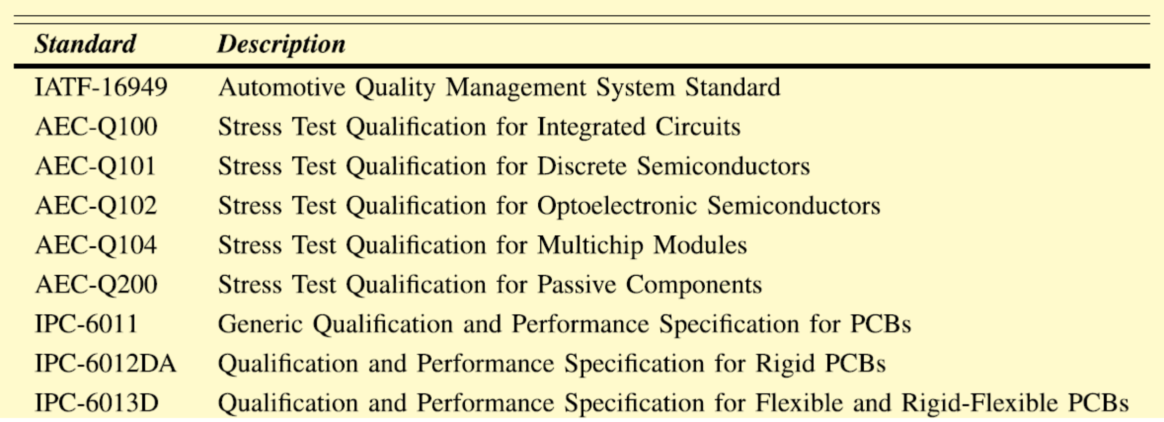
Taking a system-level perspective, failure modes within the EV/HEV power electronic system can be categorized into software failures, failures resulting from human error, and hardware failures. The hardware failures can be further distinguished as wear-out failures and random (or catastrophic) failures. Since accurate modelling or estimation approaches for failures triggered by random events or human error are often lacking, failure mode and effect analysis (FMEA) and qualitative accelerated test methods can be employed to examine the specific components/subassemblies affected by these types of failures. The main power electronic assemblies and components affected by the time-dependent wear-out failure function are showcased in Figure 9.



Conditions \ Source of Stress	*Temperature steady State & Cyclical 55 %*	*Vibration/Shock 20 %*	*Humidity/Moisture 19 %*	*Contaminants & Dust 6 %*
Typical	ambient temperature -55 °C to 150 °C	(Chasis): 2.2 to 4.4 G (Engine): 20 to 40 G	(Maximum) 38 °C / 95 % RH 27 °C / 91 % RH	
Stress Test	passive thermal cycle (SM,R & F-Cap): -55 °C to 150 °C (MG/Al-Cap): -40 °C to 150 °C active thermal cycle (SM): $\Delta T_j \geq 100$ °C	(SM): 100 Hz to 2 kHz @ 50 G (Others): 20 min, 12 cycles @ 5G	85 °C / 85 % RH	Exposing to salt spray and chemicals

SM: Semiconductor, R: Resistor, F-Cap: Film Capacitor, MG: Magnetics, Al-Cap: Aluminum Capacitor

Figure 9. Source of Stress for Power Electronic Components in Electric-Based Vehicles [31].



Standard	*Description*
IATF-16949	Automotive Quality Management System Standard
AEC-Q100	Stress Test Qualification for Integrated Circuits
AEC-Q101	Stress Test Qualification for Discrete Semiconductors
AEC-Q102	Stress Test Qualification for Optoelectronic Semiconductors
AEC-Q104	Stress Test Qualification for Multichip Modules
AEC-Q200	Stress Test Qualification for Passive Components
IPC-6011	Generic Qualification and Performance Specification for PCBs
IPC-6012DA	Qualification and Performance Specification for Rigid PCBs
IPC-6013D	Qualification and Performance Specification for Flexible and Rigid-Flexible PCBs

Figure 10. Requirements for Automotive-Grade Power Electronic Component Manufacturers [31].

The automotive application, characterized by an anticipated operational lifespan exceeding ten years, an ambient temperature range spanning from -55°C to 150°C, and a zero-tolerance policy for failures, presents one of the most demanding challenges in terms of reliability.

Figure 9 illustrates various sources of stress that impact power electronic components. Additionally, the table provides examples of typical environmental and stress test conditions specific to EV/HEV applications, with temperature stress identified as a significant factor responsible for the degradation of power electronic components. Maximum steady-state temperature and temperature cycling can be considered as key stressors in this regard. Figure 9 also highlights the importance of humidity and vibration as critical types of stressors that greatly impact automotive applications. In particular, humidity and condensation pose significant challenges to electronic circuits due to their electrically conductive and corrosive nature.

As a result, the components must withstand inhospitable conditions, and increased reliability is crucial in maximizing a vehicle's lifespan. Consequently, these components should be subjected to significantly more rigorous testing conditions in comparison to those used in typical power electronic applications. Figure 10 summarizes the commonly required certification for automotive-grade power electronic components. In 2019, the European Centre for Power Electronics (ECPE) published AQG 324, a comprehensive guideline focused on the "Qualification of Power Modules for use in Power Electronics Converter Units in Automotive Applications" Presently, a majority of manufacturers have embraced this qualification guideline as a standard for their automotive-grade power module products.

The primary cause of WBG semiconductor failures is thermal wire-out resulting from instantaneous load variations. When dynamic loads generate high temperature differences, thermo-mechanical stress occurs at various layers of SiC semiconductor modules. This stress initiates fatigue in bond wires, chip-solder, dies, and substrates.

3. State of the Art of Reliable Component- and System Design Process

3.1. State of the Art

3.1.1. Failure Criteria

Failure criteria must be emphasized, and the exact definition of failure criteria is essential for the evaluation of any test. Table 6 below states some of the common failure criteria for qualification and endurance tests, as they are specified by international standards:

Table 6: Failure criteria for acceptance after endurance tests.

Failure criteria IEC60747-9(2001):	
Gate leakage current I_G	+100% USL
Collector/Drain leakage current I_D/I_C	+100% USL
On-state voltage $V_D/V_F/ V_{C(sat)}$	+20% IMV or 0% USL
Threshold voltage V_T	+20% USL
	-20% LSL
Thermal resistance R_{thjh}/R_{thjc}	+20% IMV or 0% USL
Isolation voltage V_{ISOL}	Not below specification limit
Note USL: upper specification limit, LSL: lower specification limit, IMV: initial measured value	

However, with the development of power semiconductor devices, some of the failure criteria set previously may not be able to reveal the real end of life (EOL). As discussed in [57], a gradient-based EOL criterion has been proposed for power semiconductor modules under power cycling tests. The new criterion significantly improves the consistency in determining the cycle-to-failure of testing samples compared to the widely used absolute-value-based EOL criterion, such as the percentage change of on-state saturation voltage of IGBTs.

3.1.2. Reliability Test Standards

Many different reliability test standards are well established for the qualification of IGBT/MOSFET-modules for industrial applications with reference to conventional modules, such as [69].

The qualification tests in Table 7 can be classified into three groups. The first three tests are chip-related qualification tests, which are also part of every chip qualification. But since the chips are exposed to different substances during the module assembly process (i.e., solder flux, cleaning solvents, and silicone soft mold), a confirmation of the chip reliability in the assembled module is inevitable. This set of chip related tests is followed by a group of seven tests related to stability of the package in the specified operation and storage temperature range and under external and internal temperature swings. Especially the power cycling test is important for the lifetime of power modules in application. The last two tests are confirming the mechanical integrity of the package.

Table 7: Reliability tests for qualification of IGBT/MOSFET-modules for industrial applications with reference to conventional modules [69].

	Name	Conditions	Standards
HTRB	High Temperature Reverse Bias test	MOS/IGBT: 1000h, T_{vjmax}, 0.8*V_{cmax} Partially V_{cmax} (≤ 2kV), Conv.:1000h, T_{vjmax} -20K, $V_R/V_D=0.8*V_{RRM}/V_{DRM}$ Rsep.0.66* V_{RRM}/V_{DRM}	IEC60747-9:2007 IEC60747-2/6
HTGS (HTGB)	High temperature Gate stress test	1000h,V_{gmax}, T_{vjmax}	IEC60747-9:2007
H^3TRB(THB)	High humidity High temperature Reverse bias test	1000h,85°C,85%RH V_c = 0.8*V_{cmax}, however max.80V, V_g=0V	IEC60749-5:2003
LTS	Low temperature Storage test	T=T_{stgmin}, 1000h	JESD-22 A119:2009
HTS	High temperature Storage test	T=T_{stgmax}, 1000h	IEC60749-6:2002
TST	Thermal shock	T_{stgmin} – T_{stgmax}, typ. -40°C to +125°C, $t_{storage}$ ≥ 15min, t_{change} ≤ 30s 1000 cycles Conv.: 25 cycles	IEC60749-25:2003
PC_{sec}	Power cycling	Internal heating and external cooling T_{on} < 5s, I_L > 0.85*Inom	IEC60749-34:2011
PC_{min}	Power cycling	Internal heating and external cooling T_{on} > 15s, I_L > 0.85*Inom	IEC60749-34:2011
V	Vibration	Sinusoidal sweep, 5g, 10-1000Hz, 2h per axis, (x,y,z)	IEC60068-2-6 Test Fc
MS	Mechanical shock	Half sine pulse, 30g, 18ms, 3 times each direction (x,y,z)	IEC60068-2-27 Test Ea

3.1.3. Lifetime Models

Many different lifetime models have been established for Si, SiC and GaN devices.

3.1.3.1. Si Lifetime Models

The identified empirical lifetime models for Si power semiconductor devices are split between models available in the scientific literature and models provided by manufacturers in application notes and data sheets.

Empirical models are deduced from experience and large databases of power cycling (PC) test results, which can express the lifetime in terms of the number of cycles to failure consisting of several factors such as temperature swing, medium temperature, frequency, bond wire current, etc. It was observed that the dominant failure mechanisms in PC tests are failure of bond wires and solder interconnecting layers. The most common empirical lifetime models used for the reliability evaluation of Si IGBTs, which are disseminated in the scientific literature are presented below.

- LESIT Model [32]
- CIPS 2008 Model [33]
- U. Scheuermann et al. [34]
- G. Zeng et al. [35]
- O. Schilling et al. [36]
- M. Ciappa et al. [37]
- U. M. Choi et al. [38]
- A. Schiffmacher et al. [39]
- G. Zeng et al. [40]
- Yang et al. [41]

The main problem of the empirical lifetime model is that it is difficult to accurately extract the number and amplitude of the temperature cycles from a given temperature profile (mission profile). Instead, the physics of failure (PoF) models are based on the physical parameters reflecting corresponding failure and deformation mechanisms, so that the stress and strain development within the power module assembly is modelled and directly correlated to the number of cycles to failure. The PoF models show a promising alternative to the empirical models.

- I. F. Kovačevič et al. [42]
- P. Steinhorst et al. [43]

In some cases, power electronic component manufacturers provide the power cycling curves for specific product families or technologies in application notes or data sheets. However, similarly to most scientific literature, the statistical analysis of the power cycling analysis is not mentioned but can typically be provided upon request. The publicly available lifetime characteristics of the main Si power semiconductor manufacturers are shown below.

- Infineon application note AN2019-05 [44]
- Semikron application note AN 21-001 [45]
- ABB application note 5SYA 2043-04 [46]

3.1.3.2. SiC Lifetime Models

Based on the failure data collected from accelerated lifetime testing (ALTs), lifetime models are used to estimate the reliability performance under normal operating conditions. Each acceleration model has specific application circumstances.

In [47], the component-level lifetime model of the SiC devices has been categorized into three different types, which are physics of failure (PoF) models, data-driven models, and hybrid models in both chip level and package level.

Empirical models:

- F. Hoffmann et al. [48]

PoF models are referred to and based on specific physical failure mechanisms. Lifetime models based on failure modes such as gate oxide failure, bond wire fracture/lift-off, and solder fatigue are presented below:

- T. Santini et al. [49]
- B. Hu et al. [50]
- L. Ceccarelli et al. [51]

OEM application:

- Rohm application note AN102E [52]

3.1.3.3. GaN Lifetime Models

Empirical models:

- J. Franke et al. [53]
- F. Lippold et al. [54]
- EPC_1 [55]

PoF models:

- EPC_2 [55]
- EPC_3 [55]

OEM application:

- Infineon Whitepaper 04-2022 [56]

3.1.4. Failure Analysis Techniques

The failure analysis techniques developed for component-level are presented (Figure 11, 12, 13, 14 and 15):

- Laser decapsulation

Figure 11. Laser machine (left). Decapsulated device using laser (right).

Capacity:

- Gel- and molded resin removal
- Mixed laser and etchant process

Applications:

- Sample preparation
- Post-failure analysis
- Quality inspection

Figure 11 shows laser machine and

- Scanning acoustic microscopy
  - Non-destructive ultrasound wave inspection equipment
  - Determine if IC devices have voids, delamination or cracks
  - A versatile diagnostic tool requiring less time and having a high efficiency

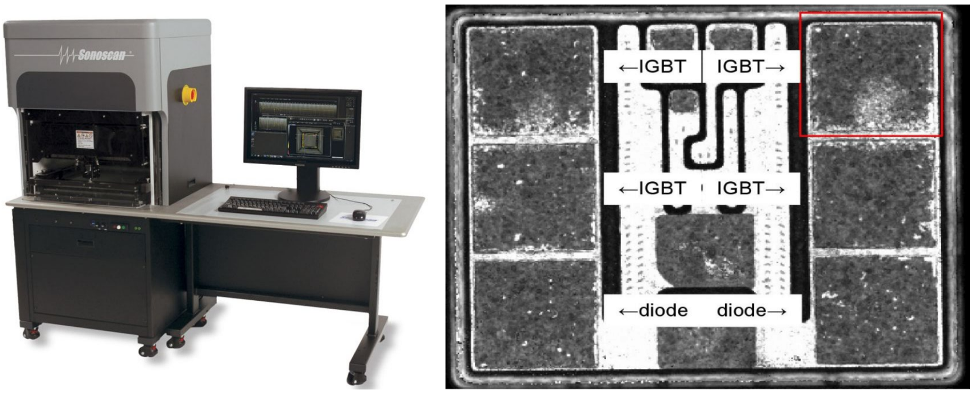


Figure 12. Acoustic Microscope (left). Scanning acoustic microscope image of chip solder - white areas indicate cracks (right).

- Thermographic Analysis
    - Assess temperature distribution across the module during operation or under stress
    - Identify hotspots, overheating, or thermal anomalies

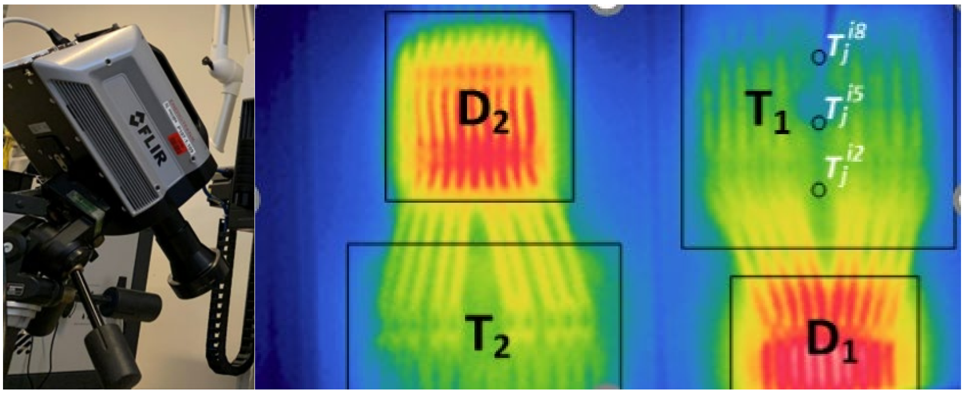


Figure 13. Infrared camera (left). Temperature distribution over chip surface measured by IR (right).

- Electrical Characterization
    - Measure Vth, Ron, Gm, leak current, breakdown voltage, stray capacitances
    - Measure turn-on, turn-off and reverse recovery characteristics
    - Provide insights into the electrical behaviour of the module, identifying issues related to short circuits, open circuits, or abnormal power losses

Figure 14. Double pulse tester(left). Curve tracer(right).

- Destructive Physical Analysis

DPA involves the selective removal of specific components or layers of the module for further examination using techniques like cross-sectioning, micro-sectioning, or delayering. It helps identify root causes of failures and enables direct observation of failure mechanisms.

- X-ray inspection (AXI) system

X-ray imaging provides non-destructive imaging of the internal structure of the module, enabling the detection of wire bond issues, solder voids, or delamination.

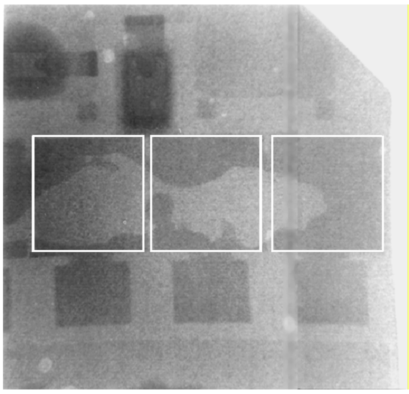


Figure 15. X-ray microscopy image of an IGBT module, which shows a large void immediately below three IGBT chips (0.8x). The void is located in the die attach layer.

3.1.5. Examples from Current- and Forthcoming Technology

Case study 1: Vicor Power [58]

- High power DC/DC converter with all necessary active and passive components
- Double sided cooling
- Robust, thermally conducting and electrically insulating encapsulation
- Space saving and robust

See Figure 16.

Figure 16. Vicor Power DC-DC converter [58].

Case study 2: Schweizer Electronic AG [59]

The Smart p² Pack technology from SCHWEIZER is a cutting-edge solution for embedding power semiconductors directly into printed circuit boards, see Figure 17. By embedding power semiconductors in the PCB, the Smart p² Pack technology simplifies the production chain for system suppliers, reduces the complexity of the system's structure and connection technology, and opens up potential for cost savings at the system level.

The Smart p² Pack technology also offers several advantages over traditional power electronic systems. For example, it reduces the need for additional components, such as heat sinks and mounting hardware, which can reduce the overall system size and weight. Additionally, it allows for better thermal management and reduces the thermal resistance between the semiconductor and the PCB, which can improve the system's efficiency and reliability.

- Reduced thermal resistance
- Reduced switching losses due to lower inductance in the system
- Reduced conduction losses in the static case
- Higher power densities possible and therefore less silicon required
- Significantly increased robustness and service life of the product

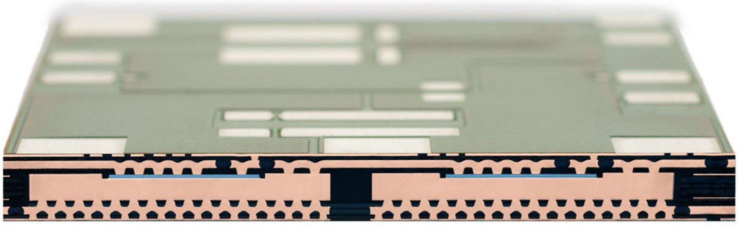


Figure 17. Schweizer Electronic PCB embedded power semiconductor [59].

Case study 3: Double side cooling [60]

Typical application: automotive

- No bond wires
- More complex cooling
- Low-voltage range

Reliability-related issues:

- Solder delamination
- Pressure-critical
- Cooling symmetry is key

Case study 4: Integrated chips in DBC [61]

Typically, custom-designed applications

- Higher power density
- No bond wires
- Single/double side cooling

Reliability-related issues

- Material(s) stiffness –interface tension
- Unknown failure mechanisms

Case study 5: Use of Liquid-Metal as the Frontside Interconnect in Power Semiconductors

- Pro: liquid metal could handle 6-10 times as many thermal cycles [62].
- Con: gallium alloys can react with the metallization in the long term.

Figure 18 shows test results for a prototype of a connection based on a liquid gallium alloy compared to traditional bond wires of two different thicknesses. The reliability can be read as how many thermal cycles (that is, repeated heating and cooling) at a given amperage and frequency, the connection can withstand before it fails. It can be seen that the prototype can withstand many more cycles – 6-10 times more – than the traditional bond wires.

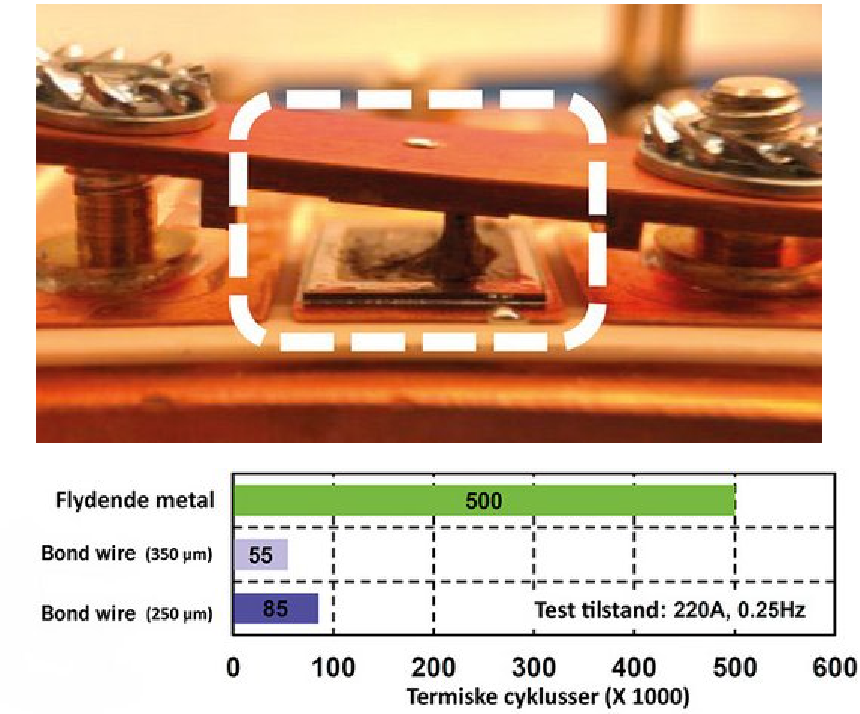


Figure 18. Liquid metal bonding technique (Courtesy of AAU Energy).

In addition to the brief introduction of this chapter to the reliable component- and system design process, chapter 5 will go into the prospects of five key indicators:

1) customer expectations
2) reliability targets
3) research and development approach
4) research and development tools
5) available technologies

4. Reliability Definitions and Methodologies in Power Electronics

4.1. Key Terms and Existing Reliability Definitions

Reliability Engineering deals with failure and focuses on:

- What will fail?
- When will it fail?

In order to avoid or delay failures, thus make products last longer.

Four major objectives:

- To apply engineering knowledge to prevent or to reduce the likelihood or frequency of failures
- To identify and correct the causes of failures that do occur, despite the efforts to prevent them
- To determine ways of coping with failures that do occur, if their causes have not been corrected
- To apply methods for estimating the likely reliability of new designs, and for analyzing reliability data

Reliability of an item is the probability it performs a required function under given conditions for a given time interval.

R(t) is the probability that a system, component or device, will operate without failure until time t.

$$R(t) = \frac{N_s(t)}{N_0} = \frac{N_0 - N_f(t)}{N_0}$$

Instantaneous failure rate, hazard rate, is the failure in time (1FIT = 1 failure per billion h operation 10 9 h)

$$h(t) = \frac{dN_f(t)}{dt}\frac{1}{N_s(t)} = \frac{-dR(t)}{dt}\frac{1}{R(t)}$$

Unreliability F(t): probability that a failure will be observed by time t also called cumulative distribution function CDF.

(Percentile) Lifetime (for a population of items): The expected life by which a certain percentage might have failed, e.g., B10 lifetime – the time when 10% fail.

Figure 19 Illustration of percentile lifetime for a population of items.

Failure Mechanism:

Root Causes ---------------------> Failure Mechanism ---------------------> Failure Mode

(Driver) (Degradation process)

PCB as an example:

- Open circuit/arcing is failure mode
- Cracked solder joint due to mechanical stress is mechanism
- Board not mounted flat (bowed or twisted) is the driver

Stresses: overstress or wear out, see Figure 20:

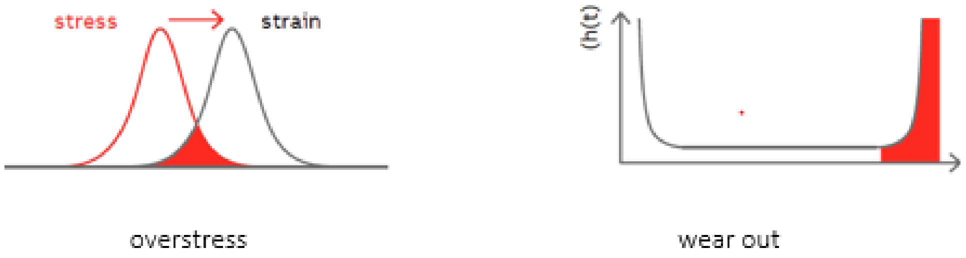


Figure 20 Illustration of overstress (left) and wear out (right)

Probability density function pdf f(t): The probability density function (pdf) is a mathematical function that describes the distribution. E.g. Normal, Poisson,… 2 parameter Weibull is the classical choice.

Mean Life (MTTF): average time that the units in the population are expected to operate before failure.

$$\mathrm{MTTF} = \overline{\mathrm{T}} = \int_0^\infty \mathrm{t}\, \mathrm{f(t)dt}$$

FIT: industry value defined as the failure rate λ per billion hours (for the exponential pdf case FIT=1/MTTF 109).

Median Life: time by which the integral of the pdf (area) equals 1/2. i.e. 50% of the devices are expected to fail (B50).

Probability Plot: It is a plot of the probability of failure over time. The probability plots are based on the linearization of a specific distribution.

Acceleration factor: is used to describe the ratio of the life characteristic at the use and accelerated test conditions, or:

$$A_F = \frac{L(use)}{L(accelerated)}$$

Confidence interval: Represent the uncertainty in the results due to the limited sample sizes.

4.2. Methodologies for Reliability Design and Assessment

4.2.1. Mission-Profile-Based Design of Power Electronics

Numerous reliability assessment procedures based on mission profiles, integrating Design for Reliability (DfR) methods and Physics of Failure (PoF) principles specific to power electronics, have been proposed and effectively implemented across various applications. Examples include wind power converters, grid-connected PV inverters, variable frequency drives, and electric aircraft. Regarding EV/HEV applications, significant emphasis has been placed on the reliability evaluation methodology for power modules employed in the electrical drive train inverter. Additionally, a comprehensive six-step procedure based on mission profiles has been proposed to estimate the lifetime and assess the reliability of power electronics, both at the component and system levels. Figure 21 provides a general overview of the reliability assessment process.

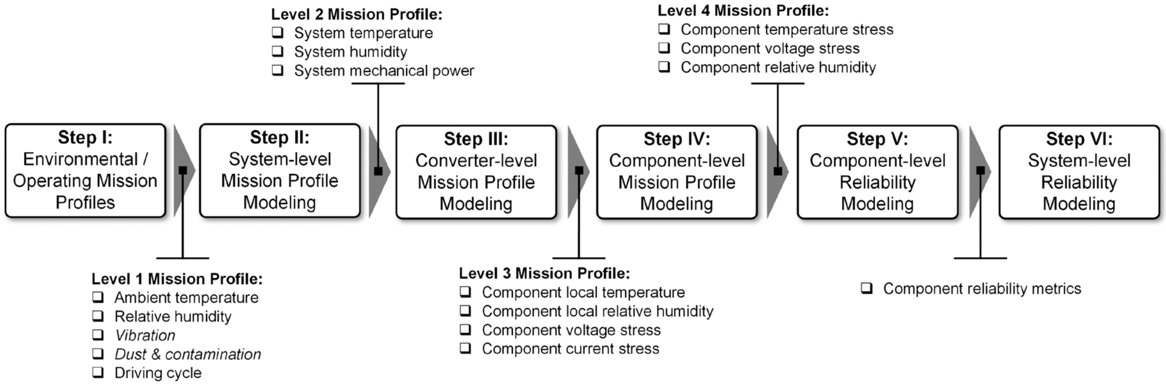


Figure 21. General mission-profile-based reliability assessment procedure for power electronic systems.

4.2.2. Digital Design

Wide band gap (WBG) semiconductors necessitate packaging techniques that minimize parasitic inductance and capacitance. To address this requirement, innovative packaging solutions are being suggested to enhance integration. However, this integration poses challenges in accurately measuring voltages, currents, and device temperature. Consequently, designers must increasingly depend on simulations to gain valuable insights into the functionality of the developed prototypes.

Moreover, employing digital design methodologies can effectively minimize the necessity for numerous physical prototype iterations, resulting in reduced development time. Enhancing the accuracy and fidelity of three-dimensional Multiphysics simulations, as well as employing reduced-order modelling and system simulation, greatly contribute to the design process of functional prototypes. These advancements further enhance the performance of new power modules that rely on WBG semiconductor devices, see example of general framework used for design of power modules in Figure 22.

Challenges:

- As the switching speed is continuously increasing with WBG devices, the need for accurate modelling necessitates the utilization of full-wave solvers, as the interaction between transient electric and magnetic fields becomes increasingly significant.
- Predict behaviour of main components in the gate driver and control circuitry.
- Few manufacturers provide detailed models of IC behaviour.

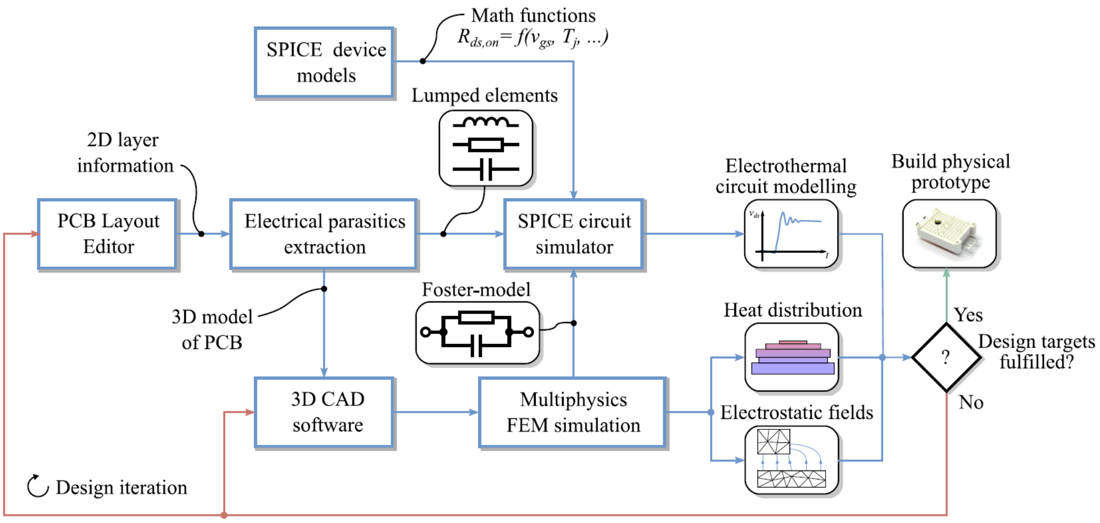


Figure 22. Example of a general framework used for digital design of power modules [63].

4.2.3. Accelerated Test

Component level: Power cycling of power modules.

Component level: Thermal cycling of power modules.

Note: Always be careful to accelerate the same (failure) mechanism.

4.2.4. Condition Monitoring

Monitoring: Integration of sensors into power electronics systems for intrinsic monitoring of device performance and real time environmental conditions, to enable estimation of remaining useful life and implementation of preventive maintenance functionalities.

4.2.5. Artificial Intelligence

AI Implementation: demand smart small solutions for PE applications.

Key Drivers:

- Energy efficiency
- Cost of energy
- Life cycle cost
- Predictive maintenance
- Time-to-market

Key Trends:

- Product + service

- Data + physics
- Digitalization

Limitations:

- Lack of rigorous answers to the application questions
- Application challenges remain to a large extent
- Limited implementation with hardware platforms

Challenges in applying AI for PE:

- Accuracy (high for part of the applications)
- Relatively limited quality data (high but expect be solved)
- Relatively limited computation resources (high but expect be solved)
- Interpretability (moderate)

Application Questions:

- Are AI-based methods better for the specific application?
- What are the application constraints?
- Are the results accurate enough and repeatable?

Prospects of AI for PE Applications:

- Math + computer science + domain expertise in PE
- Importance of data -Garbage in garbage out
- Cyber security –power grids, electrical equipment becomes target for hackers
- “The future of AI will be about less data, not more” –this could be even more true in PE applications (data availability and AI energy consumption)
- Black boxes constitute a security risk –physics-informed AI helps explainability and transparency
- PE converters are evolving towards data-rich systems for IoT implementations of data-driven solutions

4.3. Testing Standards

4.3.1. JEDEC JC-70

JC-70 Wide Bandgap Power Electronic Conversion Semiconductors stands as JEDEC's latest primary committee. The recently formed JC-70 committee comprises two distinct subcommittees: JC-70.1, dedicated to GaN Power Electronic Conversion Semiconductor Standards, and JC-70.2, focusing on SiC Power Electronic Conversion Semiconductor Standards. The committee's core areas of emphasis encompass Reliability and Qualification Procedures, Datasheet Elements and Parameters, as well as Test and Characterization Methods.

JEDEC JEP 180: GaN Switching Reliability

JEDEC JEP 183: SiC V_{th} Measurement

JEDEC JEP 184: SiC Bias Temperature Instability

JEDEC JEP 190: SiC dV/dt Robustness

JEDEC JEP 194: SiC Gate Oxide Reliability and Robustness Evaluation

JEDEC JEP 195: SiC Gate Switching Instability

JEDEC JEP 197: SiC Bipolar Degradation

JEDEC JEP 198: GaN Reverse Bias Reliability

4.3.2. IEC Standards

The international standard describes early reliability assessment methods for items based on field data and test data for components and modules.

IEC 61709:2017: guidance on the use of failure rate data for reliability prediction of electric components used in equipment.

IEC 63275-1:2022: SiC Bias Temperature Instability

IEC 63275-2:2022: SiC bipolar degradation due to body diode operation

IEC 63373:2022: GaN HEMT Dynamic on-resistance test method

4.3.3. AEC Standards

AEC-Q101: Focused on silicon discrete devices.

AEC-Q101 is a stress test qualification based on failure mechanisms, specifically designed for discrete semiconductors used in automotive applications. The Automotive Electronics Council (AEC), headquartered in the United States, was initially formed by three prominent automotive manufacturers with the goal of establishing unified standards for part qualification and quality systems. AEC-Q101 serves as an industry standard specification, defining the necessary qualification requirements and procedures for the introduction of new products and significant changes in discrete semiconductors intended for automotive applications [70].

4.3.4. MIL-HDBK-217

MIL-HDBK-217, Reliability Prediction of Electronic Equipment, has been the mainstay of reliability predictions for about 40 years.

The handbook was published by the Department of Defence, Washington DC, U.S.A, and is available via several websites on the internet. Its last issue is the Rev.F+ Notice 2.

The handbook is incorporated within several commercially available reliability software packages.

4.3.5. FIDES Standards

The FIDES is a reliability data handbook (available since January 2004) developed by a consortium of French industry under the supervision of the French DoD (DGA).

The FIDES methodology is based on physics of failures and is supported by the analysis of test data, filed returns and existing modelling. It aims to enable a realistic assessment of electronic equipment reliability, including systems operating in severe environments (e.g. defence systems, aeronautics, industry electronics, and transport).

The FIDES guide is divided in two parts: a reliability prediction guide and a reliability process control and audit guide. By identifying the factors contributing to reliability, whether technological, physical or process-based, FIDES allows the revision of product definition and intervention throughout the product lifecycle, to improve and control reliability.

The FIDES method is the most recently developed reliability prediction calculation methods for electronic systems based on physics of failures (PoF), field return (mainly military and aeronautics) and tests.

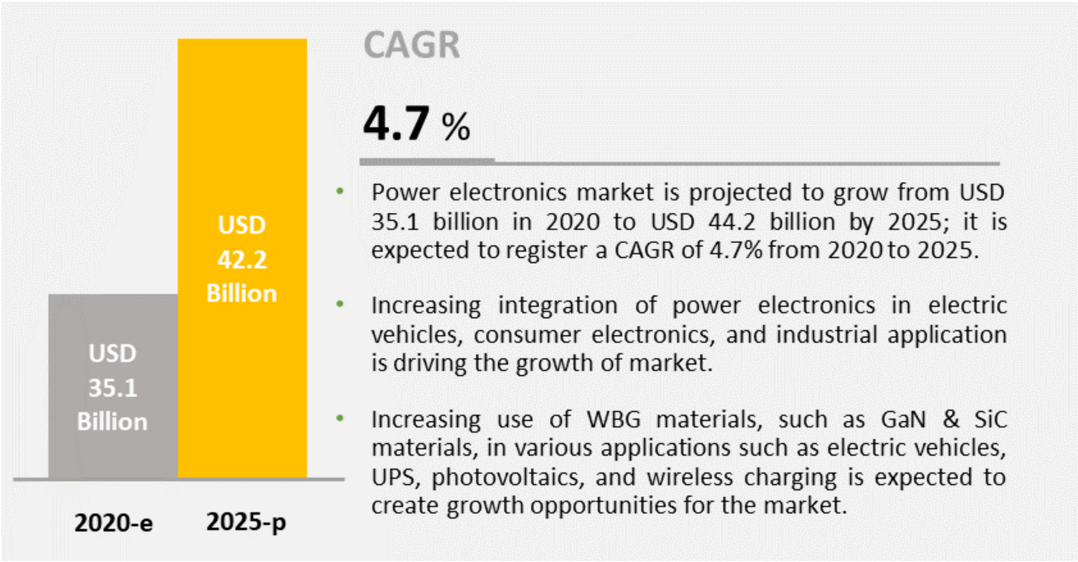
4.3.6. ECPE AQG 324 Recommendation

The ECPE Working Group AQG 324 established in June 2017 is working on a European Qualification Guideline for Power Modules for Use in Power Electronics Converter Units in Motor Vehicles. Based on the former German LV 324 (´Qualification of Power Electronics Modules for Use in Motor Vehicle Components - General Requirements, Test Conditions and Tests´) the ECPE Guideline defines a common procedure for characterizing module testing as well as for environmental and lifetime testing of power electronic modules for automotive application. The guideline has been released by the responsible Industrial Working Group comprising ECPE member companies with more than 30 industry representatives from the automotive supply chain.

The current iteration, AQG 324 version dated 31 May 2021, emphasizes Si-based power modules, with an additional Annex dedicated to the Qualification of SiC-based power modules. Subsequent releases by the Working Group will extend the coverage to include emerging wide bandgap power semiconductors such as SiC and GaN.

5. Outlook of Trends Regarding Reliability of Electronics Relevant for Promotion of WBG for Energy and End-User Applications

Power Electronics has become essential to transfer energy from many different sources, primarily referring to renewables, to the application place, including automotive, industrial automation, home appliances and electrolysers. However, due to the many conversion stages throughout the entire energy chain, i.e., from the source to the utilization places, the total losses amount up to 20%. For this reason, the massive adoption of WBG semiconductors would enable a better conversion with significantly higher efficiency, which translates into a lower CO_2 impact and a lower energy loss in general. The reduction in terms of weight, volume, and cost for large-scale applications such as laptop- and mobile phone power supplies, is another strong push toward the adoption of wide-bandgap semiconductors, as they enable operating frequencies and power densities not possible with the silicon traditional technology. A similar demand comes from wireless power transmission, where the overall system efficiency increases with the operating voltage and frequency.



- Power electronics market is projected to grow from USD 35.1 billion in 2020 to USD 44.2 billion by 2025; it is expected to register a CAGR of 4.7% from 2020 to 2025.
- Increasing integration of power electronics in electric vehicles, consumer electronics, and industrial application is driving the growth of market.
- Increasing use of WBG materials, such as GaN & SiC materials, in various applications such as electric vehicles, UPS, photovoltaics, and wireless charging is expected to create growth opportunities for the market.

Figure 23. Market growth forecast of Power Electronics [64].

The Power Electronics market is expected to grow in the coming 2-3 years as shown in Figure 23 where a projection from [64] foresees an increment of about 5% in the cumulative annual growth ratio (CAGR) from 2020 to 2025. However, this growth could be faster if some key issues would be tackled, in particular referring to the reliability uncertainty.

This demands for policy makers to implement appropriate policy measures to reduce this reliability uncertainty in order, to harvest the benefits of power electronics in general and power electronics using WBG in particular.

Referring to a survey on failure distribution and root causes in power electronic applications (see Figure 24), it is found that the component units which more often fail in power electronic systems are 1) capacitors, 2) printed circuit boards (PCBs), and 3) semiconductors. In terms of root causes, five main factors affect the expected life of power electronic components, namely:

- maximum junction temperature
- junction temperatures swing
- vibration
- humidity and moisture
- contamination and dust

In addition, being the demanded time horizon of about 20-30 years for energy production and electric vehicles, the probability of abnormal events such as short circuit, mechanical shock, and electromagnetic interference is nonnegligible, thus jeopardizing the life expectancy. Consequently, the resilience against abnormal events must be carefully considered when moving to wide-bandgap semiconductors.

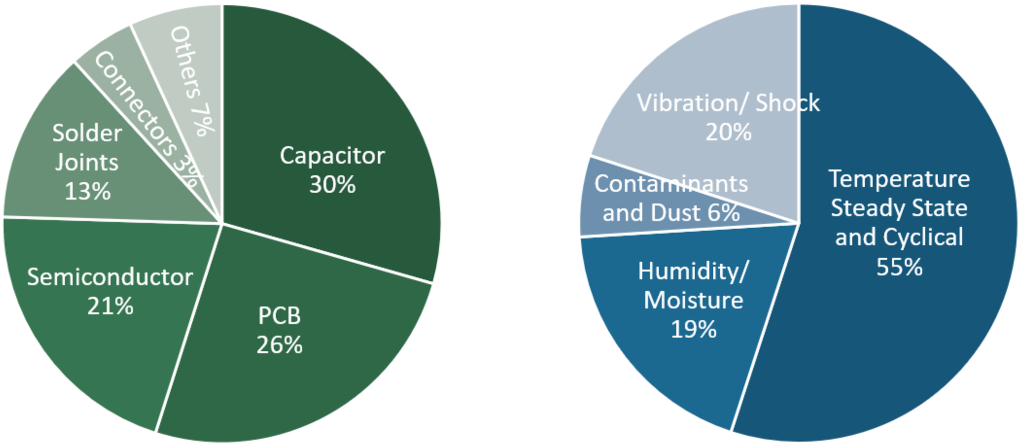


Figure 24. Failure distribution in industrial applications by unit (left) and root cause (right) [65].

Figure 25 shows what the past, present, and future scenario looks likes in relation to reliability of wide-bandgap devices. Five key indicators have been used, namely: 1) customer expectations, 2) reliability targets, 3) research and development approach, 4) research and development tools, and 5) available technologies, in particular referring to the WBG semiconductors. In the following sections, a detailed discussion is proposed for each of the above indicators.

5.1. Customer Expectations

To main actions are foreseen: 1) on-time (timely) maintenance and 2) self-diagnostics.

5.1.1. Timely Maintenance

Timely maintenance means that the state-of-health estimation of power semiconductors must be significantly more accurate than now, in order to avoid either too early or too late maintenance interventions. This is essential to exploit a power device until its end of life. In fact, a too-early intervention would waste precious useful lifetime, whereas a too late action would end up in a failure and its related unscheduled off-time.

5.1.2. Self-Diagnostics

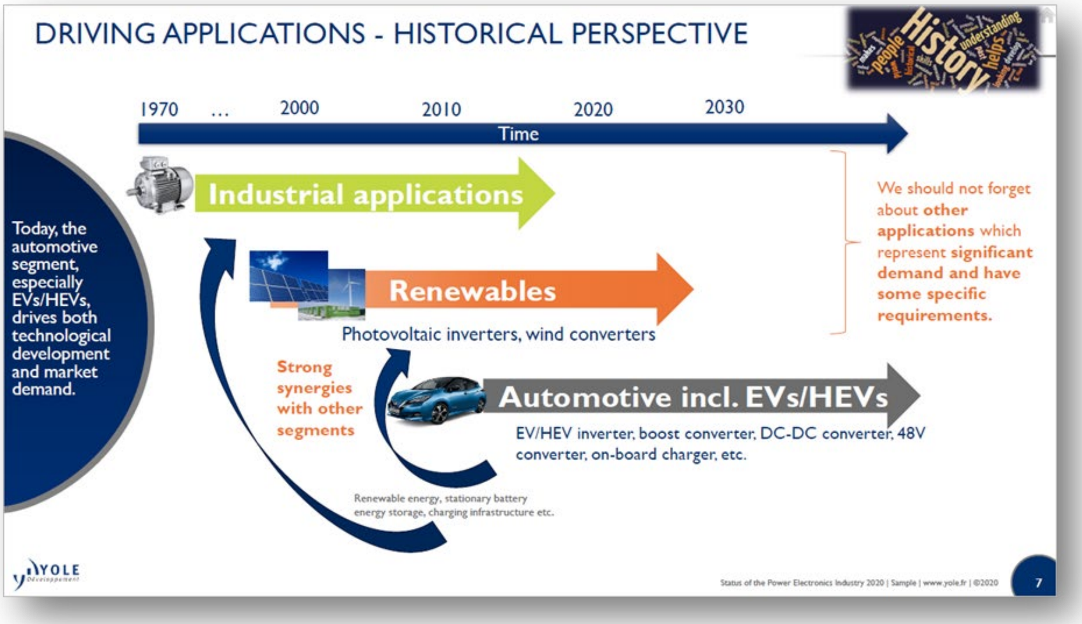
	Pre-history	Past	Present	(near) Future
Customer Expectations	✧ Replacement on failure ✧ Years of warranty	✧ Low failure risk ✧ Request for maintenance	✧ Peace of mind ✧ Predictive maintenance	✧ On-time maintenance ✧ Self-diagnostics
Reliability targets	✧ Affordable returns (%)	✧ Low return rates	✧ Ppm return rates	✧ Negligible returns
R&D approach	✧ Reliability testing ✧ Avoid catastrophes	✧ Robustness tests ✧ Weak-link approach	✧ Design for reliability ✧ Smart derating	✧ Offline condition logging ✧ Online condition monitoring
R&D key tools	✧ Operating testing	✧ Limit testing	✧ Understanding failure mechanisms, mission profiles, root causes ✧ Multi-domain simulations	✧ Beyond Temperature ✧ New concepts – challenge rainflow counting & Miner's rule ✧ Physics of degradation ✧ Digitalization ✧ 100% traceability ✧ CAD software with reliability plug-ins ✧ Reduced testing time
Available technologies		✧ Accelerated life testers ✧ CAD tools	✧ Parallel computing ✧ Land-network communication (4G)	✧ IoT ✧ Big data databases ✧ Cloud-/supercomputing ✧ AI ✧ Satellite communication (5G,..)

Figure 25. Expected paradigm shifts in the near future in terms of reliability of wide-bandgap technologies. The subset with white background was the original formulation of CORPE back in 2011 [66].

The power electronic unit should be able to perform a self-diagnosis based on specific indicators of the state of health. However, there is a lack of knowledge in terms of candidate health indicators for WBG semiconductors. This gap of knowledge should be filled to enable circuits for self-diagnosis on the next-generation power electronics.

5.2. Reliability Targets

According to Yole Développment, the adoption of power electronics is currently booming thanks to the large-scale adoption of electric vehicles [67], see Figure 26. This process will introduce up to one order of magnitude more power electronic components on the market which, in turn, will significantly increase the number of returns. This new wave requires specific competences both in terms of 1) failure mechanisms of WBG semiconductor devices and 2) treatment strategies for a given specific failure.


DRIVING APPLICATIONS - HISTORICAL PERSPECTIVE

Today, the automotive segment, especially EVs/HEVs, drives both technological development and market demand.

Industrial applications

Renewables

Photovoltaic inverters, wind converters

We should not forget about other applications which represent significant demand and have some specific requirements.

Strong synergies with other segments

Automotive incl. EVs/HEVs

EV/HEV inverter, boost converter, DC-DC converter, 48V converter, on-board charger, etc.

Renewable energy, stationary battery energy storage, charging infrastructure etc.

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Figure 26. Market forecast for power electronics according to Yole Développement [67].

5.3. Research and Development Approach

Two emerging tracks have recently become prominent in terms of research and development for improved reliability: (offline) condition logging and (online) condition monitoring.

5.3.1. Offline Condition Logging

Thanks to the reduced cost per gigabyte of non-volatile memories, it is now possible to log massive amount of data relevant for semiconductor health estimation and life prediction which, in turn, enable accuracy of diagnosis in case of failure. Typically, relevant data regard virtual junction temperature (direct or inferred), case temperature, load current, on-state voltage drop, and humidity. Figure 25 shows a demonstrator developed in CORPE, Aalborg University, in collaboration with Rimmen Reliability Consult ApS able to capture relevant quantities of a wind turbine during operation in order to estimate the status of health.

5.3.2. Online Condition Monitoring

Online condition monitoring is nowadays the most promising method for increasing operability of power electronic systems. However, a major hurdle is how to be able to access the relevant electrical and nonelectrical quantities without affecting the circuit reliability. The second hurdle is to build a cheap and reliable communication infrastructure allowing the real-time streaming of the relevant data. Figure 27 shows a prototype of a datalogger for power electronics.

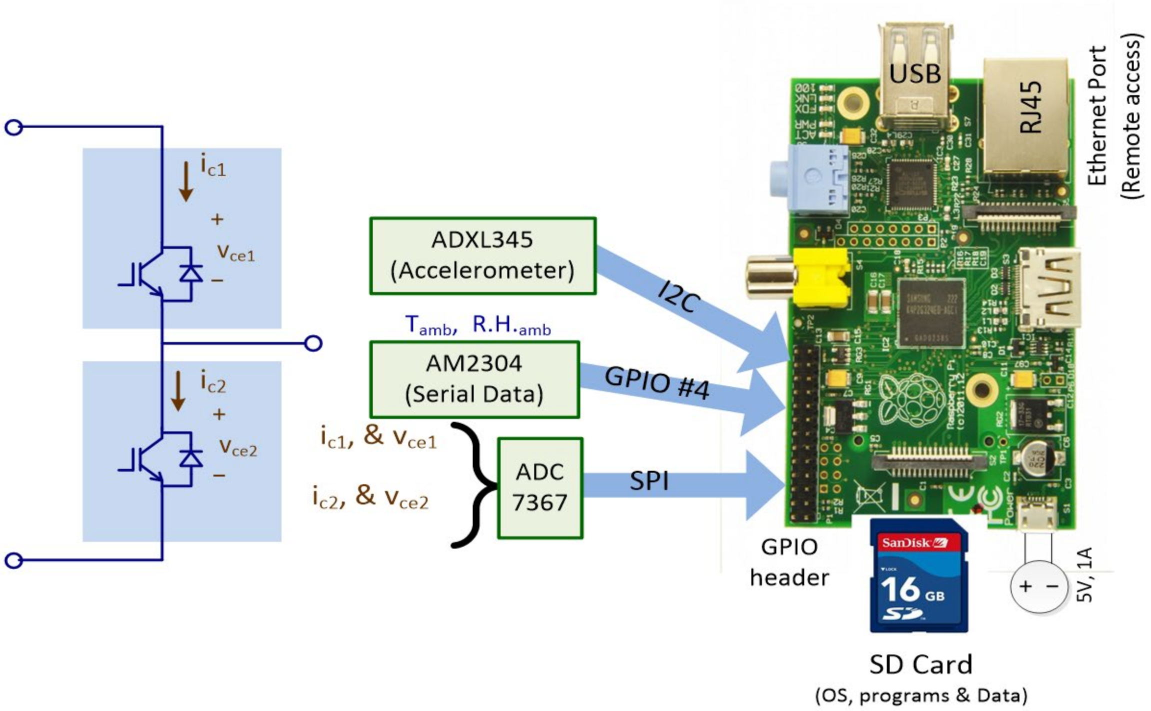

Figure 27. Prototype of a data logger built in CORPE in collaboration with Rimmen Reliability Consult ApS [68].

5.4. Research and Development – Key Tools

We have identified seven key tools which demand an endeavour in view of the adoption of WBG semiconductors. A brief description of each has been reported in the following sections.

5.4.1. Beyond Temperature

Temperature has been regarded for decades as the most dangerous variable to keep under control. However, there are several other variables, including vibration, humidity, voltage gradients, and electromagnetic interference, which deserve attention for a more accurate diagnosis. Moreover, the combination of them is often nonlinear, i.e., it is necessary to investigate combined effects of them on the expected life.

5.4.2. New Concepts

The “Rainflow counting algorithm” together with the Palmgren-Miner’s rule are the most used approach by far to predict the damage accumulation due to an arbitrary sequence of stresses. However, these approaches come from material engineering and have been conceived under several assumptions where, among other, the specimen under test is a homogeneous piece of material. In power electronics, though, components and modules are made up of complex structures, implying that those approaches can hardly be used as-is. New concepts are nowadays demanded which better consider the real structure of a power module, including the many different materials and its nonhomogeneous geometry.

5.4.3. Physics of Degradation

Physics of failure is largely used to understand how semiconductor components fail and what the mechanism underlying a given category of failure is. However, there is still a lack of knowledge regarding the physics of degradation, i.e., a systematical modelling of what the implications of a given degradation process are during the component life, particularly aimed at figuring out candidate indicators and precursors. This is especially true for WBG devices, whose degradation mechanisms are not necessarily the same as the traditional silicon semiconductors.

5.4.4. Digitalization

Digital electronics can be used more and more effectively to monitor and diagnose power electronics. More importantly, it can be used to make fast decisions in terms of operation of a power component. Nowadays, it is possible to integrate a relatively large amount of logical gates inside, e.g., the gate driver of a power switch, which was not possible until a decade ago. This approach would be considerably beneficial when moving to WBG semiconductors, which require intrinsically a more complex driving and protection logic compared to silicon counterparts.

5.4.5. Traceability

Traceability is also a key concept which is already adopted, e.g., in the food chain. By using large database management tools, production and distribution of components can be made fully back traceable, which would significantly boost the investigation process by making possible to correlate the fabrication process of the specific sample under study and the failure mechanism that took place on it.

5.4.6. Reliability Plugins for CAD Software

Modern CAD software is powerful and very much specialized in designing power electronic circuits and components, including power modules. There is no software to date, though, integrating a reliability prediction plugin to help the designer with deciding for one solution or another based on reliability considerations.

5.4.7. Reducing Testing Time

Accelerated testing or testing for reliability is still performed as many repeated stress cycles under rather harsh conditions, which typically take weeks or months to get a single measurement point. This is definitely the bottleneck in the reliability testing process because this takes to strategic choices regarding which condition to test first, and eventually taking to a systematic lack of information in terms of tested conditions. Research in the direction of making more accelerated life tests would be very beneficial to expand the experimental population and bring more data points to calibrate the life models. In support of this, test standards must be developed and updated as the methodologies evolve.

5.5. Available Technologies

Several promising technologies (although non exhaustively) are listed below.

5.5.1. Internet of Things

Internet of things (IoT) has been standardized as a common platform to exchange data with real objects which should be monitored or controlled from a human, or a base station located in a different location or even on a moving platform. This technology could be significantly contributing to monitor power electronic components, whose status would be collected, processed, and reported in real time by the same communication tools and channels which are used in the IoT technology. An endeavour is demanded though to make the type of signals and quantities to be monitored suitable to the IoT communication protocols that are not specifically designed for real-time operations.

5.5.2. Big Data Databases

Big data databases are becoming more and more used and shared over the internet. Data are typically generated by data logging stations which provide countless data in terms of monitoring of weather conditions, load profiles, and user operations. This amount of data is typically not utilized or underutilized because 1) there is a lack of software which is able to correlate the data with the specific platform they are supposed to be used for, but also because 2) the data records are often not generated and stored with the necessary accuracy in terms of, e.g., the sampling time or the required variable needed for a reasonable reliability prediction. Standardization would be highly beneficial in this field.

5.5.3. Cloud or Supercomputing

Cloud computers and supercomputers provide an excellent platform for heavy computational loads which are typically needed to an accurate evaluation of the failure mechanisms taking place in power devices. However, no specific platforms for reliability prediction are currently available.

5.5.4. AI

Artificial intelligence has become very common over the recent years. Major IT companies worldwide are providing artificial intelligence services for countless applications. This opportunity can be exploited in reliability, where the correlation between nonobvious combination of indicators and the real failure occurrence can be done in a profitable and efficient way.

5.5.5. Satellite Communication (5G and later)

An increasing quantity of power electronic components and circuits are being utilized in the transportation sector, where they are utilized for traction applications. This poses a big gap in terms of communication which can be filled by using satellite- and wireless communication which makes possible a near continuous communication to the base station at affordable price compared to customized solution which suffer from very high operational costs.

5.6. Conclusion

The various indicators discussed in this chapter form a catalogue of opportunities to reduce the reliability uncertainty of power electronics. In the next term of IEA 4E PECTA (2024-2028), this catalogue may serve as inspiration for on the one hand specific tasks to be carried out, on the other hand indicate to policy makers potential methodologies and technologies that may support policy measures in the future.

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