Latest Reliable Power Electronics Technologies for Zero-Emission

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Abstract. This paper presents use cases to demonstrate the advances in simulation, prognostic health management and digital twins, and power electronics for electric vehicles and gives an insight into the potential for the end users in the future.

Keywords: Electromobility · Design and Optimization · Reliability · Wide-bandgap Semiconductors · Digital Twin

1 Introduction

At the end of 2019, the European Commission presented "The European Green Deal". The most important objectives thereby are the reduction to zero net greenhouse gases emissions by 2050 and to ensure economic growth decoupled from resource use. HiEFFICIENT project – a Research and Innovation Action funded by the KDT Joint Undertaking – directly addresses these objectives targeted, having a focus on sustainable mobility and resource efficiency. By making use of highly reliable and integrated wide-bandgap (WBG) technologies in electronic power systems of electrified vehicles, testing systems, and charging infrastructures, HiEFFICIENT directly supports the development towards a more resource-efficient and decarbonized transportation system.

Today, the applicability of WBG semiconductors in electrified vehicles has been demonstrated, but only Silicon Carbide (SiC) is assumed by manufacturers to be introduced in vehicles in the next 3 years, but so far not Gallium Nitride (GaN). Therefore, the project has set a focus on the implementation of GaN devices in automotive applications. Furthermore, reliability becomes an issue to achieve sustainable eDrives and hence the project thoroughly investigates methodologies and strategies to enhance the lifetime and reliability of tomorrow's vehicle power electronics utilizing real-time prognostics and health monitoring (PHM). Nowadays, the advancement of sensorics and Industrial

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Internet of Things (IIoT) devices and network technologies enables intelligent edge monitoring to estimate remaining useful lifetime (RUL) in real-time and data-streaming to the cloud. The cloud leverages data from multiple EVs, forms big data analytics and machine-learning-based models, and takes necessary steps to enhance lifetime.

Therefore, the paper is prepared in three sections, highlighting advances in the project exemplarily, (1) GaN technologies for automotive PE applications, (2) Thermal simulation for power electronics applications, and (3) Power electronics design for reliability.

2 GaN Technologies for Automotive PE Applications

With the main technical drivers of OEMs being efficiency improvements, cost reductions and increase of power density, as well as the need to increase sustainability parameters, all new technologies are investigated to see how well they do support these objectives. GaN is next to SiC another, in many aspects similar, wide bandgap material of interest because it promises cost advantages. How good this can be utilized and what additional technical opportunities it enables differ for the various PE applications: OBC and DCDC, high power traction inverter, *low power auxiliar inverters* and with the battery voltage levels: 48 V, 400 V, 800 V to 1000 V.

In 48 V to 400 V systems' OBC and DCDC one GaN switch could replace one SiC switch and the high switching frequency is used to decrease size and weight of external components like magnetics making it a lower cost solution than SiC with higher power density than IGBTs. With no 1200 V GaN devices available today and in the near future a multilevel topology is necessary in 800 V to 1000 V Vbat powertrains. For DCDC several projects have already shown that there are promising advantages of multilevel with regards to EMC and further magnetics reduction that can compensate the higher effort of two or more switches vs. one SiC switch. The challenges with GaN are the versatile suppliers' solutions that make drop-in second source choices difficult for OEMs to secure their supply chain.

For traction inverters the situation is more challenging. Research needs to continue to develop reliable solutions for high powerstage solutions $>$ 150 Arms. However, for 48 V to 400 V Systems lower cost and improved drive unit efficiency at slightly higher switching frequencies of, e.g., 50 kHz compared to SiC are highly promising to address two of the main drivers of OEMs.

In HiEFFICIENT project a solution for a high power GaN powerstage with phase-currents up to 500 Arms is developed. It utilizes GaN half-bridges that are assembled in parallel to achieve various levels of output current. The modularity supports overall platform cost reduction and the newly developed embedded powerstage enables highly compact designs. With the improved thermal dissipation, a higher lifetime for a given number of dies will be targeted, further reducing cost, and improving sustainability.

Multilevel topologies for 800 V promise system advantages by reduced harmonic distortions for EMC and thermal aspects that also involve the eMotor and battery. Today a higher switching frequency than 20 kHz - 30 kHz is not necessary but might become more important with new eMotor developments and more advances in pulse pattern research to improve NVH and efficiency by software measures.

3 Thermal Simulation for PE Applications

Thermal modeling plays an important role in the development of power electronic systems and is key to understand the causes of correct or incorrect thermal behavior; it builds the basis to understand the health of the system and predict the lifetime. Since liquid cooling is increasingly applied in power electronics, 3D studies are essential because local flow characteristics on the coolant side have a significant impact on cooling effectiveness and temperature hot spots.

Traditional thermal modeling approaches [1], such as Cauer, Foster, Lumped parameter models, etc. represent the state-of-the-art in heat transfer simulation in power semiconductor modeling. However, to investigate the cooling performance in a more detailed way, an extended 3D CFD simulation methodology is needed. Modern power electronic modules exhibit multiple material layers. Hence, the applied simulation software requires multi-material and multi-physics capabilities, which is provided by the commercial software package [2] AVL FIRE™ M.

The considered cooler geometry is taken from a demonstrator of a 650 V GaN based power converter, based on a multiphase phase evaporation cooling approach. A special challenge in this task lies in the channel dimensions dealing on the micro scale level, as channel widths of 100 µm are used. The simulation domain is displayed in Fig. 1 showing one segment with four GaN chips on top of the multi-layer solid structure. The four chips provide a heat input of 4 x 20 W into the segment. A methanol/water mixture with a flow rate of 45 ml/min is entering the domain with a temperature of 35 ˚C. The simulation mesh consists of 1.8 million, mainly polyhedral, elements with a proper boundary layer structure in the fluid region to fulfil requirements for correct heat transfer calculation. The applied RPI (Rensselaer Polytechnic Institute) wall boiling model is an advanced approach to deal with the nucleate boiling regime [3]. Seen as a major target in this simulation the average temperature at the interface between the chips and the interposer material is kept at approx. 83 ˚C which is within specified limits. As a qualitative measure the distribution of the built-up of the vapor volume fraction of the coolant is also checked. Together with other quantities, e.g., flow field parameters, it provides ideas to improve the flow path and thus the heat transfer.

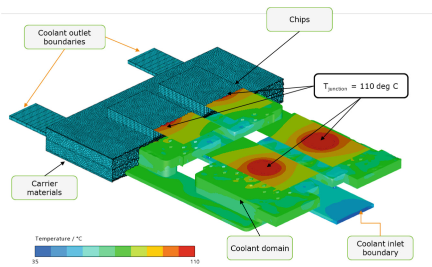

Fig. 1. Considered segment of a GaN 650 V demonstrator simulated with AVL FIRE™ M

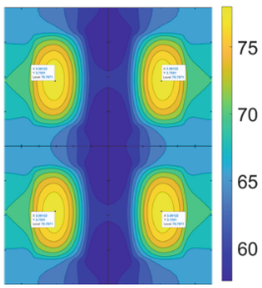

Fig. 2. Temperature at chip interface obtained by analytical model with Matlab2023a.

The applied simulation approach provides the proper tools to start investigations in an early stage of the design, because local flow characteristics on the coolant side have a significant impact on cooling. Furthermore, the results are in line with the analytical microfluidic flow boiling model, which is used to design the cooler geometry, see Fig. 2. Issues, which are detected early in advance, can avoid expensive cycles of iteration during prototyping and manufacturing phase. Furthermore, the application of RPI model includes most of the thermal management systems (e.g., general cooling phenomena in power electronics, water cooling jacket, battery cooling) in which evaporation phenomena are used to absorb heat and carry it out of the system.

4 Power Electronics Design for Reliability

With the recent advancement of Wide Band Gap (WBG) semiconductor technologies, SiC and GaN-based converters have taken the forefront [4]. The WBG semiconductors allow much higher switching frequencies and temperatures than conventional semiconductor materials. WBG-based converters have the potential to operate at elevated junction temperatures exceeding 150 ˚C, owing to their high thermal conductivity. Moreover, WBG converters operate at faster switching. Filtering components contain passive components (e.g., dc-link capacitors, magnets), which are relatively large and heavy. Higher switching frequencies make it possible to use smaller filtering components, which in turn allow a lighter and more compact system. At the same time, the higher switching rates result potentially give more switching losses, which eventually lead to higher temperatures. And according to the reliability study in articles [5, 6], the lifetime of the power electronics converters reached their limits by the progressive fatigue of the semiconductors due to repetitive subjected thermo-mechanical stress.

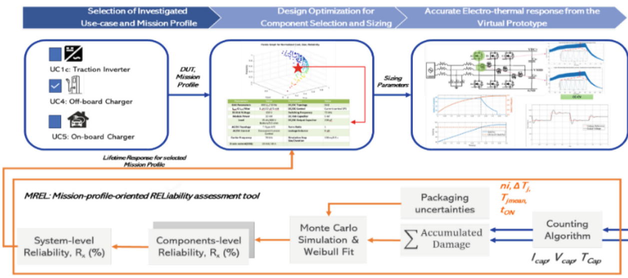

Fig. 3. A streamlined framework for reliability-oriented design and optimization for different HiEFFICIENT UCs (i.e., traction inverter, off-board charger and GaN on-board charger).

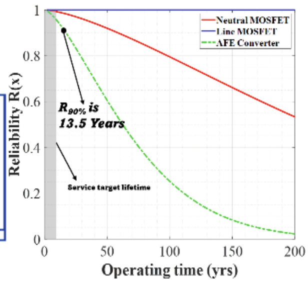

Fig. 4. Weibull reliability of the charging system for the considered charging current profiles.

Therefore, a streamlined approach is required to balance optimal component sizing, select appropriate switching frequencies to minimize losses and fulfill service lifetime requirements, which could reduce over-engineered hardware significantly. In this paper, a streamlined process to design and optimization for reliability (*DOfR*) is proposed (cf. Fig. 3), which will be used to investigate the reliability of the optimal automotive powertrain components based on mission profiles, according to the following steps: i) once the optimization of the components is completed this tool will estimate the lifetime of the new components for the targeted mission profile based on the repetitive electro-thermal stressors; ii) if the new components' target lifetime is not reached, the tool will provide input to the optimizer to re-optimize based on the reliability scorecard. Thus, this tool will allow automotive power electronics engineers to (a) optimally size components without compromising reliability and avoid over-engineered hardware and (b) decrease the environmental footprint during operation and prolong the component's lifetime to fulfill the service target.

Within HiEFFICIENT project, a multi-use DC charger that can be seamlessly used for small vehicles (48 V battery voltage), personal cars (200–920 V battery voltage), and heavy-duty vehicles (500 V-1000 V battery voltage) is being developed. The maximum power of the charger is 180 kW; hence, 3 modules of 60 kW and 3 outputs will be available. The connection of each module to one of the outputs is handled by controlling the power-switching matrix. The module of 60 kW is also composed of two equal 30 kW building blocks (BB). For the 30 kW BB module, a two-power conversion stage architecture is chosen. For the AC/DC stage, T-Type Active Front End (AFE) is selected since it has a smaller LCL filter compared to a standard 2-level AFE. For the DC/DC stage, an isolated DAB (Dual Active Bridge) topology is selected. In this paper, only the 30 kW T-type AFE converter is considered as the device under test (DuT). A multi-objective genetic algorithm-based (MOGA) optimization for the 30 kW AFE converter is developed to obtain performance improvement regarding converter-level cost, size and lifetime. Considering the obtained optimal solution, a virtual prototype of the converter is prepared using commercial PLECS software to simulate responses for the entire grid-to-vehicle (G2V) and vehicle-to-grid (V2G) events. A Look-up-Table (LuT) based detailed switching and conduction losses are estimated along with a foster thermal network, where the ambient temperature is retained at 250 ˚C. Based on the repetitive junction temperature (Tj) and junction temperature swings (ΔTj) response, the cloud-based reliability assessment framework described in the article [5] determines the actual lifetime of the converter at the subjected mission profile.

Figure 4 illustrates the AFE converter reliability as a function of the operating time in years, as the aim of this paper is to assess the impact of mission profile (i.e., G2V and V2G charging) on the lifetime of a high-power charging system, it is assumed that the DuT will be subjected to 10 same profiles/day during its entire life cycle, which means daily the charger will operate for 370 min and each time ambient will be remaining same at 25 ˚C facilitated by pre-conditioning before each mission profile cycle. Besides, it can be seen that for the 90% reliability percentile, the DuT exhibits a lifetime of 13.5 years, satisfying the OEM's requirement of 10 years. However, it must be noted that the actual lifetime of the DuT will likely be shorter than the predicted values shown in Fig. 4 as there are other failure-prone components (e.g., DC-link capacitor, LCL filter elements, micro-controller, etc.), which have not yet been factored into this framework.

5 Conclusions

The paper presented several aspects of developments in HiEFFICIENT project. GaN technology is a key enabler for future power electronic automotive applications. Due to some today's limitations innovative approaches are necessary to fulfil all market needs.

Sustainability and long lifetime are in focus of OEMs and hence advanced cooling technologies and development tools are key as well as frameworks for lifetime estimation and appropriate design. All these aspects are addressed in the one or other way in HiEFFICIENT project, tackling the needs of future applications.

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