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The application of electro-mechanical motors in rigorous, high-temperature systems is constantly adapting to suit the growing needs of developers in the automotive, construction, and aerospace industries. With improved efficiency, torque, and environmental impact over conventional internal combustion engines, electric drive trains pose more than ample incentive for manufacturers to invest considerable resources toward the design of newer, better methods of electric propulsion. This paper discusses the motives behind the electrification of heavy-duty vehicles, the state-of-the-art technology currently available on the market, and the novel application of silicon carbide to electric drive trains as a means of increasing their heat tolerance, decreasing package size, and increasing efficiency.

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I. Incentives for Electrifying Heavy-Duty Machinery

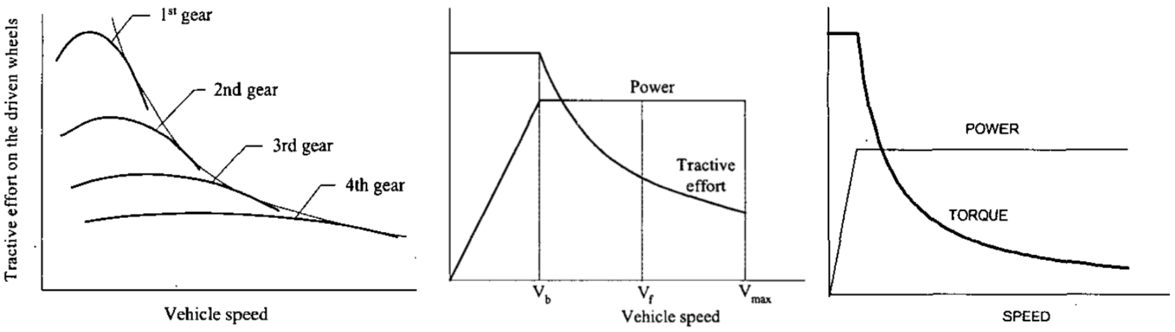
The electrification of heavy-duty commercial machinery such as city transit buses, tractors, and construction vehicles has resulted in better performance and fuel savings compared to purely mechanical drive systems in recent years, but further research and development of heavy-duty and ruggedized electric drivetrains is necessary to meet the increasing demand for broader operating temperatures, reduced maintenance, and improved cost-efficiency in these systems. Advanced control methods have contributed to this initiative by increasing the versatility of existing motor and drive configurations, and silicon carbide power devices are enabling more functionality in high-power applications by reducing cooling requirements, system weight, and volume at higher inverter power densities. An overview of the advantages of electric drivetrains in traction applications is presented in this paper followed by a review of recent literature on and analyses of the growing potential of wide band gap based power semiconductor devices to provide improved switching speeds and temperature tolerance to heavy-duty electric traction drives.

A. Advantages of Electric Drivetrains over Mechanical Drives

A conventional vehicle powertrain typically utilizes an internal combustion engine to drive an electric generator which powers the mechanism for vehicle propulsion whereas a powertrain for an all-electric vehicle uses a system of electric machines and power converters to accomplish this task. While electric drives have been applied to specialized high-power vehicles for many years, they have become increasingly cost-effective for high volume manufacturing due to new technology that increases their efficiency, reduces their size, and allows for better control. As explained by Singh et al. [17], electric drives have overtaken internal combustion engines in efficiency, energy recovery, performance, and productivity. Hybrid and all-electric drives also consume less fuel and generate fewer greenhouse gas emissions – or none in the case of all-electric vehicles – which has resulted in economic and policy incentives for vehicle manufacturers to produce more electric and hybrid powertrains.

B. Torque Characteristics of Traction Drive Systems

Drivetrains for electric vehicles may be configured very differently depending on the desired operating performance which can be largely described by the relationship between vehicle speed and tractive effort – or torque as the two are proportional. The ideal characteristics of a traction drive are high torque at low speeds – for optimal acceleration and gradeability – and low torque at high speeds for flat terrain cruising, resulting in a constant power profile. Heavy-duty vehicles require higher peak (starting) torque at low speeds and higher power over a wider speed range than lightweight vehicles in order to meet startup conditions and handle long duration operation at peak power as is necessary when traversing large slopes or highway driving at constant maximum speed [10]. This is true for both electric and mechanical drive systems, though electric drivetrains are better suited to these characteristics. A comparison of the speed-tractive effort profiles of vehicles powered by internal combustion engines and electric motors is shown in Figure 1 alongside an ideal constant power profile. Internal combustion engines can use multiple gears to approximate constant power profiles but demonstrate significantly decreased efficiency in applications with frequent starts and stops as a direct result of this multi-gear system [6]. Electric traction drive systems can achieve a smooth constant power profile without employing



(a) (b) (c)

Figure 1 - Torque-Speed Curves in Constant Power Region for Internal Combustion Engine (a) and Electric Motor (b) Driven Vehicles vs the Ideal Constant Power Profile (c) [6]

multiple gear transmissions and afford excellent speed control. Induction, permanent magnet, and switched reluctance motors are widely cited as typical candidates for electric drive systems due to their favorable torque-speed profiles. Permanent magnet synchronous motors and switched reluctance motors are generally recognized as higher-efficiency alternatives to induction motors and are evaluated further in the following chapter.

II. Electric Drivetrains for Heavy-Duty Vehicles

In the past, electric and hybrid electric vehicles have been passed over in high-volume manufacturing due to poor cost-efficiency. To be competitive in today's market, they must have cost-effective motor drives with maintenance-free operation and achieve high efficiency, power density, torque density, controllability, reliability, and robustness at a wide range of operating speeds [1]. These standards are rigid, but the multiple inverters and machines that compose electric powertrains can be optimized for specific combinations of torque, speed, and work cycle specifications to suit different environments and applications [17]. The range of speeds supported within a motor's constant power operating region and the starting torque of a driver system are particularly important considerations when determining the best configuration for traction applications. A wide speed range at constant power affords higher maximum speeds on low-gradient terrain, and a high starting torque allows for enhanced starting acceleration and gradeability – a key feature for off-road vehicles that must be able to handle obstacle negotiation at low speeds [6]. Switched reluctance motors and permanent magnet synchronous motors are two common motor configurations suited to heavy-duty electric machinery and can take on many structures to meet optimal system requirements.

A. Permanent Magnet Synchronous Motors

Permanent magnet motors are currently the more common type used in electric and hybrid electric vehicles. Unlike other synchronous motor topologies, permanent magnet synchronous motors (PMSM) operate on an ac supply and utilize rare-earth permanent magnets in their rotors instead of using an additional dc supply for field excitation [2]. The

PMSM is favorable for its wide range of constant power operating speeds, high efficiency, and increased output power due to the elimination of electromagnetic excitation losses [5]. Table 1 shows typical torque densities for permanent magnet motors and two other competing configurations, and from this comparison, it is clear that PM motors have a significant advantage in this category as well [6]. The high efficiency characteristics of these motors and their enhanced magnetic flux density afford them significantly reduced packages [15]. However, the PMSM does not fare well in cost-efficiency due to the same rare-earth metals that contribute its significant advantages over other motor types. Switched reluctance motors are far more cost competitive and may overtake permanent magnet motors as new control methods mitigate their shortcomings.

Table 1 – Torque Density Comparison [6]

Machine Type	Torque Density (Nm/m^3)	Torque-Copper Ratio (Nm/kg Cu)
Permanent Magnet (PM)	28860	28.7-48
Induction (IM)	4170	6.6
Switched Reluctance (SR)	6780	6.1

B. Switched Reluctance Motors

The switched reluctance motor (SRM), though not as torque dense as the PMSM, is already utilized in numerous industrial applications and widely anticipated to become the motor of choice for the majority of electric vehicle applications in the near future. The SRM topology is characterized by a rotor made of soft magnetic material that is solely stimulated by the motor's energized stator windings. The SRM utilizes three-phase ac power but lacks the slip suffered by similar inductance motors. A control system switches power to the stator windings to lead the rotor pole into alignment with the energized stator pole, using the inherent reduction of magnetic reluctance as a mechanism to incite torque. Switched reluctance motors are valued for the simplicity they achieve by introducing power to the stationary stator instead of the rotor. The SRM also has better flux controllability than permanent magnet motors and does not incur the material expense of the magnets themselves [1].

The disadvantages of the SRM lie in their power density, torque ripple, and efficiency compared to permanent magnet synchronous motors. The nonlinearity of the SRM mechanism causes significantly more torque ripple than permanent magnet motors which has limited the versatility of this topology in the past [18]. However, the disadvantage of lower torque density and increased torque rippling can be mitigated in double-stator designs and mechanical-offset structures in the rotor as well as in the control system [1]. Table 2 shows a comparison of PMSM and SRM in which their key attributes were scored according to their impact on the motors' suitability for high-volume manufacturing [14]. Higher numbers indicate a favorable contribution and lower numbers indicate less advantageous factors in this context. The switched reluctance motor has less favorable power density, speed range, noise, torque ripple, and size compared to the PMSM but finishes ahead of the permanent magnet synchronous motor by over ten points according to this analysis. Pindoriya et al. [14] determined that the SRM was preferable mainly due to its improved ruggedness and cost-efficiency but also acknowledged that it has the potential for greater overload, control, and maintenance characteristics over competing topologies.

Table 2 – Comparative Analysis of Electric Motor Qualities [14]

Quality	PMSM	SRM
Power Density	10	8
Overload	7	8
High Speed Range	10	8
Control	15	16
Noise	8	6
Torque Ripple	8	5
Size and Weight	9	7
Ruggedness	12	18
Maintenance	8	9
Manufacturing	12	18
Cost	18	26
Total	135	146

C. High-Power Traction Inverters

Inverter design is another integral component of the electric traction drive. The schematic in Figure 2 shows a typical inverter configuration for electric vehicles broken into functional blocks, though this system can vary widely in practice [16]. The inverter converts power from a dc energy source to ac current and voltage that drive the motor by alternating the direction of the current in the primary winding with power semiconductor devices. These power devices are determined by the required voltage rating, current rating, switching frequency, and efficiency for a system [3]. Silicon based MOSFETs are a reasonable choice for these components due to the high switching speeds of which they are capable, but

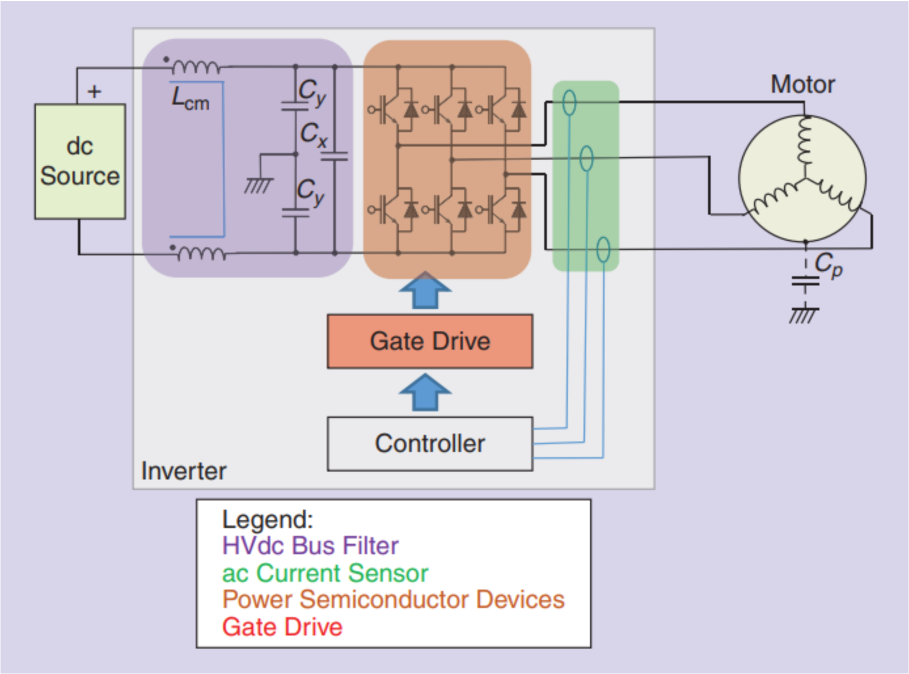


Figure 2 – Block Diagram for a Typical Traction Inverter [16]

they also suffer from high conduction losses, and this limits their usefulness in voltage classes above 600 V. The silicon based IGBT included in the gate driver section of Figure 2 provides a better alternative for higher voltage applications due to its improved conduction performance over Si MOSFETs, but it too has limitations, specifically regarding the switching speeds it can accommodate [8]. High switching frequencies are necessary to reduce acoustic noise, but increasing switching rates also increases switching loss, so sacrifices must be made in one area or another when choosing between Si MOSFETs or Si IGBTs for an inverter system [3]. These restrictions have opened the door for wide band gap semiconductor devices like silicon carbide based MOSFETs to advance drivetrain design in many ways.

For example, consider the cooling systems essential to silicon-based inverter operation. High-power inverters for heavy-duty vehicles must withstand large temperature cycles during on-time due to the general increase in starting and stopping maneuvers as well as a potentially large range of ambient temperatures during off-time storage [11]. Environmental stresses like temperature and vibrations also differ based on the inverter's location in the vehicle and the operating climate, and these in turn inform component selection and the overall energy density of the inverter and drivetrain design. Most high-power inverters for vehicle applications utilize liquid cooling systems to compensate for the heat inherent to switching and conduction losses or environmental factors and to protect the components, but the more energy dense the drivetrain is, the more advanced the cooling systems must be to provide adequate temperature regulation without adding too much bulk to the design [17][16]. Wide band gap based power semiconductor devices allow for higher operating temperatures and consequently, simpler cooling systems. These are just some of the reasons why silicon carbide based MOSFETs are an advantageous component choice in high-power traction inverters for heavy-duty and off-highway vehicles. These machines are subject to high reliability and performance standards under harsh operating conditions, and silicon carbide is making it possible to improve these characteristics.

III. Characteristics of SiC Based Semiconductor Power Devices

Because they are continually taxed to provide maximum bidirectional start-up torque, heavy-duty and off-highway vehicles must be robust and reliable with suitable energy density and temperature management. High-power electric drives are capable of providing the torque and dynamic responses vital to heavy-duty vehicles, and wide band gap devices with band gaps larger than 1 eV, especially those based on silicon carbide, have shown the potential to deliver the high voltage, low loss characteristics essential to effective high-power traction inverters [4]. Table 3 shows a comparison of the properties of silicon and silicon carbide which is most typically applied as 4H-SiC for electric traction drives [13]. Silicon carbide MOSFETs are an especially promising alternative to the silicon based IGBT due to the MOSFET's allowance for bidirectional current compared to the IGBT's limitation to unidirectional current flow [16]. The SiC MOSFET also affords higher switching frequencies, improved junction temperature tolerance, a thermal conductivity three times higher than Si devices, and higher operating voltages [17].

Table 3 – Properties of Si and SiC [13]

Property	**Si**	**4H-SiC**	**6H-SiC**
Band gap (eV)	1.10	3.30	3.00
Critical Field (MV/cm)	0.25	2.20	2.50
Electron Saturation Velocity (10^7 V/cm)	1.00	2.00	2.00
Electron Mobility (cm^2/Vs)	1350	947	380
Hole Mobility (cm^2/Vs)	480	120	80
Dielectric Constant	11.80	9.70	9.70
Thermal Conductivity (W/cmK)	1.50	5.00	5.00
Melting Point (˚C)	1420	2830	2830

A. Higher Switching Frequencies

As seen in Table 3, silicon carbide has a higher breakdown or critical field than silicon, the result of which is that SiC devices are capable of much higher switching frequencies than Si devices [7]. This has the consequent benefit of extending the lifetime of some passive components due to reduced series resistance in the inverter at higher frequencies [17]. Especially for systems above 750 V, inverter efficiency can be improved by the smaller dead times, increased dc bus voltage, lower switching and conduction losses, and reduced power temperature cycling of silicon carbide MOSFETs compared to IGBTs [16]. The reduction of switching losses and current harmonics due to improved power quality is also a great advantage attributed to SiC devices because this in turn results in little or no iron losses in the motor at higher switching frequencies, a feat difficult to achieve in high-power silicon inverters [17].

B. Improved Thermal Management

Thermal management for SiC inverters is much simpler as well. Due to its higher thermal conductivity, SiC is better suited to transient loading – where peak load is applied with near-zero speed – because it allows for less stress on the inverter than a similar silicon device. This means that the junction temperature does not rise as much as in a Si IGBT, and thermal management is less strenuous. Additionally, the specific power rating of SiC is more favorable than Si, and this increases the thermal margin of the power device. By emitting the heavy, complex cooling system applied to Si inverters, the weight of the system can be reduced from a comparable IGBT design, even more so if the switching frequency is above 20 kHz since the size of the passive components can then be reduced as well. In some cases, the cooling unit may be replaced by the engine coolant loop to achieve even more compact systems [17].

C. Higher Operating Voltage

The higher dc bus voltage attained by SiC devices allows for electric drivetrains with a higher base speed and thus energy density. Not only does this afford better scalability in high-power applications, but it also grants wider constant power and constant torque regions which are, as explained in the previous chapter, advantageous for traction drive applications. Figure 3 displays a graphical comparison of the material properties of Si and SiC that influence their operating voltage, frequency, and temperature, and SiC is shown to surpass Si in all of these areas [19]. Overall, SiC drivetrains are extremely efficient and afford all the same environmental benefits of the silicon based electric drivetrains discussed previously [17]. The next chapter will discuss the results of several studies of specific SiC applications to gain a practical perspective of the current status of this technology.

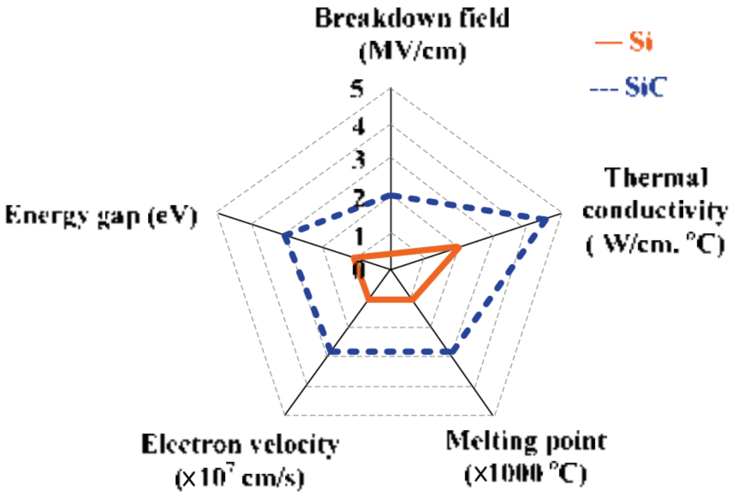


Figure 3 – Graphical comparison of Si and SiC Material Properties [19]

IV. Performance Review of Three SiC Drivetrain Systems

Silicon carbide MOSFETs have great potential to improve power electronics at the converter level through simple substitution of Si devices or through simplified inverter designs [19]. The results of three studies concerning the performance of specialized SiC based drives will be discussed according to the observed effect of SiC MOSFETs on the efficiency, thermal management, size, and high-power capabilities of the drives.

A. Comparing SiC MOSFET and Si IGBT Performance in a 60-kW Motor Drive

In a study conducted by Zhao et al. [20], the performance of 4H-SiC MOSFETs and Si IGBTs were compared for a 60-kW motor drive application. The inverters were controlled with sinusoidal pulse width modulation and evaluated according to system efficiencies, temperatures, size, and weight. It was found that the SiC inverter experienced one third of the power loss exhibited by the Si inverter, and that the SiC system had significant advantages both when the two motor drives utilized the same heatsink and when they were designed for the same junction temperature. For systems using the same heatsink, the efficiency of the SiC MOSFET lead the IGBT efficiency by 2%, had a smaller package size, and reached a junction temperature 23˚C less than the IGBT junction temperature as seen in Table 4. For inverters designed for 92˚C junction temperatures, the weight of the SiC system's heat sink was 35% the weight of the Si system's heatsink as seen in Table 5.

Table 4 – Si IGBT and SiC MOSFET Performance with Identical Heatsink [20]

	Si IGBT	**SiC MOSFET**
Power Loss Per Device	300 W	97 W
Efficiency	97.1%	99.1%
Package Size	65 cm^2	17 cm^2
Junction Temperature	92 °C	69 °C

Table 5 – Si IGBT and SiC MOSFET Performance with 92 °C Junction Temperature [20]

	Si IGBT	**SiC MOSFET**
Power Loss Per Device	300 W	97 W
Efficiency	97.1%	99.1%
Package Size	65 cm^2	17 cm^2
Heatsink Size	500W*200D*80H (mm)	290W*120D*80H (mm)
Heatsink Weight	7.8 kg	2.73 kg

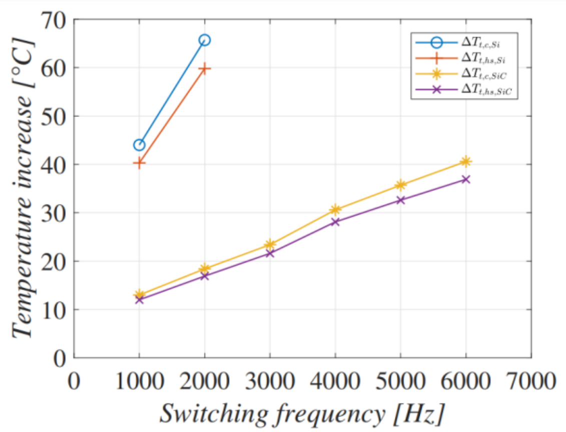
Table 6 – Loss Comparison for Si IGBT and SiC MOSFET Motor Drive Inverters [20]

F = 10 kHz	**Si IGBT**	**SiC MOSFET**
Conduction Loss Per Device	114 W (IGBT), 20W (Diode)	36 W (MOSFET), 25 W (Diode)
Switching Loss Per Device	164 W	36 W
Inverter Total Loss	1789 W	584 W
Output Power	61.2 kW	61.2 kW
Efficiency	97.1%	99.1%

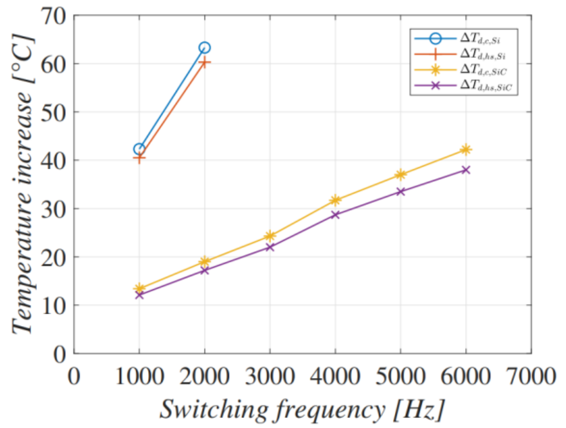
It was also found that the output power of the SiC MOSFET inverter was 187% the output power of the Si inverter when utilizing identical heatsinks and 135% when operating at the same junction temperature. The results of the loss analysis may be seen in Table 6. Zhao et al. ultimately found that SiC devices have smaller loss characteristics, better efficiency, and more compact packages that equivalent Si inverters for motor drive applications [20].

B. Reliability of a SiC MOSFET Traction Inverter in a Metro System

In a study conducted by Lindahl et al. [9], the reliability of a silicon carbide traction inverter designed for a metro system in Stockholm, Sweden was evaluated over a three-month operating period. The inverter was designed for volume and weight reductions of 51% and 22% respectively from the comparable Si IGBT inverter with an anticipated decrease in conduction and switching losses as presented in Figure 4.



(a) Transistor



(b) Diode

Figure 4 – Predicted Power Losses under Laboratory Conditions [9]

The metro system was tested with passengers under the same driving conditions as the previous Si IGBT system. It operated at a switching frequency of 1 kHz with speeds between 0 and 70 km/h, storage temperatures around 20˚C, and maximum heat sink temperature of 16˚C during daily operation. According to Lindahl et al., the inverter performed exactly as expected over the course of the three-month field test, demonstrating the energy efficiency, low maintenance, and lower noise expected of reliable traction inverters in railway transportation applications [9].

C. Performance and Reliability Analysis of SiC MOSFETs for a Specified Flight Mission Profile

In a study conducted by O'Donnell et al. [12], the performance of SiC MOSFETs was evaluated in a 5 kVA aviation power module and compared to the reliability achieved by Si IGBT modules. The aforementioned MOSFETs were rated for 1200 V with a 540 V dc bus and were tested according to a mission profile including typical ground operation, taxiing, take-off, cruising, landing, and off mode. The power module underwent an accelerated mission life-test in which the pressure and ambient temperature were varied to simulate flight at an altitude of 45,000 feet. The results of these tests showed improved power density and efficiency in the SiC MOSFET power module over a comparable Si IGBT driver in addition to confirming the viability of the SiC design under maximum stress climb and descent maneuvers [12].

V. Summary and Conclusions

In chapter one, the advantages of electric drivetrains were discussed in context of their high-power applications in heavy-duty vehicles, and the ideal torque characteristics of such a system were identified. Chapter two highlighted the structures of leading drivetrain topologies, including permanent magnet synchronous motors, switched reluctance motors, and common design traits of the high-power traction inverter. The torque density, efficiency, and design constraints were compared for permanent magnet and switched reluctance motors to provide an overview of current drivetrain development incentives. Chapter three presented the potential impact of wide band gap power devices and especially silicon carbide MOSFETs in high voltage and high-power inverters such as those utilized in heavy-duty machinery. Specifically, silicon carbide allows for higher operating voltages, frequencies, and temperatures with lower power loss than silicon based alternatives. Chapter four inspected three studies on silicon carbide MOSFET applications and their implications. The results of these studies were discussed to demonstrate the current feasibility and robustness of silicon carbide based inverters and drivetrains for heavy-duty vehicles. The first study was a comparison of SiC MOSFETs and Si IGBTs in a 60-kW motor driver which determined that the SiC based design was more compact and efficient than the comparable Si based design. The second study addressed the reliability of SiC traction inverters in the railway transportation industry. A three-month field test demonstrated that SiC inverters could perform consistently and reliably in a real-life metro system with improved efficiency over the standard Si IGBT inverters that currently have the advantage of a longer operational history. The third and final study addressed was an analysis of SiC MOSFET performance in a specialized aircraft application.

While the low volume of SiC based devices lends them higher initial costs in today's market, the development of new SiC power devices has already unearthed a multitude of incentives for manufacturers to produce more SiC inverters and drivetrains for heavy-duty, high-power machinery. The three studies reviewed in chapter four demonstrate the current advantage of silicon carbide MOSFET devices over the more common silicon IGBT in electric powertrains and heavy-duty vehicles. The application of this technology to railway and aircraft systems shows initial robustness and improved efficiency and loss characteristics not achievable in high-power silicon based devices. Silicon carbide systems must undergo further analysis to determine the limits and versatility of the technology long term, but they are beginning to be commercially available and are already affording notable efficiency benefits in ruggedized high-power vehicles.

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