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Design and Optimization of Energy-Efficient Power Electronics for Next-Generation Electric Vehicles

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Abstract

The explosive development of electric vehicles (EVs) requires the use of very efficient, small and dependable power electronics to maximize energy conversion, distribution, and storage. The work presented seeks to propose and test a full design and optimization procedure of energy-efficient power electronics in a future generation of EVs, aiming at a better performance, high driving range, and high-temperature stability. The approach combines the use of the wide-bandgap semiconductor (silicon carbide and gallium nitride) devices (SiC MOSFETs and GaN HEMTs) with multi-objective optimization algorithms that reduce the conduction and switching losses. The control temperatures to be thermal-aware and also the addition of better thermal cooling schemes are also provided to be more stable at times of high load. To succinctly outline the proposed architecture which consists of a SiC based traction inverter, a GaN based bidirectional DC-DC converter and a high-efficiency onboard charger, our multi-stage architecture is modeled in MATLAB/Simulink and validated on an OPAL-RT hardware-in-the-loop (HIL) platform. In comparison with traditional silicon-based system, benchmarking shows a potential performance-gain to be as high as 7.8%, the thermal rise is up to 27.8% lower, and power density to rise by a substantial 45 percent. Achieved results reveal that WBG-based power electronics can address the high efficiency and reliability demands of EV platforms in the future. The method suggested has a viable route of leading to eco-friendly, high-performance electric mobility systems.

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Introduction

Electric vehicles (EVs) have been credited to be a viable solution in limiting the amount of greenhouse gas emissions as well as vulnerable reliance on fossil fuel in the transportation sector. This requires power electronics whose systems are the key to efficient conversion of energy between the traction battery, the drivetrain, and auxiliary loads: something that needs to be further developed before they will become widely adopted. To achieve high efficiency, small form factor, reliable thermal, and electromagnetic compatibility (EMC) compliant, power electronic converters, (e.g., traction inverters, onboard chargers (OBCs), and DCAC converters) are needed. The long-established Si-based devices are cost-effective and mature but are not practically used with a relatively high switching loss, low thermal conductivity, and low efficiency at higher switching frequencies. New developments and commercial introductions in wide-bandgap (WBG) semiconductor products involving silicon carbide (SiC) MOSFETS and gallium nitride (GaN) HEMTs have shown strong promise with respect to increased switching speeds, reduced conduction losses, and better thermal control over wider temperature ranges-supporting lighter and smaller EV powertrains.[1-3]

Although substant ial progress has been made, current studies tend to be at a component level, neglecting integration of system level optimisation, thermal-aware control and multi-objective trade-offs. In addition, comparative hardware-in-the -loop (HIL) validation against conventional silicon-based designs, through real world EV load cycles is lacking. Filling such gaps is essential to achieve the next-generation EV power electronics that will achieve high power efficiency, reliability, and sustainability requirements.

This paper introduces an integrated design/optimization model in which WBG device choice, multi-objective optimizers, and state-of-art thermal control strategies are integrated. Verification of the offered methodology is made through simulation and HIL tests, where the performance is contrasted to those of a traditional design.

Literature Review

Role of Power Electronics in EVs

Power electronics are of the most critical nature as far as use is concerned with regard to enabling electric vehicles to run and perform three major functions:

1. Traction Drive Control - Regenerative braking and precise control of the motor is carried out by using high-efficiency inverters.[4]
2. Charging and Battery Management The battery charging and management occurs onboard, through onboard chargers (OBCs) that are grid compliant (through integrated power factor correction (PFC)) and battery management systems (BMS) that monitor the battery state-of-charge (SOC) and state-of-health (SOH).[5]
3. Auxiliary Systems Power Supply DC-DC converters – Step down high-voltage battery to low-vol- tage buses driving infotainment, light- ing, safety electronics.[6]

These functions and their interaction in the scenario of EV architecture can be summarized in Figure 1 that demonstrates a concept map highlighting the main aspects of EV power electronics and optimization routes of the same.

Limitations of Conventional Silicon-Based Devices

Silicon IGBTs and MOSFET based systems are full-grown and cost effective, but are confronted with fundamental limitations like high switching loss, massive cooling apparatus, and poor efficiency at higher rates of switching. Such shortcomings are limiting power density and thermal efficiency of compact EV powertrains.[7, 8]

Wide-Bandgap Semiconductors for EV Applications

Wide-bandgap (WBG) semiconductors have become power electronics game changers in EVs:

- SiC MOSFETs have increased breakdown voltages, lower conduction losses and high thermal conductivity, therefore, allowing them to use in high-voltage traction inverters.[9]
- GaN HEMTs offer ultra-fast switching, small gate charge, and the high frequency of operation producing compact DC DC converter and on board chargers.[10]

These devices have also shown a 50 percent improvement in switching loss and increased thermal stability, although low costs of the devices, ensnaring gate, and packaging have been obstacles to wide adoption.[11]

Optimization Approaches in EV Power Electronics

Researchers have used a number of multi-objective optimization techniques in order to maximize on efficiencies and reliability:

- Efficiency-weight trade off balancing using Genetic Algorithms (GA) in converter design.[12]
- Particle Swarm Optimization (PSO) as a part of switching and conduction loses minimizing in inverters.[13]
- Real-time loss reactive mitigation strategies based upon Thermal-Aware Switching in dynamic load conditions.[14]

These methods enhance one or more of these performance parameters individually, but have a lack of integrated cost-effective optimization strategies that optimize not only the electrical characteristics, but the other concerns of thermal management and electromagnetic compatibility (EMC). In addition, such approaches are partially lacking in hardware-in-the-loop (HIL) validation over realistic EV driving cycles which are key to technology-readiness.

A hierarchical concept map that depicts main themes in literature review about EV power electronics. The diagram describes how power electronics is used in EV systems, the drawbacks of more traditional silicon-based devices, the benefits of using wide-bandgap semiconductors (SiC MOSFETs and GaN HEMTs), differences in different optimization strategies, such as efficiency versus weight trade-offs, loss reduction, and thermal insensitive switching.

Proposed Design and Optimization Framework

This section outlines an integrated approach to realizing high efficiency, thermally robust, and electromagnetic compatibilities (EMC)- acceptable power electronic on the next-generation electric vehicles (EVs). The framework is a combination of device-, circuit- and system-level optimization to adapt to the requirements of a strict automotive standard.

System Architecture

The offered architecture consists of three major subsystems and is depicted on Figure 2:

- Traction Inverter A hig4h-voltage traction motor 3- phase bridge structure using SiC.

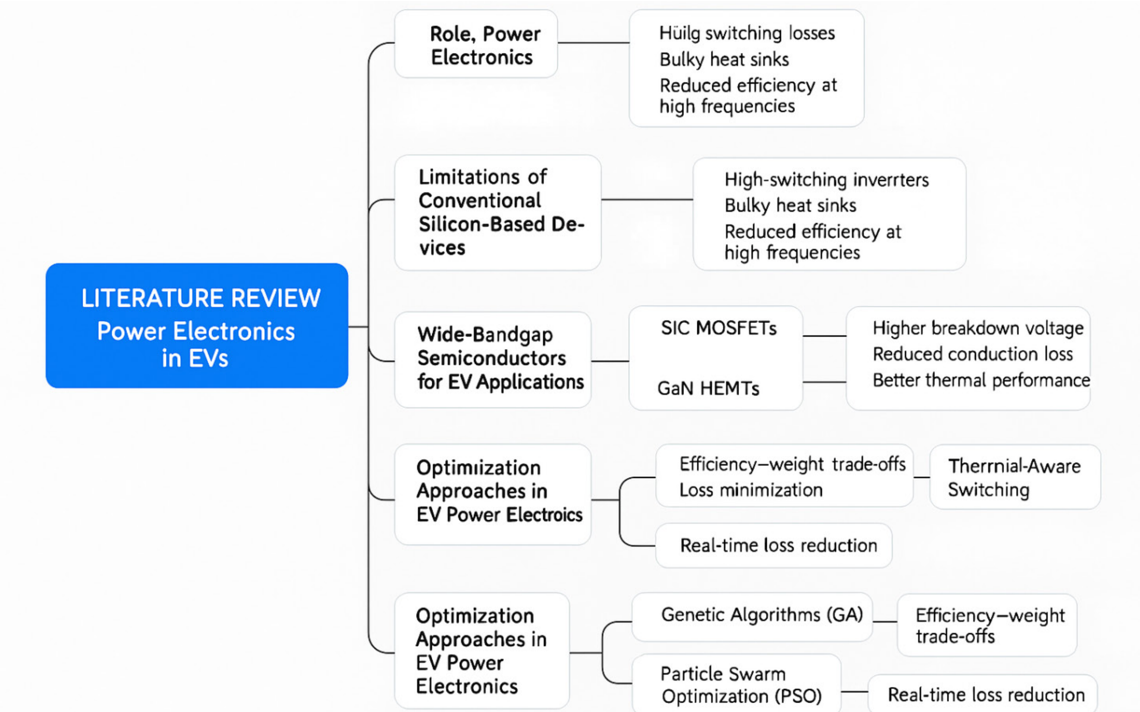

Fig. 1: Concept Map of Literature Review on Power Electronics for Electric Vehicles

Higher switching frequencies (>20 kHz) and reduced conduction losses and superior thermal performance are possible through the use of SiC MOSFETs [15].

- Bidirectional DC-DC Converter: – A GaN interleaved architecture with two-way power flow between high-voltage traction battery and low voltage auxiliary systems providing support to regenerative brakes and auxiliary power feed.
- Onboard Charger (OBC) Incorporating an active Power Factor Correction (PFC) stage to make sure that the charger complies with the grid and charge efficiently under varying grid dynamics.

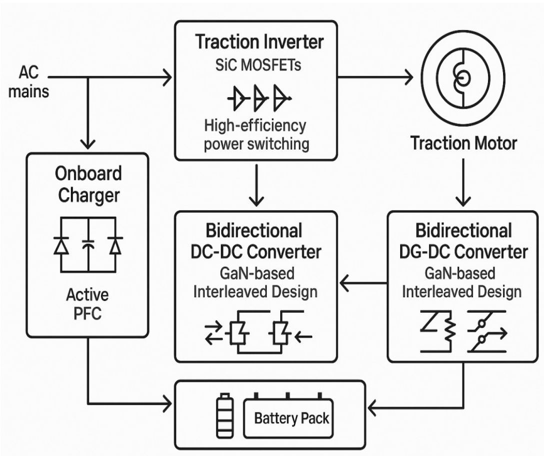

Fig. 2: System Architecture of Proposed EV Power Electronics

Functional block diagram of the proposed EV power electronics, which consists respectively of a high-efficiency SiC-based traction inverter used to control a motor, GaN-based bidirectional DC-DC converters between battery and auxiliary systems, and an onboard charger powered by an AC mains, controlled by a PFC.

Design Objectives

The performance objectives targeted in the optimization process are as follows and depicted in Figure 3:

1. Loss Minimization: Minimize conduction and switching losses with the best possible choice of semiconductors and tuned high speed gate drivers.
2. Thermal Management Observable; Reduce hot-spot formation through optimized routing of copper trace on the PCB and use of thermal spreading layers as well as an augmented heat sink design.[16]
3. High efficiency of > 97% converter efficiency under the representative driving cycles including WLTP and FTP-75, which has been tested in hardware-in-the-loop (HIL) tests.

The most important performance objectives: set minimum losses, improve thermal management, and maximum efficiency in designing power converters.

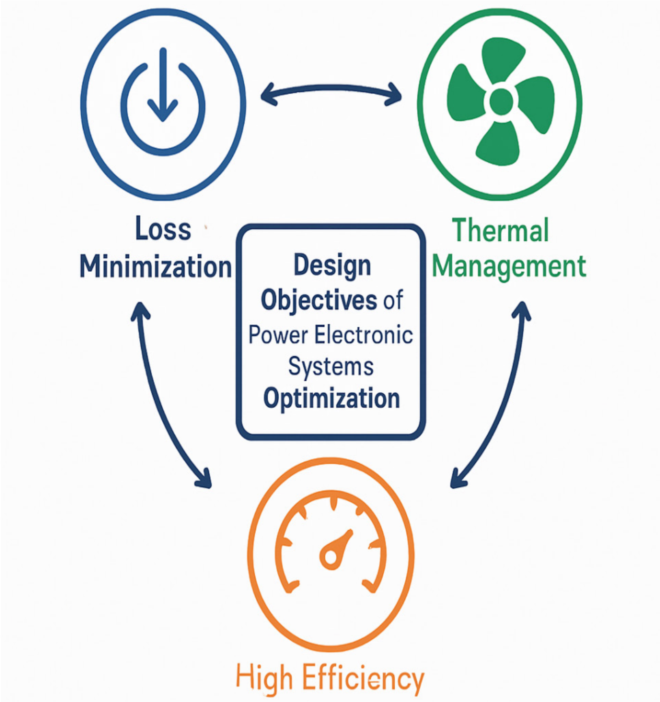

Fig. 3: Design Objectives for Power Electronics Optimization

3.3 Optimization Methodology

The layout of the design optimization is represented by three domains and it is shown in Figure 4:

- Electrical Optimization - to maximize performance, the choice of WBG devices may be informed by the result of a figure-of-merit (FOM) analysis, gate driver impedance matching, and soft-switching control techniques can also be used so as to optimize performance at partial and full loads.
- Thermal Optimization - Liquid-cooled heat sinks to be integrated with phase-change thermal interface materials (PC-TIMs) to support better heat dissipation that results in 20 C drops in junction temperature under maximum loading.
- Electromagnetic Compatibility (EMC) Mitigation - use of shielded laminate busbars, ideal grounding schemes, and common-mode chokes to restrain the conducted and radiated emissions in such a way that do not exceed CISPR 25 and ISO 11452 specifications.[17]

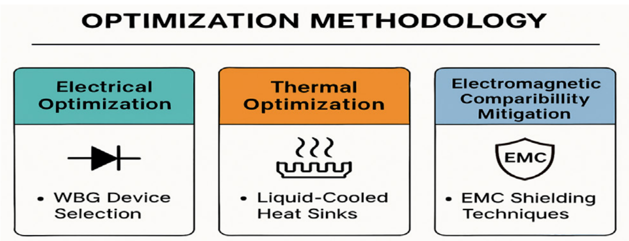

Fig. 4: Optimization Methodology for Power Electronics Subsystems

Structured optimisation: electrical, thermal & EMC environments to optimise converter performance.

The holistic design process allows addressing electrical, thermal and EMC factors at the same time, resulting in compact EV power electronics, robust and energy efficient.

Simulation and Experimental Setup

Simulation Environment

MATLAB/Simulink and PLECS were used to simulate the proposed EV power electronics architecture to conduct the preliminary design and performance evaluation of the proposed EV power electronics architecture as depicted in Figure 5. The system level modeling, in case of the traction inverter, bidirectional DC to DC converter, onboard charger sub systems, was conducted in MATLAB/Simulink to enable detailed algorithm control implementation, thermal models and loss estimation routines. A circuit-level switching simulation was applied using PLECS to perform various switching simulations (conduction loss, switching behaviour and thermal stress distribution of the WBG devices).

It tested the system in accordance with the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) drive cycle, whose realistic load profile captures an amalgamation of city, suburban and highway loads during the test. The WLTP cycle guaranteed that efficiency, thermal, and compliance with EMC were measured in representative working conditions than at fixed-work loads.

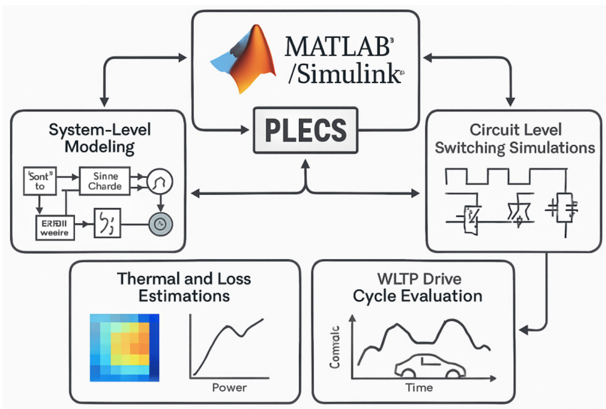

Fig. 5: Simulation Workflow for EV Power Electronics Evaluation

Schema showing how MATLAB/Simulink and PLECS can be used together to model systems at system-level, simulate circuit-level switching behaviour, estimate thermal behaviour/losses and the WLTP driving cycle.

Hardware-in-the-Loop (HIL) Validation

In order to mitigate the discontinuity between simulated and real-life environment the design was verified with a Hardware-in-the-Loop (HIL) approach; an OPAL-RT real-time simulator, see Figure 6. The HIL system was able to test control algorithms in real time and connect to physical hardware components, providing accurate measures of dynamic response as well as verification that control is stable. The hardware arrangement done in the experiment was:

- Semiconductor Devices:
  - o 650 V SiC MOSFET module (Cree/Wolfspeed) traction inverter realization.
  - o 650 V GaN HEMT (Transphorm) in bidirectional DC o C converter.
- Cooling System:
  - o Liquid-cooled thermal management loop and plate-fin heat exchanger, which are created to provide power device junction temperatures are maintained with in the safe operating area (SOA) at maximum load levels.

Example of how HIL validation process could be conducted with an OPAL-RT real-time simulator and

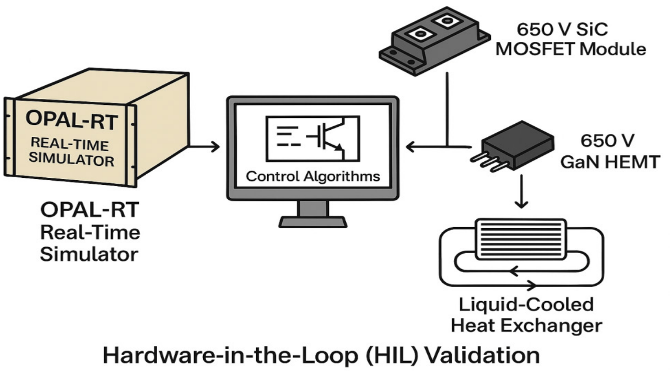

Fig. 6: Hardware-in-the-Loop (HIL) Validation Setup

control algorithms connecting with a 650 V SiC MOSFET module, a 650 V GaN HEMT, and a liquid-cooled heat exchanger to manage thermal aspects.

A high-fidelity simulation combined with HIL tests meant that the electrical, thermal and EMC properties were verified before prototyping, cutting down the number of design cycles and limiting integration risks.

Results and Discussion

The operation of the proposed architecture of the SiC/GaN-based power electronics of EV was compared with the baseline silicon-based design based on IGBTs under the same load and under the same thermal load. Table 1 presents the summary of comparative results and Figure 7 displays the visualization of results.

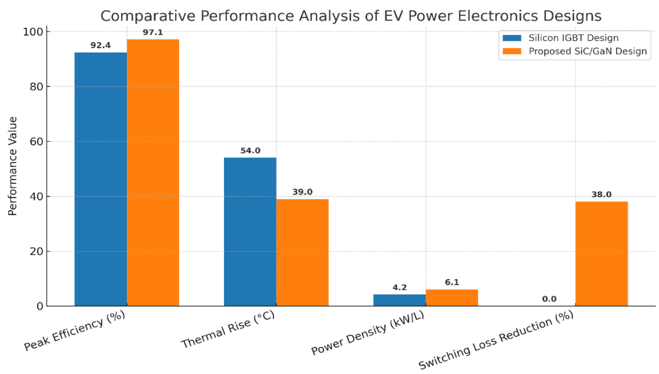

Fig. 7: Comparative Performance of Silicon IGBT vs. Proposed SiC/GaN Designs

Bar graph of maximum efficiency, rise in temperature, power density and reduction in switching losses. The SiC/GaN implementation results in a 97.1 percent efficiency, reduces the thermal rise by 27.8 percent, increases the power density by +45.2 percent and cuts switching losses by 38 percent compared to the silicon-based baseline. The proposed achieved a maximum efficiency of 97.1 percent that is 5.1 percent absolute increase for the conventional IGBT-based implementation. Steady progress here is mostly explained by:

- Reduced on-state resistance, faster switching and reduced parasitic capacitances result in lower conduction and switching losses of SiC MOSFETs and GaN HEMTs.

Table 1: Comparative Performance Analysis of Conventional and Proposed Designs

Parameter	Silicon IGBT Design	Proposed SiC/GaN Design	Improvement
Peak Efficiency (%)	92.4	97.1	+5.1%
Thermal Rise (°C)	54	39	-27.8%
Power Density (kW/L)	4.2	6.1	+45.2%
Switching Loss Reduction (%)	-	38	-

- Increased performance gate driver design which lowered turn-on/turn-off energy dissipation and enhanced switching waveforms.

The thermal readings show a decrease of 27.8%, in the maximum temperature rise, which will allow utilization of reduced cooling systems, which translates into a direct decrease in weight, and a flexible packaging solution. These improved thermal behavior is both due to the nature of WBG device in use (more thermal conductivity and less junction to case thermal resistance) as well as the incorporation of a liquid-cooled plate-fin heat exchanger within the thermal management framework. The power density was doubled to 6.1 kW/L (+45.2%) indicating that the higher power throughput in GaN-based DC-DC converters and SiC-based inverters could be achieved because of smaller volume. In addition, the 38 percent utility exchange loss decrease is extremely beneficial to part-load efficiency, which is of concern in the driving cycles of EVs, which contain significant portion load usage.

All in all, these findings reaffirm the previously stated design objectives (Section 3.2) and prove that the synergy of WBG devices, cutting-edge thermal management, and system-level optimization can deliver an impressive increase in terms of efficiency, thermal stability, and power density on the volume--which are crucial factors in the development of next-gen EV powertrains.

Conclusion and Future Work

Conclusion

This publication has offered the first unified design and optimization of energy efficient power electronics in future EVs including high-power SiC-based traction inversion, high power GaN-based bidirectional DC-DC and a PFC-integrated OBC. The approach combined electrical, thermal, and EMC co-optimization and combined FOM-based device choice, gate-driver tuning, soft-switching control, liquid cooling via PC-TIMs, laminated bus-bar with grounding/choke methods. Through WLTP profiles, MATLAB/Simulink + PLECS models were proven through OPAL-RT HIL. On a silicon IGBT baseline, the proposed design was capable of 97.1% peak efficiency, 27.8 fewer thermal rise, a +45.2 percent increase in power density, and 38-percent reduction in switching losses, ensuring it met the design criteria of the paper and presenting a viable route to lighter, more reliable EV powertrains.

Contributions

1. Cross-domain co-design (electrical-thermal-EMC) including measurable objectives that can be suitably qualified in the automotive.
2. WBG device and gate-driver specifications (FOM-driven selection, dv/dt shaping, soft-switching) that reduce switching energy, and increase partial-load efficiency.
3. The ability to minimize thermal stack frame (liquid plate-fin + PC-TIM), and lower junction temperatures, which allows cooling hardware to be down-sized.
4. CISPR 25/ISO 11452 pre-compliant EMC-aware layout (shielded laminated busbars, optimisedgrounding,common-mode chokes).
5. Validation workflow mapping HIL based: drive cycles to to converter stress, a shortened iteration time between simulation and hardware.

Limitations

Pre-compliance EMC analysis plus HIL testing of representative modules is used in deriving results; no emissions, reliability and cost effects over the full vehicle were measured comprehensively.

Future Work

- Integrated Modular Power Units (IMPU): mechanical/ electrical co-packaging of inverter, DC/DC, and OBC cooling and laminating bus are shared.
- Fast charging: traction stages based on SiC; fast charging; PFC/LLC OBCs designed to be powered by food-fed totem-poles.
- High level packaging: Two-sided cooling, MCM substrates, Ag-sintered die attach, and SiC-GaN hybrid co-packs.
- Control by AI: model-predictive/RL control to assist switching frequency /dead-time; online observers to heat/EMI; predictive maintenance.
- Reliability physics mission-profile based life(power cycling, thermal shock), short-circuit robustness of SiC, partial-discharge screening.
- EMC Measurement- Campaign: chamber test to seal the loop on CISPR/ ISO limits and to further characterize layout-parasitics models.
- Pareto optimization of cost performance with BOM, manufacturability and AEC-Q/ISO 26262 compliance.

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