INVITED PAPER

# Reliability of Power Electronic Systems for EV/HEV Applications

*This article focuses on the power electronic systems reliability in electric vehicles (EVs) and hybrid EVs (HEVs) where both their reliability requirements and challenges are highlighted for the used power electronics technology.*

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**ABSTRACT** | The electrification of the transportation sector is moving on at a fast pace. All car manufacturers have strong programs to electrify their car fleet to fulfill the demands of society and customers by offering carbon-neutral technologies to bring goods and persons from one location to another. Power electronics technology is, in this evolution, essential and also in a rapid development technology-wise. Some of the introduced technologies are quite mature, and the systems designed must have high reliability as they can be quite complicated from an electrical perspective. Therefore, this article focuses on the reliability of the used power electronic systems applied in electric vehicles (EVs) and hybrid EVs (HEVs). It introduces the reliability requirements and challenges given for the power electronics applied in EV/HEV applications. Then, the advances in power electronic components to address the reliability challenges are introduced as they individually contribute to the overall system reliability. The reliability-oriented design methodology is also discussed, including two examples: an EV onboard charger and the drive train inverter. Finally, an outlook in terms of research opportunities in power electronics reliability related to EV/HEVs is provided. It can be concluded that many topics are already well handled in terms of reliability, but issues related to complete new technology introduction are important to keep the focus on.

**KEYWORDS** | Charger; drive train; electric vehicle (EV); hybrid EV (HEV); power converter; power electronics; reliability; thermal management.

## I. INTRODUCTION

The electrification of modern society is evolving at a very rapid pace to make the society more efficient and sustainable and reduces carbon footprint—the electrical generation needs to be renewable-based [1], the electrical transmission and distribution systems are expanded, and all aspects of consumption are demanded to be more efficient—mostly enabled by the power electronics technology ability to control the electrical power efficiently. One of the main areas that can dramatically reduce carbon emissions is the electrification of the transportation sector which is now in development, and it is moving with a very fast pace and accelerated penetration. The electrification will not only reduce the carbon emission but it will also improve the air quality in cities and reduce the noise level significantly. Countries are, by legislation, moving in that direction—Norway has announced that, by 2025, all new cars should be carbon emission-free, and Denmark has the same goal by 2030—thus, such decisions will pave the way for a very fast implementation [2] if the necessary electrical infrastructure will follow. Germany has analyzed how to become decarbonized by 2050 [3], indicating that many technical solutions are possible and there are also many challenges. However, a recent study by Bloomberg [4] said that, by 2040, more than 50% of all sold cars will be electrified, meaning a market of +40 million electric cars. Car technology can be different—it can be fully electric vehicles (EVs), it can be hybrid EVs

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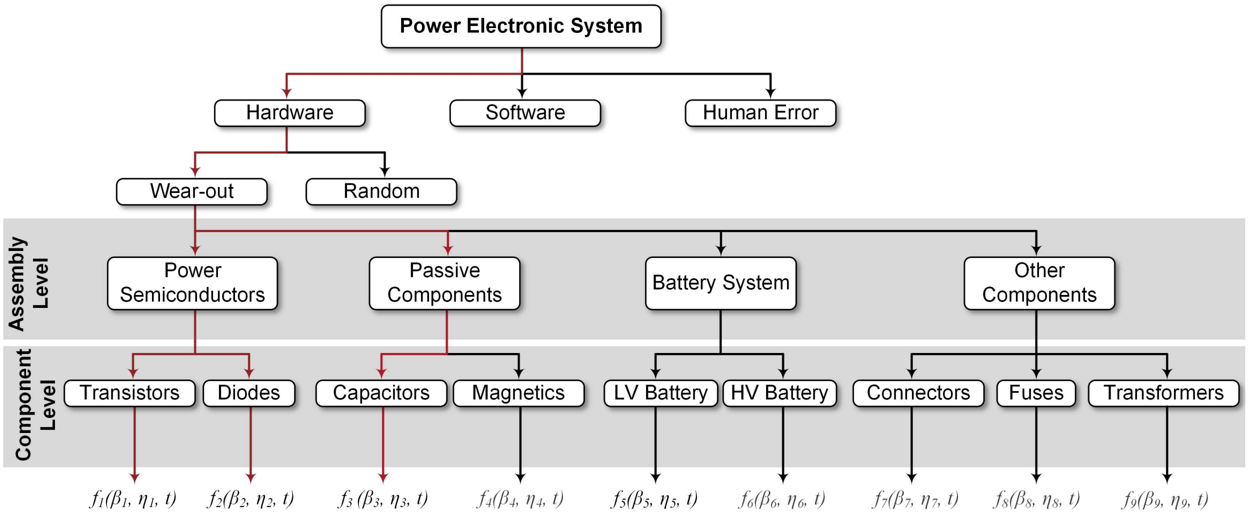


**Fig. 1.** ***Typical failure modes of the EV/HEV power electronic system.***

(HEVs), where the battery size typically is the defining difference in order to obtain the wanted range of the car, or it can be based on systems where the generated electricity is converted into gas or fuel [3]. Common for all electrical solutions is that power electronics technology is applied for power processing in many aspects—it is used for the drive train, the battery management system, charging the battery, and delivering power to all auxiliary units in a vehicle. A common demand for applied technology is that it should be as reliable as needed to the lowest cost, and for some of the parts, failure is not an option due to safety. As the EV/HEV is not fully mature yet, for example, the promising wide bandgap, power devices are not fully developed; also, more and more specialized integration (thermal management) of the power electronics is seen in the solutions with uncertainties. Furthermore, condition monitoring enters into the vehicle with advantages and potential risks in terms of higher complexity. Therefore, modern reliability engineering methods are steadily being developed and applied to the transportation sector.

Reliability is an important performance metric, which needs to be carefully considered during the design, manufacturing, testing, and field operation of EVs/HEVs. iReliability is defined as the probability that a product will perform its designated function without failure, under stated conditions, for a given period of time [5]. However, due to its large number of interdependent components and subassemblies, the power electronics system of the EV/HEV is susceptible to a wide range of failure modes and failure mechanisms. Also, having in mind that vehicles are mass-produced, there is an expectation of high reliability and low operational/maintenance cost. To achieve this, it demands life-cycle-cost reduction and performance boost of power electronic converters through innovative design and testing methods, an in-depth understanding of the component and system failure mechanisms, and predictive maintenance programs when the car fleet is operating. With such information, it is also possible to online learn about the design and how to do predictive maintenance if needed. Reliability involves many aspects in terms of handling and optimizing it, for example, the application lifetimes (e.g., private or autonomous car), longer time between its maintenance, very few early failures (even zero), and the ability to survive fault events in the power electronic systems.

From the system-level perspective, the failure modes that occur in the EV/HEV power electronic system can be divided into software failure, failures caused by human error, and hardware failures. The latter can be further classified into wear-out failures and random (or catastrophic) failures. Due to the lack of accurate modeling or estimation approaches for failures induced by random events or human error, failure mode and effect analysis (FMEA) and qualitative accelerated test methods can be used to investigate the target components/subassemblies under these types of failures. Software failures are not included in the scope of this article, but several software reliability modeling and assessment methods are presented in [6]. On the other hand, for hardware wear-out failures, a more realistic reliability assessment procedure can be carried out based on the Design for Reliability (DfR) [7] and Physics-of-Failure (PoF) [8], complementing conventional reliability methods. The main power electronic assemblies and components affected by the time-dependent wear-out failure function $f_x(\beta_x, \eta_x, t)$ are showcased in Fig. 1. In this article, the main focus is placed on the wear-out failure of the power semiconductor devices and capacitors as they are two of the most prone-to-failure components of the power electronic system [9].

Three main aspects exist for power electronics reliability engineering, which are related to a fundamental knowledge base (physics of failure), a design stage (DfR and robustness validation), and an operational phase (intelligent control and condition monitoring) [10]–[12]. Therefore, to master power electronics reliability engineering, many aspects are important. Power cycling testing of power modules is essential to understand the wear out of the power components, when they are in operation, and predict when failures might occur [13], for example, through degradation. Variations in packaging technologies, test strategies for power cycling, failure mechanisms, and failure analysis methods are all aspects to consider. Methods to estimate the stress conditions (i.e., junction temperature) and health conditions of power modules are of high interest [14]–[16]. Using wide bandgap devices and new packaging technologies [17], [18], which are being adapted to the transportation sector and their reliability requirements, is also important. Chip- and packaging-level failure mechanisms, testing, and condition monitoring health indicators of SiC/GaN devices are also attractive topics [19]. Besides active components, the capacitor reliability is also essential to understand and take into consideration when doing reliability analysis for the complete system [20]. Batteries, their state-of-charge, and remaining useful life are important to know though, in this article, the battery technology itself, including power electronics for balancing, is not discussed. Reliability standardization is already moving forward in the EV/HEV industry. In [21], the robustness of the power electronics, including validation, has been published for the automotive applications, and in [22], a standard was defined on how to make reliability prediction based on field return data. More recommendations/standards are under development. This article focuses on the reliability aspects of the power electronic systems in EVs and HEVs. First, it will start with the reliability requirements and challenges for the power electronics applied in EV/HEV applications in Section II. Next, the advances in power electronic components to address the reliability challenges will be discussed as they individually contribute to the overall system reliability, which is discussed in Section III. To improve system reliability, reliability-oriented design can also be applied, and it is exemplified in Section IV. In Section V, a specific outlook in power electronics reliability research opportunities related to EV/HEVs will be provided. Section VI gives the main conclusions of this article.

## II. RELIABILITY REQUIREMENTS AND CHALLENGES OF POWER ELECTRONICS FOR EV/HEV APPLICATION

Automotive application with a typical expected operating life of more than ten years, ambient temperature operating range of $-55$ °C to 150 °C, and zero acceptable failure rate is one of the most challenging applications from the reliability aspect. These requirements are in place for both combustion engine-based and electric vehicles. Furthermore, a high safety level is another requirement for this type of application. It is expected that the incorporated systems fail gracefully. This implies considering system redundancy or the ability of an alternative system (which was not originally designed for that particular task) to take over the operation of the failed system. For EV/HEV, the power electronics technology is the main key enabler and the main driver for advances in automotive electronics technology. EV/HEV electrification involves different power levels and voltage levels (e.g., 12 and 450 V), which requires the incorporation of power electronics technology at various levels. Therefore, to fulfill automotive expected operating life, acceptable failure rate, and safety level, high reliability of power electronic components is an essential requirement for EV/HEV applications.

### A. Power Conversion Architecture in EV/HEV

To understand the involvement of power electronics at various levels in an electric vehicle power system, Fig. 2 shows a block diagram of a typical electrical power system architecture in EV/HEV, including the major power electronic systems that can be found in an electric-based vehicle [23], [24]. Here, the high-voltage (HV) dc bus is typically in the range of 250–450 $V_{dc}$ depending on the utilized battery voltage, and the low-voltage (LV) dc bus is rated at 12/48 $V_{dc}$. Notably, different possible configurations for the power train in EV/HEV can be found in the automotive market [25]–[28].

The onboard charger (OBC) is an essential part of the EV and plug-in HEV. OBC has two main roles: first, charging the battery through the main power grid; second, power factor correction (PFC) to provide high power factor (≈0.99) and low harmonic distortion following the standard grid codes. According to SAE J1772 [29], three power levels are defined for OBCs. The power level depends on the available voltage and current capacity from the main grid, and it can be as low as 1.9–43 kW [30]. Single-phase OBC is the most adopted charger in the current vehicles, and it can be rated as high as 19.2 kW. However, it is more suitable to adopt three-phase OBC for power levels above 7.4 kW (or up to 7.7-kW single phase with 240 V at 32 A) due to components' count and efficiency. This is why most EVs/HEVs worldwide are currently utilizing OBC between 6.6 and 7.4 kW. Fig. 3(a) shows the most popular single-phase OBC topology, also known as interleaved boost PFC. Although interleaved boost PFC has advantages from efficiency and power density over single-switch boost PFC, it requires higher components' count, which may lead to lower reliability. However, since each boosting stage in the interleaved PFC is designed to handle half of the rated power, it can provide redundancy to the system if one boosting stage fails. Therefore, the OBC can continue charging the battery up to half of its rated power. Currently, research and development on more advanced topologies are undergoing, such as totem-pole PFC with wide bandgap (WBG) devices, to further improve the efficiency and the power density of OBC. The long-term trend

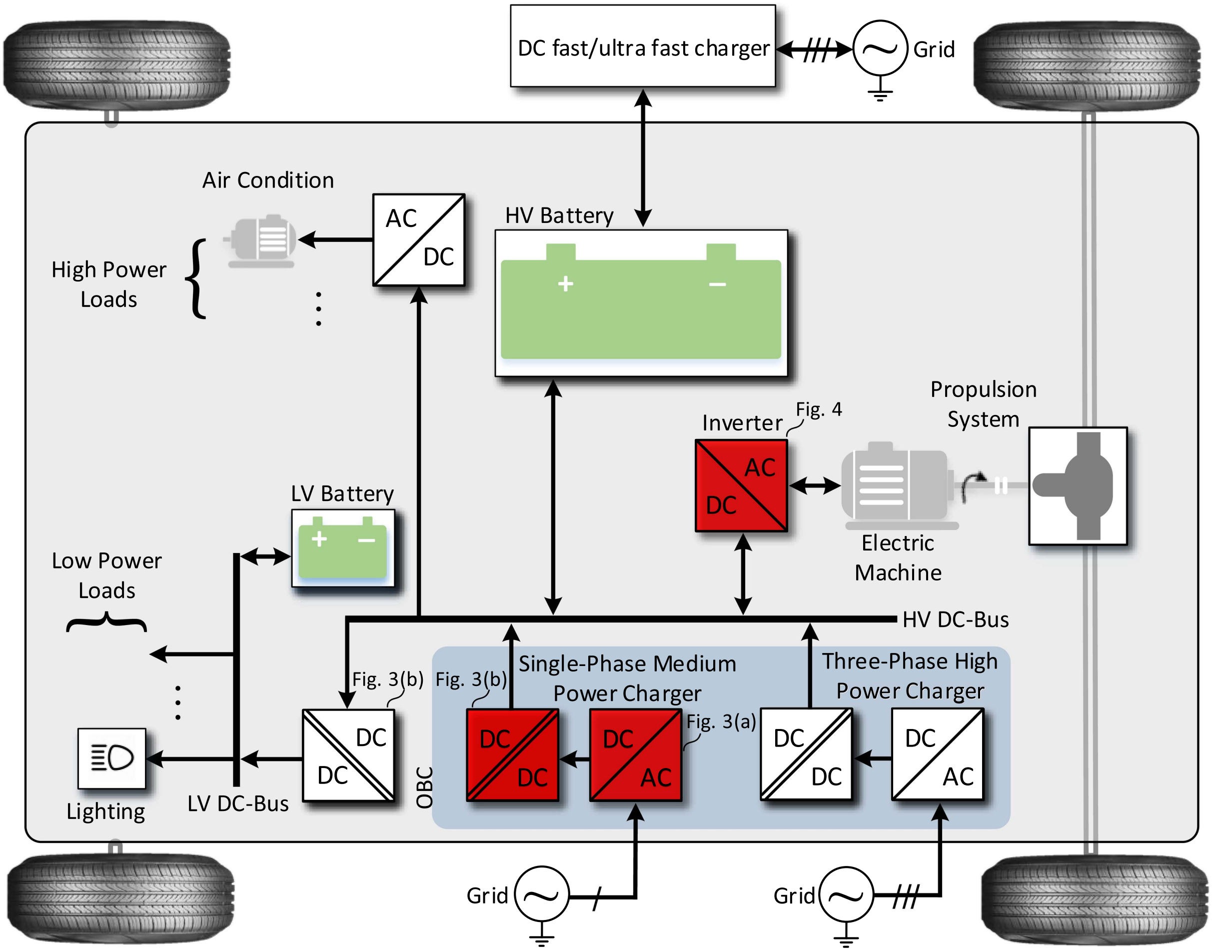


**Fig. 2.** ***Overview of the electrical power system in EV/HEV.***

is moving toward bidirectional charging, where EV/HEV can support the power grid by feeding the battery power back to the grid [31].

One of the main challenges with OBC is the charging time. With the continuous increase of battery capacity (i.e., extended vehicle driving range), the demand for higher power chargers increases. Although fast and ultrafast dc charging stations (i.e., >350 kW) [1] can minimize the charging time (e.g., 10–15 min), since they are not widely available yet, car manufacturers are adopting high-power OBC through a three-phase supply (see Fig. 2). In most commercial vehicles due to power density and size limitations, the three-phase OBC power level is from 11 up to 20 kW except for Renault Zoe, which is rated at 43 kW using the integrated motor drive and OBC configuration [30]. Notably, depending on the topology, the HV dc bus voltage will be different [32], [33].

Fig. 3(b) shows a typical isolated dc–dc converter topologies employed in electric-based vehicles. The dc–dc converter is employed at two stages. The first is to charge the battery from the active front-end rectifier. At this stage, the dc–dc converter should provide the HV dc bus (e.g., typically, at 250 V–450 $V_{\mathrm{dc}}$). Another dc–dc converter based on the same topology is adopted to form the LV dc bus that can be at 12 or 48 $V_{\mathrm{dc}}$ depending on the vehicle LV load types (see Fig. 2). Due to the safety requirements, the dc–dc converter should isolate the power grid from the HV dc bus and the HV dc bus from the LV dc bus [34], [35].

As it is depicted in Fig. 3(b), the converter comprises primary and secondary sides. The isolation transformer can be formed employing a resonant network based on a series resonant converter (SRC), also known as an *LLC* configuration. As shown in Fig. 3(b), an alternative method is to adapt the transformer leakage inductance (additional inductance may be required), which is known as phase shift full bridge (PSFB) converter.

While the primary side is based on an H-bridge configuration, the most in use configuration for the secondary is a diode bridge. Although it can only provide a unidirectional power flow, utilizing a diode bridge can simplify the converter from gate driver requirement, reduce cost, and improve reliability. However, it may adversely affect the converter performance from an efficiency point of view,

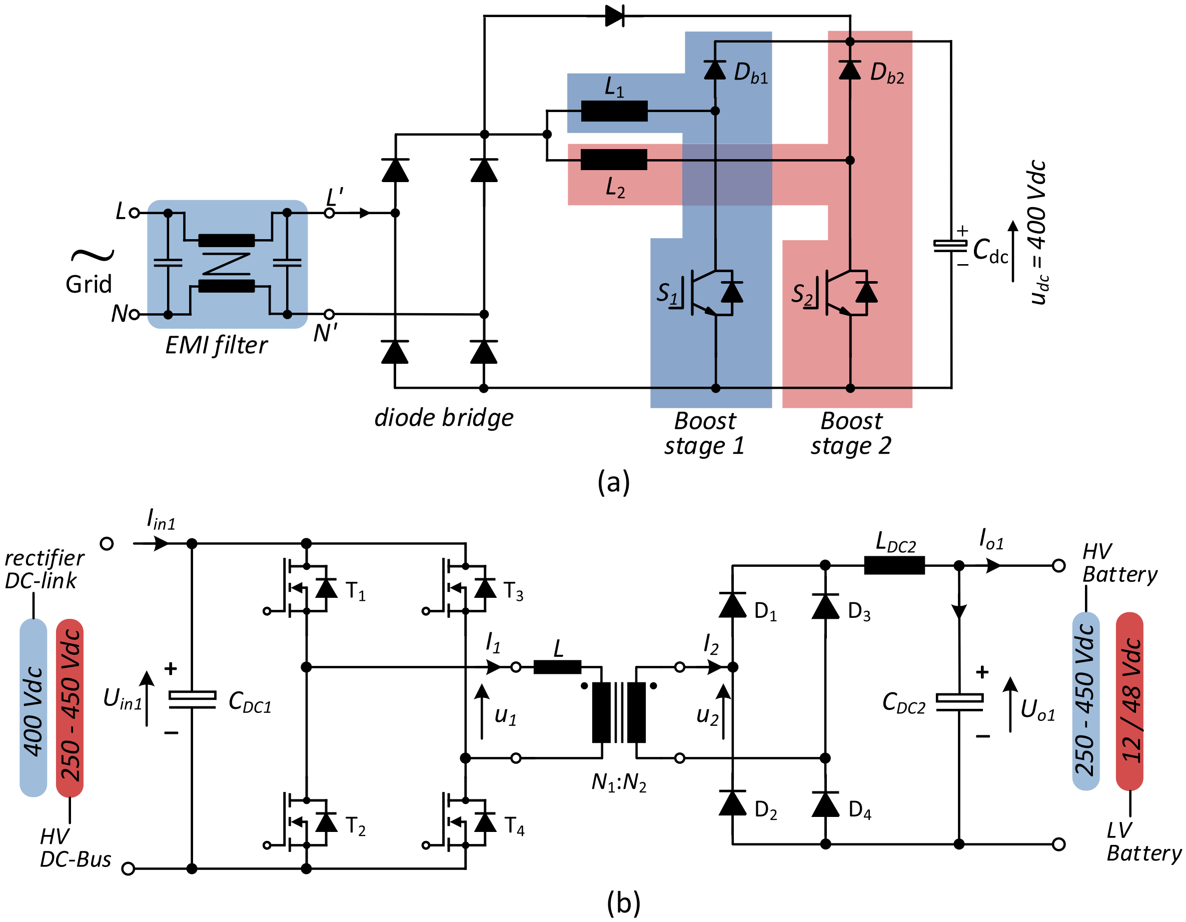


**Fig. 3.** ***Block diagram of OBC and dc–dc converters. (a) Single-phase ac/dc with interleaved boost PFC topology. (b) Isolated dc–dc converter with unidirectional PSFB configuration.***

causing high conduction losses from diodes and having low flexibility on the applied modulation technique.

The PSFB converter can provide a promising performance of operation with the fixed switching frequency, soft-switching, low filter requirement, and wide power and voltage ranges [34], [36]. The resonant-based converters can achieve high performance for specific application needs. However, maintaining their performance over a wide range of power levels and voltage gain ratios and their variable switching frequency nature may also reduce the converter efficiency. Furthermore, tuning the resonant network for high-frequency operation considering the layout, switches, and transformer parasitic is challenging. Therefore, the PSFB converter shows promising performance over resonant-based in adapting to different application needs while maintaining a desirable converter performance. This has become a new trend to adapt PSFB converters based on the WBG devices for EV/HEV applications [31], [34], [35], [37].

One of the main components in an electric-based vehicle is the electric machine (EM) and its inverter (see Fig. 4). The EMs utilized in today's EV/HEV are commonly ac induction machine or ac permanent magnet (PM) type [46], [47]. The majority of the main inverters for HEV are in the range of 30–60 kW, while, in EVs, the rated power is beyond 100 kW. In the near future, the power rating will reach 500 kW [47]. Intensive research and development are currently going on enhancing PM EMs and adopting different types of EMs in order to further improve the performance of future electric-based vehicles [48]. Compared with the OBC, the main inverter will be imposed on more power cycling, which means that the

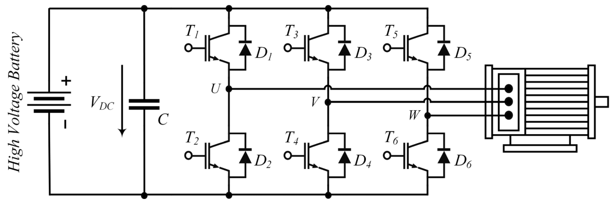


**Fig. 4.** ***Block diagram of standard VSI topology used in the propulsion system.***

**Table 1** Source of Stress for Power Electronic Components in Electric-Based Vehicles [20], [38]–[45]

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

adopted power electronic components should endure a higher number of active and passive thermal cycles. Due to their higher power capabilities, in some EV/HEV applications, the main inverter is reused for OBC, which are referred to as onboard integrated chargers or propulsion-system-integrated OBCs [30], [49]. For instance, Renault Zoe uses an integrated Chameleon charger rated up to 43 kW [23], [30]. Further investigations are required from a reliability perspective since the components are utilized for both OBC and main inverter operation exposing them to higher thermal cycling stress.

Different types of commercial power switching devices are designed for all mentioned power converters in automotive applications. Currently, most of the EVs/HEVs are employing insulated-gate bipolar transistors (IGBTs) for high power while using silicon metal–oxide–semiconductor field-effect transistors (Si MOSFETs) for dc–dc converters, which can achieve zero-voltage switching (ZVS) for further loss reduction. The future trend is to replace the silicon switches with silicon carbide (SiC) and gallium nitride (GaN) devices (i.e., WBG devices), which can further reduce the power loss and system size through their high switching operation capability. For instance, Tesla has moved to utilized SiC devices for both OBC and the main inverter [23].

## B. Reliability Aspect Challenges

Fig. 5 shows the automotive lifetime requirements and power electronics research and development for electric-based vehicles [38]–[42]. As shown in the figure, with the everlasting need for efficiency and power density improvement, power electronic components face more and more stringent operating conditions in EV/HEV applications [38], [42]. High-power, HV, and higher converter switching frequency operations are required to fulfill these needs, which, combined with vehicle stringent operating conditions, creates a harsh environment.

Table 1 shows different sources of stress for power electronic components [43]. Furthermore, this table has exemplified typical environmental and stress test conditions for EV/HEV applications [20], [44], [45]. As can be seen from the table, temperature stress is a major stressor that destroys power electronic components. This stress factor can be counted as maximum steady-state temperature and temperature cycling.

To account for the first one, it is vital to make a good cooling system so that component's temperature never exceeds its specified maximum rated temperature. In automotive applications, to prevent an oversized cooling system, it is important to make a good thermal design by identifying the worst case operating case from the vehicle mission profiles due to size and volume limitations. However, this will not guarantee the expected lifetime of power devices, as the high probability of power device failures is primarily due to temperature cycling [43]. The main causes of temperature cycles are active power cycling and passive temperature cycling [50], [51]. Although both results in temperature swings adversely affect power component lifetime, they are different.

The active power cycling leads to temperature swings due to the power dissipated in the power electronic components. This generates high-temperature gradients and inhomogeneous temperature distribution among power electronic devices and components. To minimize the thermal swings due to active power cycling, active thermal control methods can be applied [52]–[54]. Active thermal controls are based on two principles: first, minimizing the power dissipation through switching and conduction loss reduction; second, by rerouting the flowing path of the current among the power devices [55], [56]; both cases can be achieved through suitable selection of the modulation strategy and reactive power control. As it is exemplified in Table 1 in EVs/HEVs, the active thermal cycles can go beyond 100 °C, which might significantly reduce the life of the power devices.

In EVs/HEVs, passive temperature cycling represents a challenging condition considering the reliability requirements in automobiles comparing to other applications. Passive temperature cycles occur due to environmental temperature changes, such as variation in the ambient temperature or cooling liquid temperature. This becomes further challenging when the hot-engine liquid-cooling system is utilized for the power electronics, with a typical high

**Table 2** Regulatory Requirements for Automotive-Grade Power Electronic Component Manufacturers

| *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 |

temperature of cooling liquid in 90 °C–125 °C [57]. Due to the high dwell time during passive temperature cycles, there are no temperature gradients. Besides, the temperature ranges may go as low as −55 °C–150 °C. Passive thermal cycles may cause higher stress on the power devices [51]. Therefore, electric-based vehicle power electronic components need to be designed and tested considering the possible passive thermal cycles (as exemplified in Table 1).

Table 1 also shows that humidity and vibration are another two critical types of stressors, which are of high relevance to automotive applications. Humidity and condensation cause problems in electronic circuits due to its electrically conductive and corrosive nature [58]. Understanding the humidity-related failure mechanisms and component- and system-level mitigation methods is needed to reduce corrosion-related failure [59]. With the higher mechatronics integration level of power electronics, increased vibration and shock stresses are expected in EV/HEV applications. For example, a multilayer ceramic capacitor is one type of vibration and shock sensitive electronic components [60].

Considering the different stress factors and field return data in power electronics, the reliability issues of power semiconductors and capacitors stand out [9]. In automotive applications, the interconnects among components and within the packaging are also reliability-critical due to vibration and thermal–mechanical stresses. Combined with the ability to withstand transient HV and current (e.g., during sudden acceleration and braking), power components must be selected to withstand EV/HEV operating conditions and perform smoothly in those conditions.

This means that the components need to deal with inhospitable conditions with increased reliability helping to maximize a vehicle's lifetime, and consequently, they should be subjected to much harsher test conditions compared with components utilized in common power electronic applications.

### C. Automotive-Grade Power Electronic Components

To ensure essential requirements for automotive-grade power electronic components, specific certification requirements are put in place by the International Automotive Task Force (IATF) and the Automotive Electronics Council (AEC). While IATF ensures an optimal level of quality for automotive-grade components, AEC determines the stress test qualification of components. Furthermore, the Industry Association for Printed Circuit Board (IPC) provides the specification for the design and development process of printed circuit boards (PCBs). Table 2 summarizes the commonly required certification for automotive-grade power electronic components.

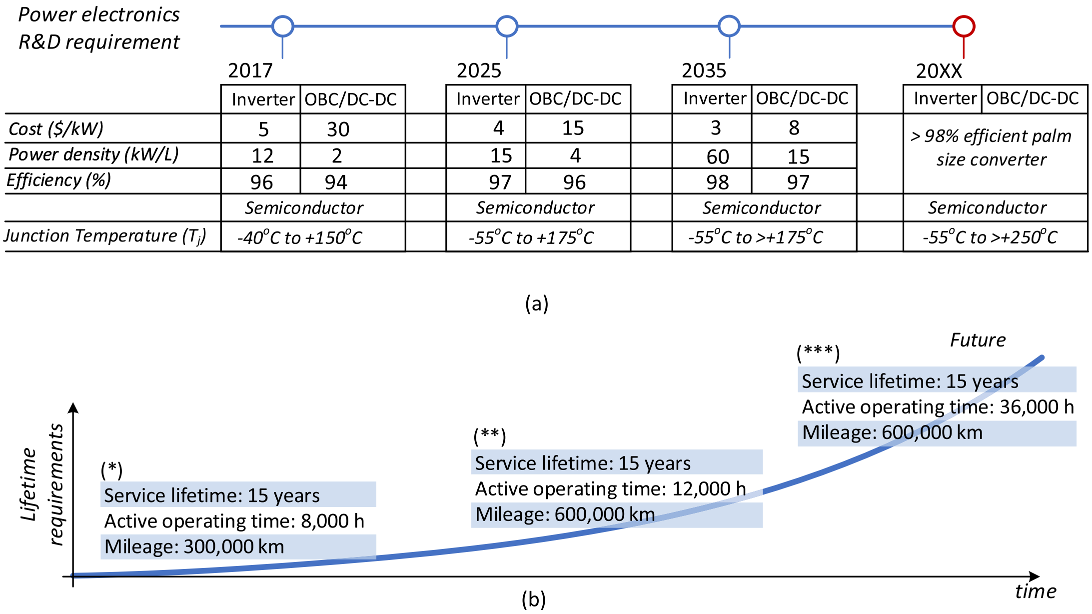
Notably, depending on the design specification, power semiconductor modules might be a better choice over discrete semiconductors due to lower processing requirements, tooling, and engineering costs. However, as shown in Table 2, there is a lack of qualification standards for power semiconductor modules. In 2019, the European Center for Power Electronics (ECPE) has released AQG 324 that is a guideline on the "Qualification of Power Modules for use in Power Electronics Converter Units in Automotive Application" [61]. Currently, most manufacturers have adopted this qualification guideline for their automotive-grade power module products.

## III. ADVANCES IN POWER ELECTRONIC COMPONENTS TO ADDRESS RELIABILITY CHALLENGES

Sections III and IV present the power electronic component-level technology advancements and system-level design methodologies to address the challenges discussed in Section II. They represent the joint efforts from power electronic component suppliers and system designers, respectively. To limit their scope, this article focuses on the advances in power modules and capacitors only in Section III as follows and mission-profile-based DfR method considering thermal-related wear-out issues in Section IV.

### A. Power Modules

The advancements in wide bandgap semiconductor materials and power module packaging technologies are two of the enablers to realize the roadmap, as shown in Fig. 5. It is reported that SiC MOSFETs with conventional packaging have lower power cycling capability than Si IGBTs [62]. Various advanced packaging concepts are proposed as surveyed in [18] to overcome the challenges



| | 2017 | | 2025 | | 2035 | | 20XX | |
|---|---|---|---|---|---|---|---|---|
| | Inverter | OBC/DC-DC | Inverter | OBC/DC-DC | Inverter | OBC/DC-DC | Inverter | OBC/DC-DC |
| *Cost ($/kW)* | 5 | 30 | 4 | 15 | 3 | 8 | *> 98% efficient palm size converter* | |
| *Power density (kW/L)* | 12 | 2 | 15 | 4 | 60 | 15 | | |
| *Efficiency (%)* | 96 | 94 | 97 | 96 | 98 | 97 | | |
| | *Semiconductor* | | *Semiconductor* | | *Semiconductor* | | *Semiconductor* | |
| *Junction Temperature ($T_j$)* | *-40°C to +150°C* | | *-55°C to +175°C* | | *-55°C to >+175°C* | | *-55°C to >+250°C* | |

**Fig. 5.** ***R&D and lifetime requirements in EV/HEV. (a) Power electronics R&D development roadmap for electric-based vehicles based on the reports in [38] and [39]. (b) Automotive lifetime requirements based on [39], * [40], ** [38], and *** [41].***

in reliability, high-temperature operation, and low parasitic inductance. Fig. 6 shows the respective advances in packaging elements for interconnection, substrate, and die attach of power modules, as presented in [18]. The maximum temperature of the next-generation automotive module is expected to reach 175 °C. This can substantially enhance reliability. Since the temperature is closely dependent on the thermal resistance, a low overall thermal resistance is expected by using high-thermal-conductivity materials from the chip to the base plate, such as AlN and $Si_3N_4$ ceramic. For the manufacturers, enhancing the interconnections between chips is a potential choice to delay the bond wire liftoff [63]. Relevant techniques include heavy copper wire bonding, sintered connections, and buffer layers between different materials [64], [65]. Moreover, the bond wire-related failures can be avoided by removing the bond wires from the power module and replacing them with direct lead bonds [66], [67].

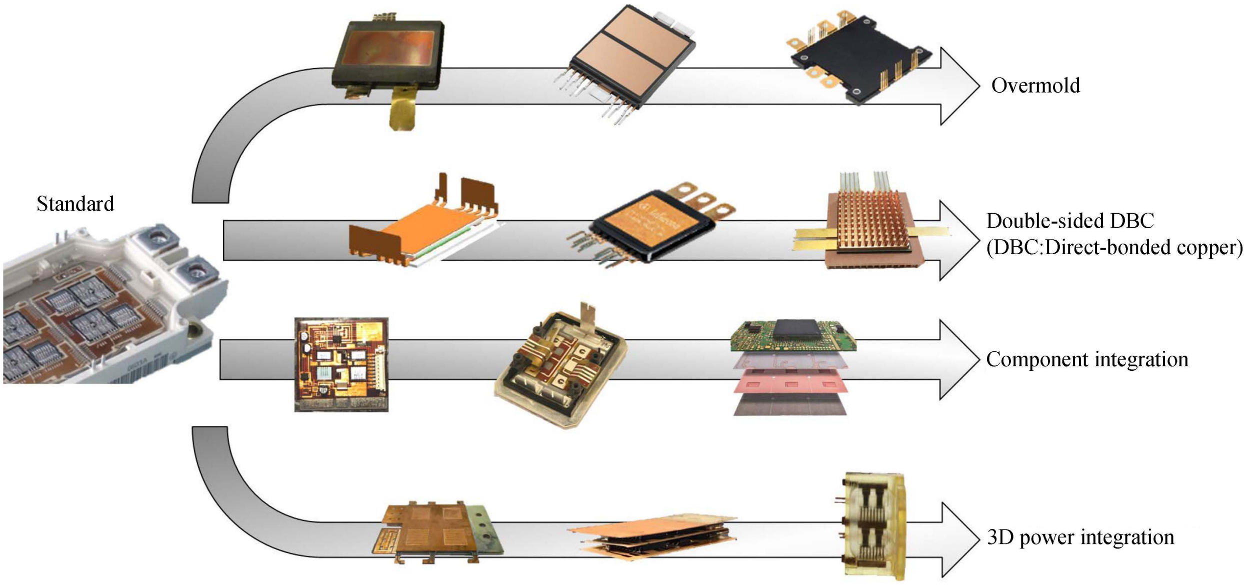


**Fig. 6.** ***Advances in packaging elements for power modules [18].***

By leveraging the emerging concepts in packaging elements, different package structures are proposed, which helps overcome the challenges in automotive applications. Fig. 6 shows the advances in packaging structures, as presented in [18]. Overmold structures enhance modularity and reduce the size and weight of power modules. The packaging structure optimization efforts could be developing the cooling structure from the conventional indirect water cooling to single- or double-sided direct water cooling [68]. Besides, the pin fins of the direct liquid cooling can also be optimized in terms of shape and layout. Examples can be found in [69]–[72]. The Hitachi double-sided cooling power modules from Audi e-tron's inverters are introduced in [73]. New technology itself may imply uncertainties in reliability aspect performance. Therefore, adequate testing methods and standards are important tools to accelerate the adoption of the latest advancements in power modules.

### B. Capacitors

In EV and HEV applications, film capacitors, electrolytic capacitors, and ceramic capacitors are widely used for vehicle motor drives, OBCs, and other electronic systems. Three aspects of advancements are going on for different types of capacitors. First, at the material level, research activities on dielectric films to increase energy density and upper temperature limits of existing film capacitors are discussed in [74]. Antiferroelectric ceramics are applied in the CeraLink capacitors from TDK-EPCOS, which overcomes the capacitance stability issues under voltage bias and maintain performance at high operation temperature up to 150 °C. Second, at the packaging level, high vibration and mechanical stress create demands for antivibration methods. Third, at the application level, design strategies for low-inductive dc-link capacitor bank design are developed for the trend of using an increasing switching frequency [75].

### C. Cooling Assemblies and Concepts

The demands for increasing power density and reducing cost bring a great challenge for the onboard cooling system. Besides, the ambient temperature under the hood could be as high as 100 °C with high humidity [77]. Furthermore, the frequent acceleration/deceleration of the vehicle could lead to large power cycling and surging, which will further challenge the cooling system. Another challenge is that the traction inverter is expected to share one cooling system with the engine for the sake of cost and complexity. To cope with the challenges above, currently, there are three research directions to protect the power electronic components from being overheated, that is, improving the power package design, as discussed in Section III-A, developing advanced thermal interface material [78] and utilizing more powerful cooling techniques [79].

Regarding the cooling techniques, the conventional natural and forced convection of air cooling are no longer practical. In the earlier versions of electric cars, such as the Nissan Leaf, forced air cooling is used for the OBC at the charging level 1 (1.44 kW). With motor driving and boosted charging power, liquid cooling becomes a popular choice in the automotive industry. The extensively utilized forced convention of liquid cooling and the simple two-phase boiling technique is gradually difficult to satisfy the heat transfer requirement with the adoption of WBG devices and higher power density requirements. Therefore, advanced cooling technologies, such as spray cooling and jet impingement, are developed to meet the demands of the automotive industry [79].

## IV. RELIABILITY-ORIENTED DESIGN OF POWER ELECTRONIC SYSTEMS

### A. Concepts of Mission-Profile-Based Design of Power Electronics

In past decades, a paradigm shift from the conventional statistics-based reliability evaluation procedures toward a PoF-based lifetime estimation of power electronics has been gaining more attraction [11]. The PoF concept implies that the root failure causes and failure mechanisms of the electrical/electronic components are well understood, before being modeled under realistic operating and environmental conditions [8]. However, most of the available PoF models focus on microelectronic components and cannot be scaled and utilized for power electronics. Thus, empirical lifetime models based on PoF understandings are commonly applied for modeling the wear-out failure of power electronic components [82]. In addition, the DfR method, which is defined as the process carried out during early product development stages to ensure certain reliability and quality targets, is used alongside the PoF concept [7], [83].

As a result, many mission-profile-based reliability assessment procedures, which incorporate the DfR method and PoF understandings of power electronics, have been proposed and successfully applied for various applications (e.g., wind power converters [84], grid-connected PV inverters [85], variable frequency drives [86], or more electric aircraft [87]). For EV/HEV applications, the main focus has been placed on the reliability evaluation methodology of the power module used within the electrical drive train inverter [88]–[90]. Moreover, a thorough six-step mission-profile-based lifetime estimation procedure, which assesses the reliability of power electronics, both at the component level and the system level, has been proposed in [76]. A general overview of the reliability assessment process is given in Fig. 7.

The abovementioned methodology requires extensive knowledge of the mechanical, electrothermal, and lifetime parameters of the vehicle drive train and the individual power electronic components. The vehicle driving cycle and the ambient temperature form a representative

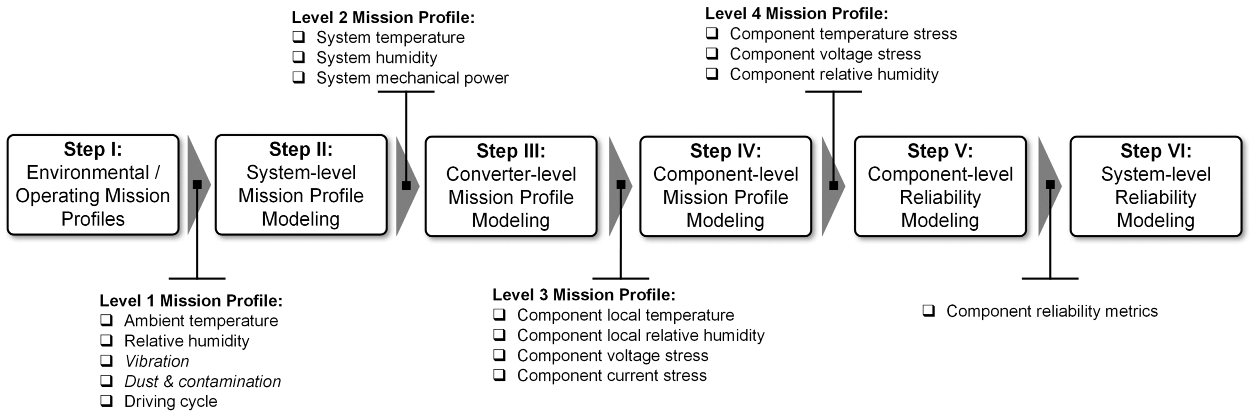


**Fig. 7.** ***General mission-profile-based reliability assessment procedure for power electronic systems [76].***

collection of operating and environmental conditions and are considered as the input mission profiles for the reliability assessment procedure. It should be noted that stressors, such as vibration or dust and contamination, are currently not considered during the reliability modeling procedure due to the lack of empirical lifetime models. According to the mechanical parameters of the vehicle, in Step II, the input mission profiles are converted into the mechanical power required by the electrical machine (EM) used in the drive train. By employing the electromechanical models of the vehicle drive train, the mechanical power is used to determine the voltage and current loadings of the power electronic components in Step III. The resulting electrical stressors (e.g., current and voltage) represent the inputs to Step IV, in which electrothermal models are utilized for calculating the thermal loading of the components of interest. In Step V, the thermal and electrical stressors are used together with empirical lifetime models in order to estimate some of the vital reliability metrics (e.g., lifetime distribution and unreliability curve) of the power electronic components. Finally, within Step VI, using a reliability block diagram (RBD) analysis, the individual component reliability information can be merged, and the system-level reliability estimation can be determined. A more detailed description of the mission-profile-based reliability assessment procedure is given in [76]

## B. Reliability Analysis of an Electric Vehicle Case Study

To demonstrate the applicability of the proposed reliability evaluation method, two subassemblies (e.g., main traction inverter and OBC) of an EV case study are investigated. The reliability performance of the electrical drive train power module is analyzed under a typical vehicle driving cycle profile [as shown in Fig. 8(a)], while the reliability of the electrolytic capacitor used in the EV OBC is studied according to a standard charging profile [as shown in Fig. 8(b)]. The overall topology configurations of the electrical drive train main inverter and the onboard EV charger for the two selected subassemblies are shown in Figs. 3 and 5, respectively.

A typical electrical drive train used to drive a fully electric battery-based electric vehicle is selected as a study case as shown in Fig. 4. The mechanical power of the EV is generated by a 75-kW PM synchronous machine (PMSM), which is supplied by a 330-V high-voltage battery. The main parameters of the EM are given in Table 3. The interface between the battery and the motor is assured by the electronic power stack, which consists of the 300-$\mu$F/450-V

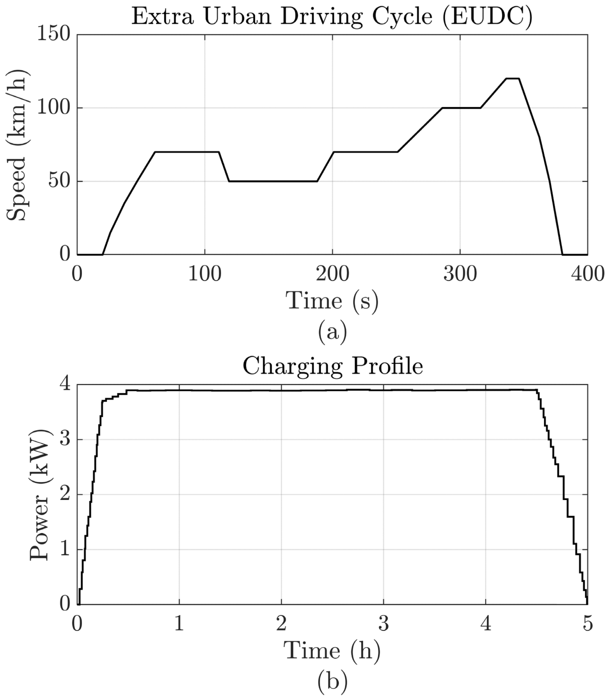


**Fig. 8.** ***Typical operational mission profiles for the two subassemblies. (a) Electric vehicle driving cycle [80]. (b) Scaled-down power demand for an EV OBC (based on [81]).***

**Table 3** Parameters of a 75-kW Drive Train PMSM Used for Reliability Study

| ***Parameter*** | ***Value*** |
|---|---|
| Peak motor power | 75 $(kW)$ |
| Stator resistance | 1 $(m\Omega)$ |
| d-axis Inductance | 7.2 $(\mu H)$ |
| q-axis Inductance | 7.5 $(\mu H)$ |
| Magnetic flux | 0.0095 $(V s)$ |
| Number of pole pairs | 10 (-) |
| Rotor inertia | 0.023 $(kg \cdot m^2)$ |

film capacitor dc-link and a three-phase 400-A/650-V IGBT power module fully qualified for automotive applications.

The abovementioned mission-profile-based reliability assessment procedure is used to evaluate the lifetime estimation of the power semiconductor devices and, inherently of the power module, under the given extra-urban driving cycle (EUDC) mission profile [see Fig. 8(a)].

Initially, the driving cycle of the vehicle is converted into the mechanical power required by the PMSM. This is achieved through the vehicle's mathematical models that take into account its mechanical parameters (e.g., mass, gear radio, wheel radius, and drag coefficient). The mechanical equations introduced in [90] (and their corresponding coefficients) have been employed, and the resulting speed and torque requirements of the PMSM are presented in Fig. 9.

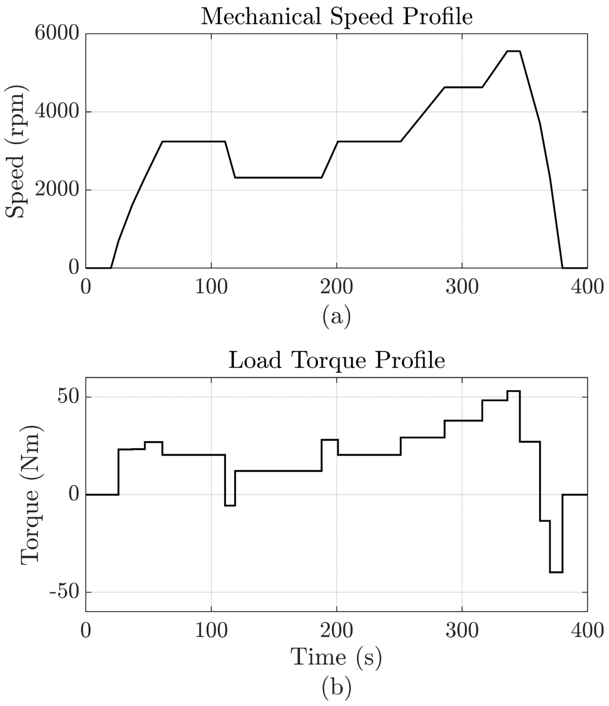


**Fig. 9.** ***Mission profile of the electric drive train with (a) mechanical speed profile and (b) load torque profile.***

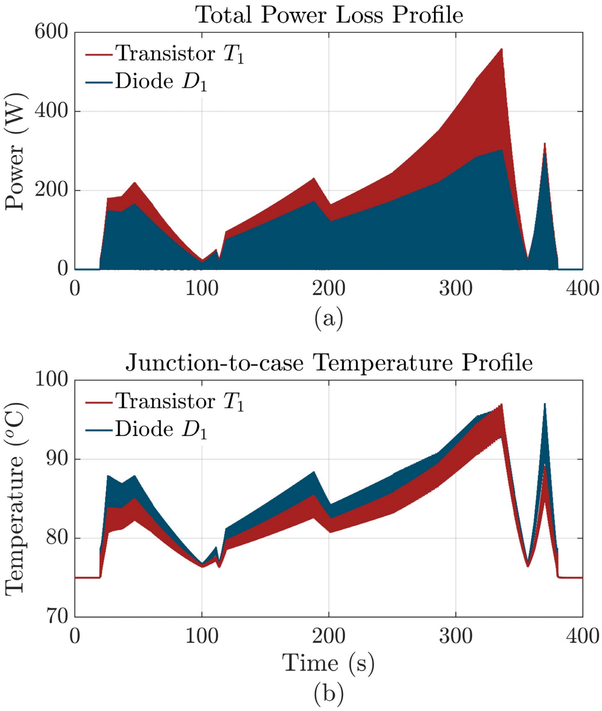


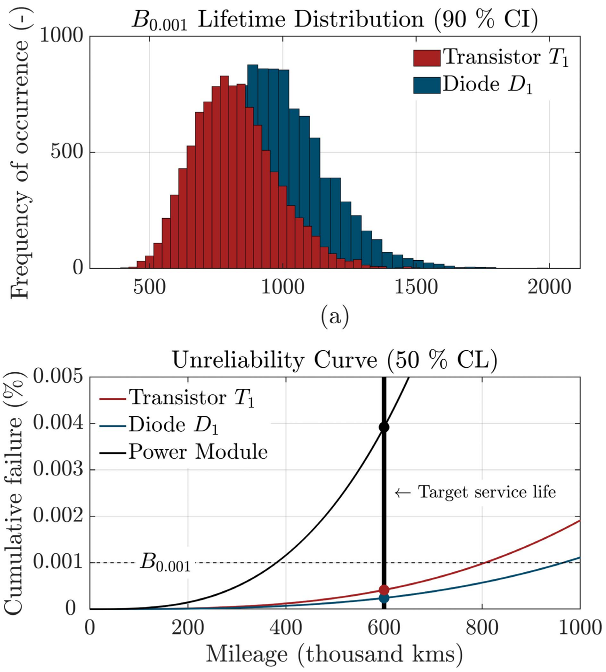
**Fig. 10.** ***Electrothermal loading profiles of the drive train power semiconductor devices under the given mission profiles. (a) Total power losses. (b) Junction-to-case temperature for the drive train.***

Afterward, similar to any typical motor drive application, the speed and torque profiles of the motor are used to determine the current flowing through each of the components of interest. This is achieved by modeling the drive systems and their control in the $dq$-reference frame. A detailed description of the electromechanical models for the PMSM and voltage-source inverter (VSI) is given in [84].

The resulting current and voltage loadings of the power semiconductor devices are then utilized using electrothermal models. Average switching cycle power loss models [91], [92] are first used to calculate the total losses (e.g., switching losses and conduction losses) generated by the power semiconductor devices. Based on the loss characteristics provided by the IGBT power module manufacturer in the datasheet, the total power loss profile of the upper transistor/diode pair (T1/D1) is calculated and shown in Fig. 10(a). As expected, due to the limited braking/stop periods of the selected EUDC mission profile, the motor operates mainly in the motor mode. Thus, more stress is focused on the transistor. Afterward, the power loss profile is fed into the thermal models, where RC Foster thermal networks are used to determine the thermal loading behavior of the power devices [93]. The required thermal parameters (e.g., thermal resistance and thermal capacitance) are extracted from the power module datasheet as a four-level thermal network. However, due to the limited information regarding the outer thermal network of the IGBT module (e.g., thermal grease, case, and coolant), only the junction-to-case temperature is modeled, while the coolant temperature is assumed to be 75 °C [70]. The resulting thermal behavior of the power semiconductor devices is shown in Fig. 10(b). Despite generating higher losses than the diode, the transistor exhibits a lower average temperature during the low-speed operation of the vehicle. This is mainly due to its thermal impedance characteristic, which is approximately twice as low as the thermal impedance of the diode.

To apply a lifetime model, the resulting junction temperature data need to be represented in terms of thermal cycle amplitude and thermal cycle mean value. This is done with the help of a Rainflow counting algorithm [94], [95]. Due to the lack of publicly available empirical lifetime models for automotive-qualified IGBT modules, the obtained thermal cycle representation of the power device thermal stress is applied to the lifetime model proposed in the LESIT project [96], [97]. However, the given lifetime model is used to describe the general failure of IGBT modules at the 10% lifetime percentile ($\mathrm{B}_{10}$ lifetime) with 50% confidence. Because such a high probability of failure (e.g., 10%) is not realistic for automotive applications, which expects failure rates in the ppm range, lower probabilities of failure (e.g., 0.001% or lower) are required. By assuming the shape parameters of the Weibull distribution ($\beta = 3$), the Weibull cumulative distribution function (cdf) is used to estimate the lifetime of the power semiconductor devices at a lower probability of failure levels [5]. In addition, to provide a more realistic lifetime estimation, the variations that might occur in the lifetime model coefficients need to be considered. Thus, by assuming a 5% deviation in the lifetime model coefficients, a Monte Carlo simulation is used to calculate the lifetime distribution on the components of interest. The outcomes of the Monte Carlo analysis are shown in Fig. 11(a), where it can be noticed that the $\mathrm{B}_{0.001}$ lifetime (0.001% probability of failure) of the transistor is between approximately 500 000 and 1 300 000 km, with a 90% confidence interval (CI). On the other hand, due to its lower thermal cycle amplitude, the diode seems to be less prone to failure, with a 0.001% probability of failure ranging between approximately 600 000 and 1 500 000 km.

Finally, the cdf of the wear-out failure of the power semiconductors can be used to estimate the system-level reliability (e.g., IGBT power module). Assuming that all six transistors and all six diodes of the IGBT power module have the same reliable performance as the upper transistor/diode pair (T1/D1), the RBD analysis [98] is used to merge the reliability information of each device and to calculate the unreliability curve of the IGBT power module. The outcomes of the RBD analysis are shown in Fig. 11(b). Considering a typical service life target of 600 000 km [43], the probability that the transistor and the diode fail before the target service life is approximately 0.0004% and 0.0002%, respectively. On the other hand, at the assembly level, in the case of the entire power module, the probability of failure before the 600 000-km target is approximately 0.004%.



(a)

(b)

**Fig. 11.** ***Reliability metrics of the drive train IGBT power stage for the driving cycle. (a) $B_{0.001}$ lifetime distribution with 90% CI. (b) Cumulative failure distribution of the $B_X$ lifetime with 50% confidence level (CL).***

A similar reliability modeling approach can be carried out for estimating the lifetime of a 560-$\mu$F/400-V dc-link capacitor used in a 3.3-kW single-phase OBC, as shown in Fig. 3. The main parameters of the charging system are presented in Table 4.

The charging profile shown in Fig. 8(b) is used to calculate the capacitor's electrical and thermal loading [77], [86]. The resulting core-to-ambient temperature profile is then used to determine the capacitor's reliability metrics, under the given mission profiles. Considering the empirical lifetime model presented in [86] and a 5% variation in its coefficients, the capacitor's $\mathrm{B}_1$ lifetime distribution is

**Table 4** Parameters of the 3.3-kW Onboard Charging System

| ***Parameter*** | ***Value*** |
|---|---|
| Input grid voltage | 220 V |
| PFC inductance | 130 $\mu$H |
| PSFB leakage inductance | 8 $\mu$H |
| PSFB output inductance | 400 $\mu$H |
| PSFB output capacitance | 33 $\mu$F |
| Transformer turns ratio | 12 : 16 |
| DC-link voltage | 400 V |
| DC-link capacitance | 1.68 mF |

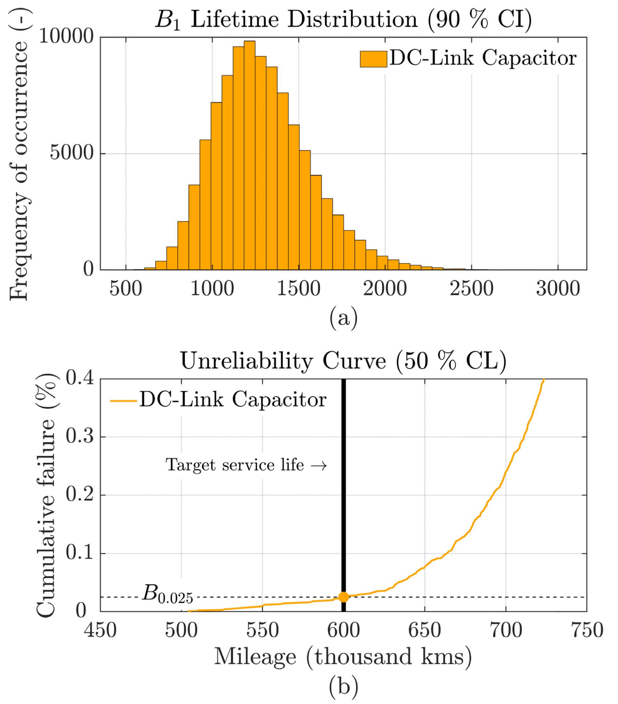


**Fig. 12.** ***Reliability metrics of the onboard charger dc-link capacitor. (a) $B_1$ lifetime distribution with 90% CI. (b) Cumulative failure distribution of the $B_X$ lifetime with 50% CL.***

calculated by Monte Carlo simulations. As shown in Fig. 12(a), the dc-link capacitor of the OBC has a 1% probability of failure between 500 000 and 2 500 000 km, with a 90% confidence interval.

Finally, assuming the shape parameter of the Weibull distribution ($\beta = 3$), the cdf is needed to estimate the lifetime of the capacitor at other probabilities of failure than the one associated with the utilized lifetime model. Considering the same target service lifetime as for the drive train power module, it can be seen from Fig. 12(b) that the probability of the OBC dc-link capacitor failing before the 600 000-km target is approximately 0.025%.

### C. Reliability Design Guidelines and Implementation Approaches

Despite being a relatively straightforward and fast approach for determining the critical reliability metrics of the EV/HEV power electronic system, the results of the abovementioned reliability assessment procedure are subject to many uncertainties.

As shown in [99]–[101], certain degrees of uncertainty can be introduced by various factors, such as environmental mission profiles, electrothermal modeling, and lifetime models. The error margins introduced by the different modeling approaches can lead to significant deviations in the lifetime estimation and reduce the confidence in the predicted result. Thus, before taking any reliability-related decisions and/or actions regarding the design of the power electronic system, one must be fully aware of the underlying assumptions and uncertainties behind the reliability metrics.

For cases in which many aspects of the system/reliability modeling are unknown and "rule-of-thumb" approximations need to be made, the abovementioned mission-profile-based reliability assessment methodology can be used for relative lifetime prediction purposes. Thus, due to the high degree of uncertainty, the reliability metrics are not considered as direct lifetime indicators of the power electronic systems but rather used in order to benchmark different solutions (e.g., control algorithms, system topologies, and cooling methods). In this way, the impact of various solutions on the reliability of the power electronic system can be quantified, and thus, educated reliability-oriented design actions can be taken.

## V. FUTURE RESEARCH DIRECTIONS

Research opportunities related to dealing with power electronics reliability challenges for EV and HEV applications are discussed below from three aspects of component technology, design and testing method, and operation management.

### A. Component Technology

The increasing EV and HEV market paves the way to bring new resources and strong motivations to advance further science and technology in power semiconductors, capacitors, and converter-level interconnects. Due to the harsh environment, high-temperature power electronic components enable improved reliability and reduced cooling requirements. Vibration-robust component packaging and interconnect design are also relevant research areas.

### B. Design and Testing Methods

The design to build reliability into power electronic converters is the first layer to fulfill reliability aspects specifications. Design methodologies, such as DfR and digital-twin-based design, could create promising added values. Research is needed to develop relevant multiphysics models, digital design procedures, and platforms.

There is a continuous demand for reducing the time required for accelerated degradation testing and reliability demonstration testing. New testing concepts and methods are needed. Virtual-physical hybrid testing methods and accelerated testing methods combined with the early wear-out prediction model could be promising directions. In a recent case study on battery testing presented in [102], it demonstrates that the required time for identifying high-cycle-life charging protocols among 224 candidates is reduced to 3.2% of the expected time without early prediction. It is worth exploring the application of such a concept into other accelerated degradation testing methods for other types of electronic components.

### C. Condition Monitoring and Operation Management

Smart control and condition monitoring of power converters are the second layer to ensure reliability and availability in field operation. Control strategies that can adapt to the *in situ* mission profile to optimize the electrical and thermal performance could bring additional benefits by leveraging the capability of digital controllers. With the demand for high-reliability power electronic converters in automotive applications, a failure-free operation may become a requirement for many applications. If failure is not an option, the understanding of the degradation process becomes important. Condition monitoring becomes an even more important tool in reliability engineering if failure is not allowed within the service life. Degradation modeling helps to predict the time for maintenances. Robust and cost-effective condition monitoring methods are demanded. Even though a wide range of health precursors and implementations have been proposed in the literature, the fact is that they are rarely adopted in field operation, both for power semiconductors and capacitors. Complexity, cost, converter-level design constraints and accessibility, and effectiveness under field operation environment are of great concern.

### D. Understanding and Modeling for Multicomponents and Multistressors

This article mainly focuses on thermal-related failures of power semiconductor devices and capacitors. Nevertheless, an in-depth understanding of other types of components, such as interconnects, PCBs, and cooling assemblies, and other stressors, such as humidity, vibration, and shock, is needed. Moreover, the methods for the reliability aspect investigations for the power stage and low-power control and signal-conditioning stage could be different due to different dominant failure mechanisms, critical stressors, standardization, and modularity of components.

## VI. CONCLUSION

The power electronics is an essential technology for EVs and HEVs. Its design and implementation are essential; especially the reliability is a success criterion for the penetration of EVs/HEVs. Many power electronic components are applied, and DfR and predictive maintenance programs can make such systems highly reliable. This article gives a broad overview of power electronic architectures in EVs/HEVs, where the reliability requirements are specified. Some of them are already given in standards, while others are needed. It can though be concluded that, still, reliability challenges will continue to come as the technology is evolving. In power electronics, the first condition for evolution is component development. This article highlights the issues related to capacitors and active devices but also with respect to cooling aspects to make the power electronic systems reliable and safe. At the system level, the reliability-oriented design is a key to reduce/optimize cost combined with the possibility of condition monitoring when an EV/HEV fleet is operating. Multidisciplinary simulation tools are essential to a proper DfR, which is demonstrated in two case studies in this article. Some of the future challenges and research opportunities are: more widely use of wide bandgap devices to reduce size and increase power density, overall system control during life operation where reliability indexes of the parts are used to make decision about system operation, making better packaging technologies including thermal management, as well as handling large data dynamically and pro-actively in terms of preventive maintenance. ■

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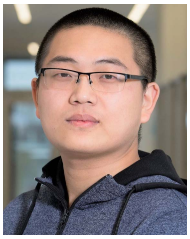

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