Benefits of Si/SiC Fusion Switch for EREV Architectures

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Abstract: This paper examines the benefits of Si/SiC Fusion switch power modules for Extended-Range Electric Vehicles (EREVs) operating in charge depletion mode, where electric driving range is a critical factor. A system simulation of the vehicle powertrain was conducted, comparing IGBT, SiC MOSFET, and Si/SiC Fusion switch power modules. The simulation approach and resulting electric drive range gains are discussed in detail. The case study included various drive cycles and a parameter study of environmental conditions, such as driving up a hill, which represents real-world application use cases. The findings are further integrated into a system cost comparison, considering both current and future cost scenarios. The results show that the Si/SiC Fusion switch power module offers the best efficiency-cost tradeoff for typical EREV vehicles and battery sizes.

Keywords: Automotive; Traction Inverter; Si/SiC Fusion switch; IGBT; SiC MOSFET.

1. Introduction

Along the transition of the automotive industry towards e-mobility, two main obstacles still need to be overcome, specifically when considering battery electric vehicles as final target. First, affordability of battery electric vehicles is still a challenge in many countries. Second, range anxiety is still very much present, despite remarkable efforts in building up charging infrastructure. Therefore, recent efforts of major car manufacturers are visible to foster developments of a new generation of hybrid architectures, addressing both challenges by combining the internal combustion engine and the electric drives in an optimized way, which has leaded to increasing market share of Extended-Range Electric Vehicle (EREV) in last years. To support this approach of re-thinking electrification from a power semiconductor perspective, a similar consideration is shown in this paper as a complement: Combining Si IGBTs and SiC MOSFETs for these new hybrid architectures in an optimized way.

2. EREV Architecture Introduction

An overview of different EREV architectures and control strategies can be found in [1]. This paper focuses on the powertrain unit, from energy storage to the wheel, specifically in the charge depletion area, where the generating units (or auxiliary power units, APUs) are inactive. In charge depletion mode, the EREV architecture behaves similarly to an Electric Vehicle (EV), with the notable exceptions that an EREV typically have lower weight, primarily due to a reduced total battery capacity, and the 470 V architecture is still the mainstream as 850 V fast charging options [2] like demanded in pure EVs is not needed. The energy efficiency in charge depletion mode is a top priority, whereas in charge sustain or recharging mode, the focus shifts to minimizing the cost of the electric powertrain units. Consequently, EREVs require a balance between low cost and high efficiency. This paper examines the benefits of Si/SiC Fusion power modules for EREV architectures and provides a benchmark comparison with the latest IGBT and full SiC MOSFET power modules.

The paper is structured as follows: Chapter 3 reviews the fundamental principles of the Si/SiC Fusion switch. Chapter 4 outlines the methodology applied in the benchmark study, providing insights into the applied parameters and devices under test (DUTs) used in the comparison. Chapter 5 presents the results of the benchmarking, including a discussion of the key influencing parameters. Chapter 6 incorporates cost considerations into the benchmarking results. Finally, Chapter 7 concludes the paper and offers an outlook on recommended future work.

3. Si/SiC Fusion Introduction

Si/SiC switches have been extensively researched in various studies [3],[4],[5],[6],[7]. However, their implementation in automotive volume applications has been hindered due to the complex control requirements and the associated risks. The introduction of the Si/SiC Fusion switch has changed this landscape, as it can operate under a single gate drive configuration [8],[9].

This configuration inherently performs efficient and reliable current sharing is guaranteed across the entire operating range, including different working voltages, switching currents, and operating temperatures [9] (see Figure 1). As a result, this solution has become an attractive alternative to traditional silicon IGBT/Diode and SiC MOSFET power modules. The fundamental principle behind the Si/SiC Fusion switch is that at light load conditions, the more efficient SiC MOSFET handles the current, while at increasing loads, the larger and more cost-efficient Si IGBT/Diode automatically supports the dissipation of power losses via the power module into the coolant circuits in a cost-effective manner.

These new Si/SiC Fusion switches are designed to target applications with high peak power demands, ranging from 120 to 250 kW. Notably, the average power required for drive cycle efficiency is significantly lower, typically only 10-20% of the peak power capability. A more detailed analysis of the benefits of Si/SiC Fusion switches within EREV architectures will be presented in subsequent chapters.

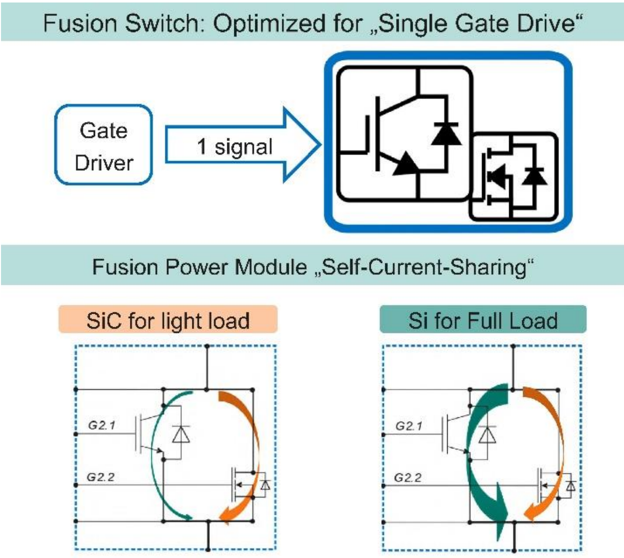

Figure 1: Si/SiC Fusion switch with simultaneous gate drive. The SiC MOSFET and Si IGBT gates are connected to form a "standard 3 terminal transistor".

4. Benchmarking Approach

A system simulation was used to benchmark different types of power modules, including various IGBT/Diode, SiC MOSFET, and Si/SiC Fusion chipset technologies. The simulation utilizes different drive profiles, which describe vehicle speed over time, to calculate the required torque-speed vector at the tires. This vector is then translated to the electric machine using a fixed gear ratio and a vehicle longitudinal behavioural model. The behavioural model of the electric machine provides the necessary input parameters for the traction inverter, which is processed in an electric model coupled with a thermal model. The thermal model provides the necessary inputs for the electric model from the previous simulation step. The calculated total vehicle drivetrain power and power losses of the switches is integrated over time to determine the energy consumption over the drive profiles. These results are finally compared for different devices under test.
The key elements of the modelling approach will be explained in more detail in the following sections. The simplifications made to the vehicle and motor models were intentional, as the primary objective of this study was to draw relative conclusions between the different chip technologies. To achieve this, it was essential to establish equal boundary conditions for comparison. The high-order nonlinearities in the vehicle, battery, and machine behaviour will be addressed through parameter studies of different vehicle drag coefficients (i.e. cw values) and driving profiles with varying uphill slopes. These studies will provide a comprehensive understanding of how the different technologies perform in various real-world use cases.

4.1. Mission Profiles

For benchmarking purposes, the standardized WLTP Class 3 and CLTC-P profiles are utilized (see Figure 2). Notably, the CLTC profile features lower driving speeds and lower acceleration/deacceleration slopes compared to the WLTP cycle. The WLTP drive profile is further divided into two subgroups: the standard full WLTP cycle and a modified "WLTP city" version that focuses only on low- and mid-speed sections, excluding high-speed areas typically encountered outside city use-cases.

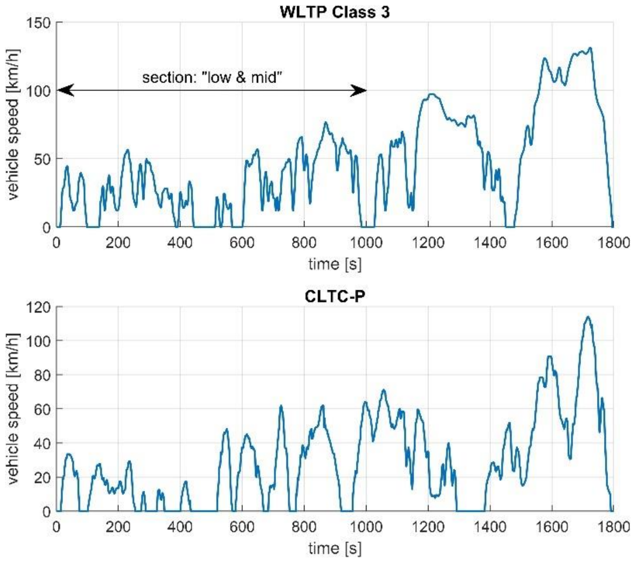

Figure 2: Vehicle mission profiles in scope of this study.

4.2. Vehicle Model

For the EREV vehicle, a standard-sized sedan was assumed, with a vehicle mass of 1800 kg and an additional payload of 160 kg. Although this may seem lightweight compared to a pure BEV, the EREV architecture's use of smaller battery sizes (typical about 25 kWh) also results in a lower overall vehicle weight. A drag coefficient of 0.23 and a front area of 2.4 m² were assumed. The impact of different drag coefficients is analysed in sections 5.2 and 5.3. A linear model for roll resistance was used, assuming standard tires. The transmission is modelled with a fixed gear ratio and a simplified linear loss model. The modular simulation approach allows the vehicle model to be easily exchanged, enabling the study of different car models and environmental conditions in future studies, as well as supporting project-specific designs.

4.3. Motor Model

For the electric motor, a permanent magnet synchronous machine (PMSM) design was used, which offers advantages in efficiency and power density compared to asynchronous machines (ASM) and switched reluctance machines (SRM). Specifically, PMSMs have fewer (NVH) noise vibration harshness challenges than SRMs. As a result, PMSMs are the most widely used machine type in the automotive electric drivetrain. For this study, a generic machine model was developed, which utilizes a 2D lookup table to determine motor phase currents over various speed and torque values. The study employed a 150 kW nominal-rated machine type with a maximum torque of 310 Nm, resulting in a field weakening area that begins above 4600 rpm. The motor map used for benchmarking is illustrated in Figure 3. Similar to the vehicle model, the motor model can be easily exchanged to support analysis with project-specific machine types.

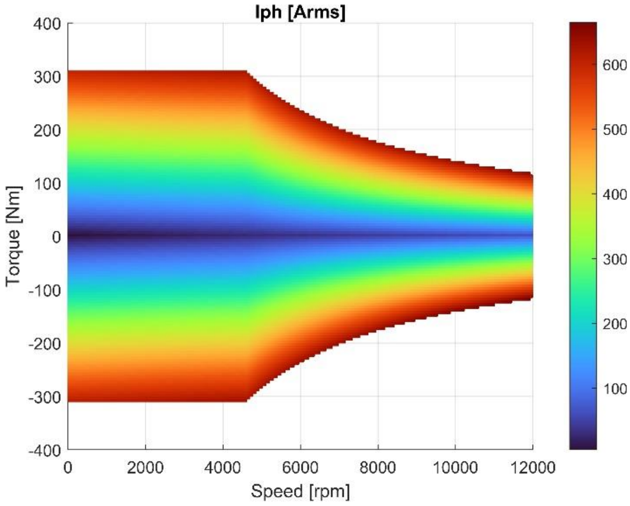

Figure 3: Generic motor current map (z-axis) over speed and torque of 150 kW permanent magnet synchronous machine (PMSM).

4.4. Inverter Power Module Modelling

The inverter was modelled using a modular approach. The first sub-model calculates conduction losses based on piecewise linearized models averaged over one sine rotation output. The input parameters are derived from measured device characteristics and adjusted according to feedback from resulting junction temperatures of the thermal sub-model of the last simulation step. This approach is precise enough for normal operating conditions, such as drive cycle simulations. For more information on behavioural model approaches, refer to [10] for standard IGBT/Diode or SiC MOSFET-based inverters and [8] for Si/SiC Fusion switch inverters. However, exceptional cases like stress simulations under motor stall/hill hold or failure conditions like short circuits require alternative methods and are outside the scope of this paper.

For dynamic switching losses, a more sophisticated approach was applied, as classical behavioural models often lack in accuracy, particularly in the light load area as discussed in [11]. However, this light load area is crucial for drive cycle efficiency, as it is the most frequent operating condition, whereas high load occurs rarely and only for short periods.

To achieve high precision over the entire drive cycle-relevant operating area, dynamic switching losses were characterized using a fine-granular 3D matrix covering currents from 0 to 1600 A, working voltages from 300 to 470 V, and temperatures from 25°C to 175°C.

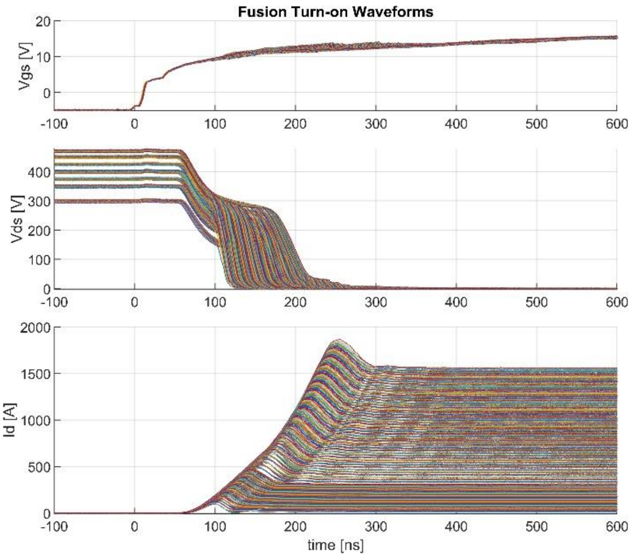

Figure 4: Measured Fusion turn-on waveforms 0..1600 A, 300..470 V at different temperatures. These waveforms provide the dataset for 3D lookup tables: Switching-energy as a function of Current,Voltage,Temperature.

The measured switching waveforms for the Si/SiC Fusion switches are shown in Figure 4, Figure 5, and Figure 6. Under all conditions the voltages are below its specified maximum ratings. With respect to the high switching speed the behaviour is extremely smooth, which is a major advantage of the Si/SiC Fusion switch and can lead also to optimized EMI behaviour.

The same measurement procedure was applied for the IGBT and the newest generation of full SiC MOSFET power modules.

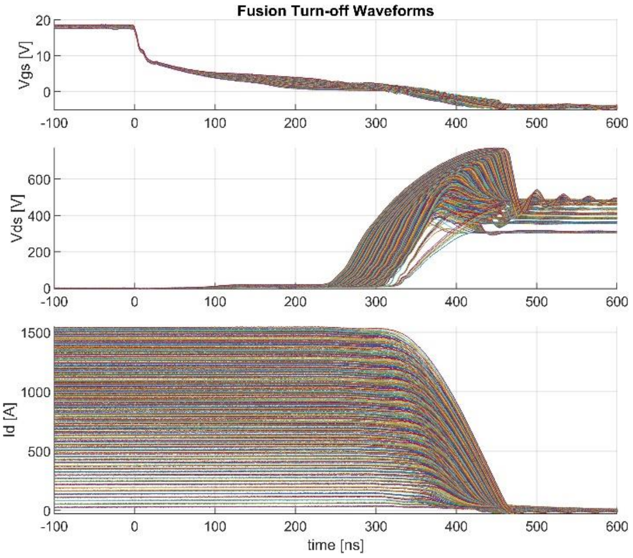

Figure 5: Measured Fusion turn-off waveforms 0..1600 A, 300..470 V at different temperatures.

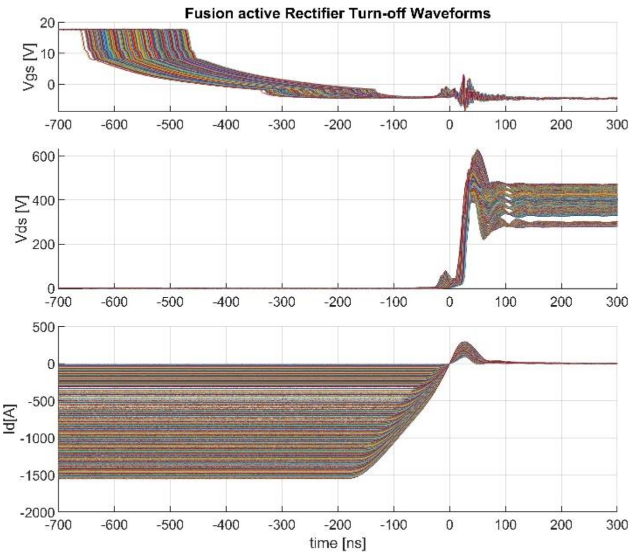

Figure 6: Measured Fusion active rectifier turn-off waveforms 0..1600 A, 300..470 V at different temperatures.

The resulting switching energies, obtained by integrating the voltage and current product over time, was then organized in 3D lookup tables, with the third dimension being temperature. The lookup matrix at one temperature is shown in Figure 7 to provide a comprehensive picture of the dataset organization.

Although this approach with measured lookup tables may seem to require a high characterization effort, it provides a precise insight into the resulting power losses in real drive cycles.

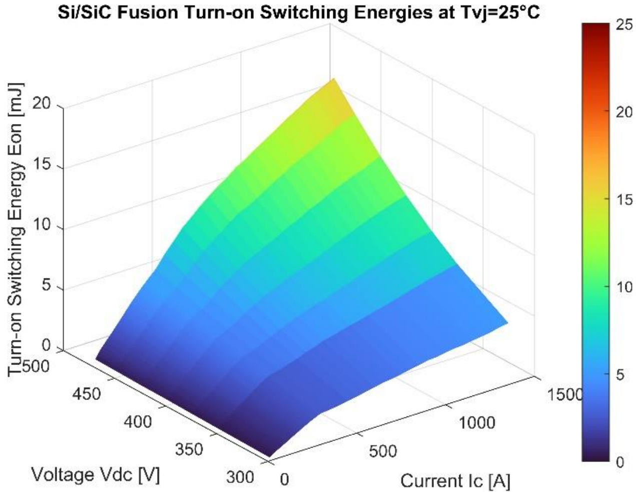

Figure 7 Measured Fusion turn-on switching energies from 0..1500 A and 300..470 V as 2D lookup table at 25°C.

For the thermal model, a standard thermal impedance (Zth) model based on Foster models was applied. The thermal cross-coupling of switches placed closely together was covered. The standard thermal model approach can be considered sufficient, as temperature differences of a few Kelvin will not significantly impact power losses and therefore have a negligible influence on drive cycle efficiency analysis.

4.5. Power Module types under investigation

This section provides an illustrative overview of the different devices under test (DUTs) focused on in this paper. The lowest-cost device is the IGBT/Diode power module, shown in Figure 8.

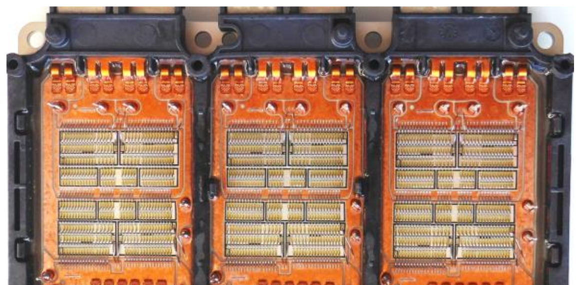

Figure 8 IGBT/Diode power module layout and signal connections. Each topological switch comprises 2x160 mm² IGBT with 3x60 mm² antiparallel Si Diodes of latest EDT3 750V chip generation.

In contrast, the highest-cost device, despite having a comparable lower chip area, is the SiC MOSFET power module, shown in Figure 9. For the comparison, the SiC MOSFETs were operated in the switching application up to its specified 900 V short-term extended reverse bias safe operating area to achieve high switching speed at system stray inductances of approximately 25 nH in the commutation loop. Therefore, the relative comparison to the other DUTs should remain valid even when considering other SiC MOSFET technologies with lower breakdown voltages combined with lower system stray inductances.

Figure 9: SiC MOSFET power module layout and signal connections. Each topological switch comprises 8x20 mm² SiC MOSFET from latest generation in parallel.

The Si/SiC Fusion switch power module utilizes dies an optimized layouted substrate enabling the single gate drive feature. Unlike for SiC MOSFET chips, the stray inductance is less critical for the Si/SiC Fusion switch, as the IGBT/Diode combination provides an intrinsic snubber effect. Experimental testing demonstrated stable switching performance over a wide range of system stray inductances, from 20 to 35 nH.

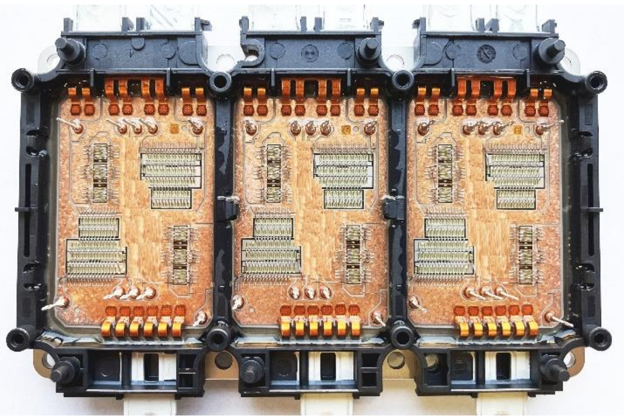

Figure 10: Si/SiC Fusion internal power module layout and signal connections. Each topological switch comprises 3x20 mm² SiC MOSFET in parallel with 160 mm² IGBT and 60 mm² Diode dies.

4.6. Comparison of DUT switching losses

The total switching energies, comprising turn-on (Eon), turn-off (Eoff), and rectifier turn-off (Erec) losses, are compared in Figure 10 for all three devices under test (DUTs) from Section 3.5, at both room temperature and 175°C junction temperature. The IGBT power module exhibits a steep rise in switching losses at low currents for both temperatures, primarily due to the Diode recovery charge. Notably, the IGBT/Diode power module with the EDT3 chipset, introduced in 2023, has achieved a benchmark-low recovery charge for traction inverter power modules, with a more than 20% reduction in Erec compared to the previous benchmark IGBT/Diode generation from 2017 [12].

Upon analyzing the results, it may be surprising at first glance that the Si/SiC Fusion switch can support lower switching losses at low to medium temperatures compared to the SiC MOSFET. However, this is mainly due to the intrinsic damping effect provided by the IGBT/Diode combination, which avoids excessive voltage overshoots. As a result, the Fusion switch can be switched extremely fast without leading to high overvoltage spikes. This effect is particularly beneficial for high volume applications where DC-link capacitors are designed with a focus on part and integration cost, rather than ultra-high performance.

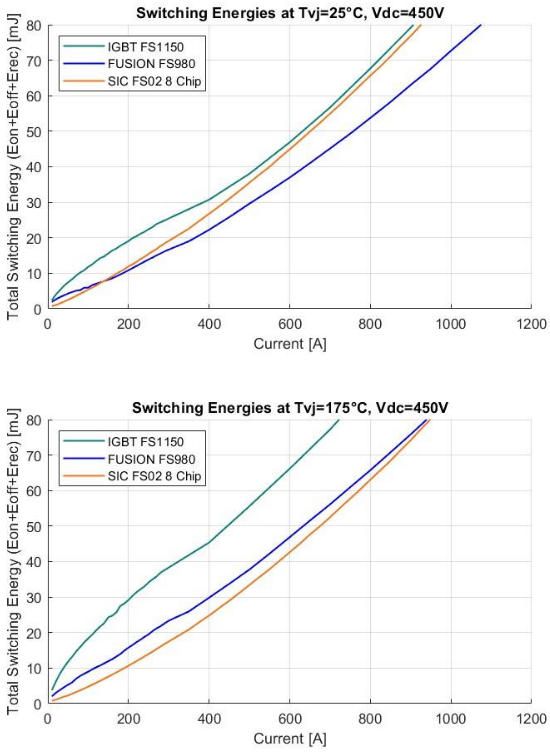

Figure 11 Extract of the measured 3D switching energy lookup tables for direct comparison of IGBT, SiC MOSFET and Fusion power module.

5. Benchmarking Results

A drive cycle efficiency study was conducted using the simulation approach and data from the previous chapter. The total energy consumption of the IGBT power module solution served as the baseline value. The resulting driving range gain of the Si/SiC Fusion and SiC MOSFET power module solutions is shown relative to the IGBT as baseline value. A value of +5%

indicates that, with the same car, driving profile, and battery size, the car can be driven 5% longer in distance.

5.1. Drive Cycle Range Gain

As shown in Figure 12, the SiC power module solutions offer significant driving range gains of 5% to nearly 9%, depending on the driving profile. Profiles with lower average power demand, such as skipping the high-speed area of the WLTP (i.e., WLTP low&mid), or the relaxed CLTC profile, result in higher range gains. When comparing the SiC and Fusion solutions, it is clear that the difference between them decreases as driving profiles become harsher or when road characteristics require limiting recuperation on rear electric drive to prevent tire slipping and critical driving situations (e.g., on wet or slippery roads). This situation was studied with limitation of the deacceleration torque at the WLTP cycle. The Si/SiC Fusion solution consistently achieves remarkable range gains, significantly higher than the IGBT solution, and often approaches nearly the efficiency of a full SiC MOSFET solution in many situations.

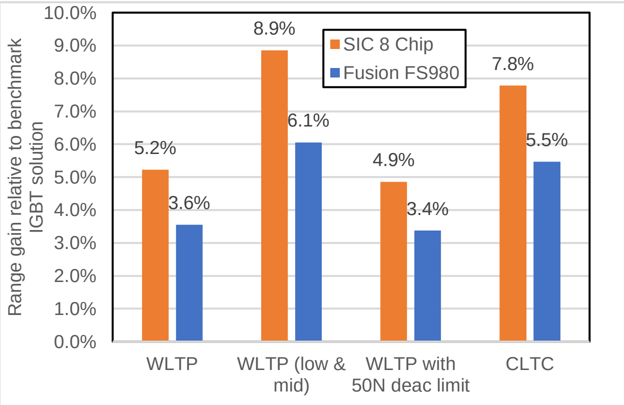

Figure 12 Drive cycle range gain of Fusion and SiC power module relative to IGBT power module at different driving profiles.

5.2. Variation of vehicle drag coefficient

In a subsequent study, the vehicle drag coefficient was varied to simulate the effects of less optimized vehicle shapes and the impact of external accessories such as roof racks or bike racks (i.e. a real-world vehicle operation where EV driving range is critically lower). The results are shown in Figure 13. As vehicle drag resistance increases, the range gain of both SiC power modules and Fusion switch power modules decreases relative to IGBT power modules, causing all solutions to converge slightly. Although vehicle drag resistance has a significant impact on the total driving range, the relative difference between the different power module solutions is limited to approximately 1%. This is because the drag coefficient primarily affects the required inverter currents during high-speed operation, which has a relatively short duration in standardized drive cycles. In contrast, the influence of this parameter is negligible at low speeds.

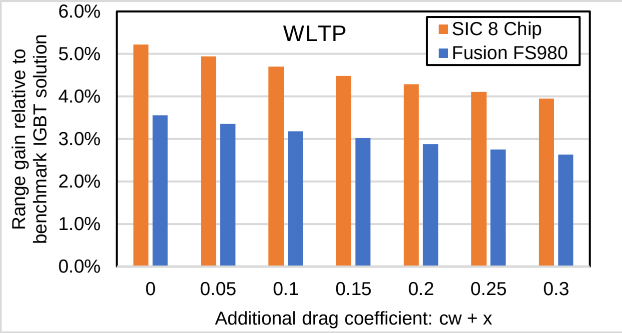

Figure 13 Drive cycle range gain of Fusion and SiC power module relative to IGBT power module at the WLTP drive cycle with variation on the vehicle drag coefficient.

5.3. Variation of drive “hill-up” slope

A further real-world driving scenario that highlights the importance of driving range was investigated by adding a hill-up slope. To ensure simplicity and reproducibility, a constant slope was applied to the standardized drive cycle. The results for the WLTP are presented in Figure 14, where only the low and mid sections (see Figure 2) were driven. The hill-up slope affects the required phase currents across all driving conditions, both low and high speed. Notably, even a relatively gentle slope of 1-2% significantly reduces the relative range gains of the three power module types by up to 3.5%. This finding suggests that cost-balanced solutions, such as Si/SiC Fusion power modules, can offer a good compromise between achieving high range gains in standardized drive cycles and delivering substantial savings in real-world driving scenarios where driving range is critical for end-users.

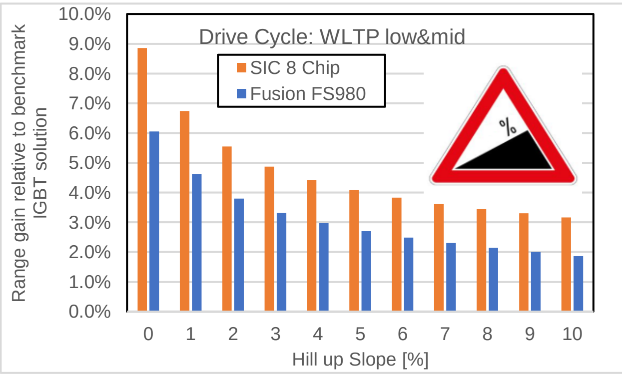

Figure 14 Drive cycle range gain of Fusion and SiC power module relative to IGBT power module at the WLTP low&mid drive cycle with the modification that the car is driven up a constant slope.

6. Cost Effectiveness

The cost-effectiveness of the three types of power modules at the vehicle level was assessed in two scenarios. In the first scenario, representing up to the next three years, a battery cost of 60 € per kWh was assumed [13]. The chip cost was based on current 300 mm (12 inch) silicon wafer fabrication and modern 200 mm (8 inch) silicon carbide MOSFET fabrication. The results showed that the IGBT power module solution was the most cost-effective for EREVs with batteries smaller than 10 kWh. In contrast, SiC MOSFET power modules offered the best tradeoff for EREVs with batteries larger than 40 kWh. The Fusion power module solution was optimal for batteries between 10 and 40 kWh.

In the second scenario, representing the 5 to 8-year future time frame, a battery cost of approximately 40 € per kWh was assumed. An optimistic scenario for SiC MOSFET cost reduction was also considered, with a cost decline three times faster than that of silicon chips. In this mid-term future scenario, the Fusion power module solution still offered the best system cost tradeoff for EREV batteries between 5 and 35 kWh capacity.

It is essential to note that different vehicle sizes, mission profiles, and cost assumptions can lead to varying results. However, both scenarios clearly demonstrate that Si/SiC Fusion power modules can provide significant advantages in EREV vehicle efficiency at a low system cost.

7. Summary and Conclusion

For Extended-Range Electric Vehicle (EREV) applications, the charge depletion mode is the most critical operating mode in terms of energy efficiency and electric driving range. The Si/SiC Fusion power module approach offers a compelling solution by combining a reduced SiC MOSFET die area for common light load operations with lower-cost Si IGBT/Diode die content to handle short-term vehicle acceleration and deceleration events. This Fusion approach achieves high efficiency, resulting in increased electric drive ranges of approximately 3 to 6%, depending on the driving profiles.

Notably, the control complexity of the Si/SiC Fusion power module is comparable to that of conventional full SiC MOSFET or IGBT/Diode power modules, thanks to the simultaneous single gate drive capability of Si/SiC Fusion switches. Furthermore, for EREVs with battery capacities between 10 and 40 kWh and relatively light vehicle masses, the Si/SiC Fusion switch offers the best system cost tradeoff. This advantage is expected to persist for at least 8 years, even in scenarios with rapidly declining SiC MOSFET chip costs and decreasing battery costs.

Future research may include investigating range gains and cost tradeoffs for different vehicle types and sizes beyond the EREV architecture and combination with different machine types.

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