Applications of Wide Bandgap (WBG) Devices in AC Electric Drives: A Technology Status Review

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***Abstract*—This paper is an effort to put together all the potential applications of Wide Bandgap (WBG) devices in AC electric drives. Low inductance motors, high speed motors, and electric drives operating in a high temperature environment are the main application areas of WBG devices. Low voltage permanent magnet motors and slotless motors have a low inductance and require a stringent high-bandwidth current regulation strategy to obtain an acceptable current ripple. Silicon (Si) devices cannot be used in this case due to their limited switching frequency. MW-level high speed motors have devices operating at high voltage and current levels and a high fundamental frequency (600-1200 Hz) that cause very high switching losses in Si IGBT devices. SiC devices have enabled the use of power electronic converters for MW-level high speed motors. Integrated motor drives (IMDs) are also benefitted by WBG devices as they reduce the size of the power converter and allow operation at a high junction temperature. Therefore, the inverter can be mounted on the motor itself which can be a significant heat source due to motor losses. Cooling requirements in high temperature environment applications such as hybrid Electric Vehicle (EV), ground vehicles in combat zones, and power converters used in space technology like land rovers etc., are greatly reduced due to low losses and high junction temperatures. Operation at high frequencies and high temperatures reduces the size of electric drive significantly.**

***Index Terms*—electric vehicle, integrated motor drive, low inductance motors, MW level high speed motors, reliability, silicon carbide, slotless motor, wide bandgap device**

I. Introduction

Significant research has been going on in the development of Wide Bandgap (WBG) semiconductor devices [1]-[3] and their applications in power electronics [4], [5]. Heavy investments from various United States government agencies have helped bring WBG devices closer to widespread adoption. The Advanced Research Projects Agency–Energy (ARPA-E) of the United States Department of Energy (DOE) is working to improve energy efficiency and developing and deploying advanced energy technologies [6]. The CIRCUITS (Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors) program of the ARPA-E seeks to accelerate the development and deployment of a new class of efficient, lightweight, and reliable power converters based on WBG semiconductors through transformational system-level advances that enable effective operation at high switching frequency, high temperature, and low loss. Higher performance converters for motor drives for industrial, automotive, ship propulsion, aerospace, and rail applications is a major area of interest of CIRCUITS program.

Fig. 1 shows some important material properties of WBG semiconductors. Higher critical electric fields (≥ 200 V/μm) in WBG materials enable thinner, more highly doped voltage-blocking layers in the devices, which can reduce on-resistance by two orders of magnitude in majority carrier devices like MOSFETs relative to Si, which has a critical electric field of 30 V/μm. To reduce conduction losses, high-voltage Si MOSFETs have large footprints that result in high gate capacitance and significant losses at high switching frequencies. Si IGBTs have smaller die footprints than MOSFETs because they utilize minority carriers and conductivity modulation, but the long lifetime of minority carriers limits the maximum switching frequency. The switching frequency and size of passive components are inversely proportional, which results in large form factors for low frequency silicon-based power converters. As a result of high breakdown electric fields, low conduction losses, and short carrier lifetimes, WBG materials can achieve the same blocking voltage and on-resistance with a smaller footprint and operate at much higher frequency than a comparable Si device. The low intrinsic carrier concentration of WBG materials (≤ $\sim 10^{-9}/cm^3$) enables robust high-temperature performance due to low leakage currents at high temperatures.

Silicon Carbide (SiC) and Gallium Nitride (GaN) are two prominent WBG materials for power devices. GaN is suitable for low-voltage, less than 600 V, whereas SiC is suitable for higher voltage. Gen5 GaN chips from Efficient Power Conversion (EPC) corporation, a leading GaN manufacturer,

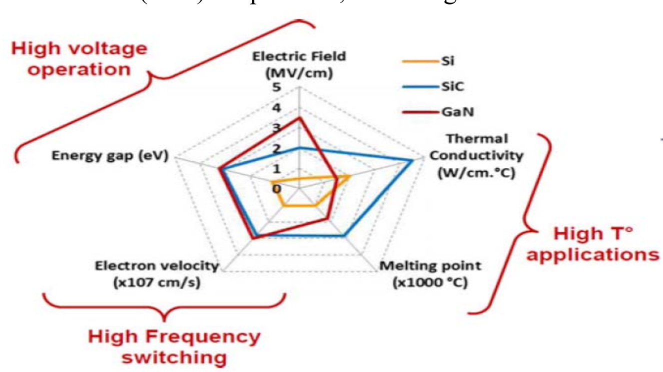

Fig. 1. Properties of wide band gap materials [7]

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are about 15 time smaller than Si MOSFET chips of similar rating. The Gen5 100 V and 200 V GaN devices offer better performance and cost over the best equivalent Si MOSFETs [8]. SiC devices are available up to 50 kV [9]. Simulation results indicate that the SiC MOSFET has the highest current capability up to approximately 15 kV, while the SiC IGBT is suitable in the range of 15 kV to 35 kV, and the SiC Gate Turn Off (GTO) thyristor has best loss performance from 35 kV to 50 kV. Due to continued advancements in SiC substrate quality, epitaxial growth capabilities, and device processing, the maturity of SiC MOSFETs is growing, and these devices are becoming very promising candidates to replace Si IGBTs in high voltage applications. Device design and processing improvements have resulted in lower specific on-resistance for each successive device generation. Enhancement-mode GaN (eGaN) Field Effect Transistors (FETs) deliver the performance of GaN at the price of Si and can replace Si in applications where voltage is less than 600 V [10]. Figure of merit (FOM) is defined as the product of on-state resistance ($R_{DS(on)}$) and gate charge (Q_g) for a switch. Lower Figure of merit means better performance. Fig. 2 shows the comparison of FOM of GaN with Si in low voltage range. GaN devices have much better FOM. Therefore, industry is moving quickly toward replacing Si with GaN in different power electronics applications. GaN transistors offer very good electrical and radiation performance that establish a new state of the art for space applications [12]. These devices demonstrate readiness for use in the most stringent radiation environments and far exceed the capabilities of Si power MOSFETs.

The characterization of switching loss, turn-on and turn-off times, and static characteristics, such as forward conduction and transfer characteristics, of WBG devices is widely available in literature [13]-[17]. Various design considerations of Voltage Source Converter (VSC) for WBG devices like gate drive design, bus-bar packaging, and thermal management have been elaborated [14]. In [18], switching performance and inverter losses of SiC MOSFET and Si IGBT have been compared for a three phase motor drive inverter. The analysis shows that SiC outperforms Si IGBT over all switching frequency ranges. At higher frequency and temperature, the advantages of SiC are more pronounced.

Low inductance motors require a high-bandwidth, high-frequency current regulation strategy to obtain an acceptable current ripple which is typically lower than 5% for many applications [19]. Current ripple is undesirable because it wastes energy in the motor windings and may cause unwanted pulsations in the torque. Surface Mount Permanent Magnet (SMPM) motors have a low inductance due to their long effective air gap. The use of a slotless stator in SMPM motors further reduces the inductance, sometimes to less than 100 µH [20]. For low inductance motors rated at a few kilowatts, Si MOSFETs are used because they can provide the desired current ripple by switching at up to 50 kHz. However, at power levels higher than a few kilowatts, the switching frequency of an IGBT is limited to 20 kHz [20]-[22] which

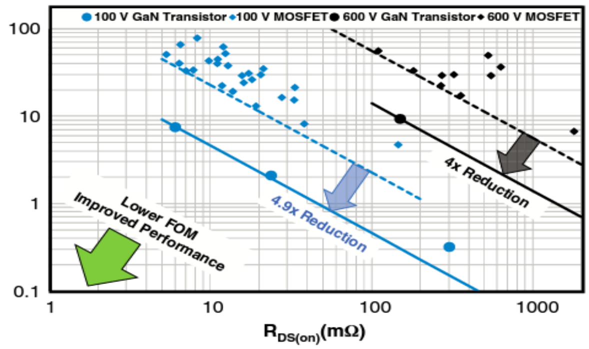

Fig. 2. On-resistance vs. total gate charge comparison for Si- and GaN-based power devices [11]

fails to meet the current regulation demand of low inductance motors. SiC converters can operate at high switching frequencies at medium and high power levels and hence can meet current regulation demand of low inductance motors. For low voltage applications, GaN can be used at high frequency.

Along with the recent technological advances in motors, SiC devices are enabling the next generation of high-speed, direct-drive Medium-Voltage (MV) drives for MW class motors in a wide variety of critical energy applications [23]. The primary applications are petroleum refining industries, natural gas infrastructure, and other industrial applications [24]. According to a US Department of Energy (DOE) study, it is estimated that currently only 6% of MW class motors are equipped with medium voltage (> 2 kV) Variable Speed Drives (VSDs) [25]. Low adoption of VSDs in the MV and high power range is due to the large footprint, low switching frequency capability, and high losses of today's Si power electronic VSDs. These limitations can be overcome by using SiC devices that offer a higher switching frequency with lower switching losses and smaller footprint than Si devices. The demand for high-speed motors in drilling, milling, grinding, and machining applications, turbo compressors and flywheels is increasing. The speed of motors is approaching 1 million rpm in some applications [26]. WBG based converters will have lower losses at the high switching frequencies required for these motors when compared to Si devices. This will make the system efficient, light-weight, and compact, which is particularly important in portable applications.

Another electric drive area benefitting from WBG devices is motor drives operating in high-temperature environments, such as in hybrid electric vehicle, sub-sea and down-hole pump applications, deep earth drilling, combat electric vehicles, space crafts, and NASA probe and landers for space exploration [27]-[29].

II. Low Inductance Motors

As high frequency switches and PWM drivers become more prevalent, adoption of low inductance motors is increasing because high frequency PWM can maintain a stable current control even with low inductances. Low inductance motors may require a PWM frequency of 50-100 kHz to keep current ripple within the acceptable limits [30]. In super-high speed PM motors, the air gap is intentionally made large to reduce the flux harmonics caused by stator slots. Therefore, the resultant iron loss in the stator is significantly decreased [31].

A. Slotless Motors

The good dynamic performance and absence of cogging torque, which is an unwanted characteristic especially in low-speed motor applications (less than 500 rpm), are the most important advantages of a slotless stator. Slotless motors can produce torque more linearly related to the stator current because there is no iron saturation in stator teeth.

A typical diagram of a slotless motor is shown in Fig. 3. In a slotless motor, conductors are wound inside a cylindrical stator and are encapsulated in a high temperature epoxy resin. Utilization of high-energy PMs, such as samarium cobalt (SmCo) and neodymium iron boron (NdFeB), makes it possible to produce significant torque even with the large effective air-gap in slotless motors. In a slotted stator machine, significant rotor losses occur due to the harmonics generated by the teeth, in addition to the iron losses in the teeth. Particularly, at high speeds rotor losses are difficult to handle [33]. Slotless stator structure reduces the flux harmonics that cause rotor losses.

In recent years, there has been a worldwide interest in the gas industry with increased shale and reservoir gas exploitation, which has led to new emerging turbo compressor and turbo expander applications. In this scenario, the need for high-speed turbomachinery coupled electric motors and generators is expected to increase [34]. Reliability, direct-drive capability, and high efficiency combined with high dynamic performance requirements are important for turbomachinery. Due to these requirements, research has started in high power slotless motors for these applications [35]. A high-speed toothless toroidal winding SMPM machine enabled by SiC based converter has been presented [36]. This machine has low inductance due to large effective air gap. An SiC based converter can achieve the high fundamental frequency necessary to maintain low Total Harmonic Distortion (THD) in the current waveform with the low inductance. The 8-pole toothless toroidal winding machine supplied by an SiC inverter operating at 100 kHz switching frequency has 6.75% current THD which is just 1.48% more than the THD obtained with same machine having stator teeth. The low inductance of the toothless machine results in 9.25% higher current THD than the machine with teeth when using a Si inverter operating at 20 kHz switching frequency.

ThinGap, with its core proprietary technology of ironless composite stator, designs high performance motors [37]. These motors have low inductances ranging from 10-100 μH. ThinGap's approach is to use 125 kHz or higher frequency PWM as controllability increases drastically at high operating frequencies. ThinGap motors are available with rated power from 50 W to 550 kW. These motors are very good in applications requiring torque linearity, velocity smoothness, positioning accuracy, and a high power-to-weight ratio. All these features make ironless motors extremely suitable for industrial applications like unmanned systems, aerospace, defense, precision manufacturing, electric ground and water vehicles, and portable industrial applications. In [38], the current regulation problem in low-inductance axial flux Brushless DC (BLDC) motor drive for more electric aircraft has been discussed. In More Electric Aircraft (MEA), low-power motors of up to 30 kVA, are typically used for various flight control actuators, fans, compressors, engine fuel pumps, and electric brake system. Permanent Magnet BLDC (PMBLDC) is often the motor of choice for these applications. High-speed PMBLDC motors are compact, reliable, and efficient which is critical for MEA [39]. These motors generally have low inductance, and making them ironless further reduces the inductance. Ironless axial flux motors have potential efficiency of more than 95% over a wide torque and speed range.

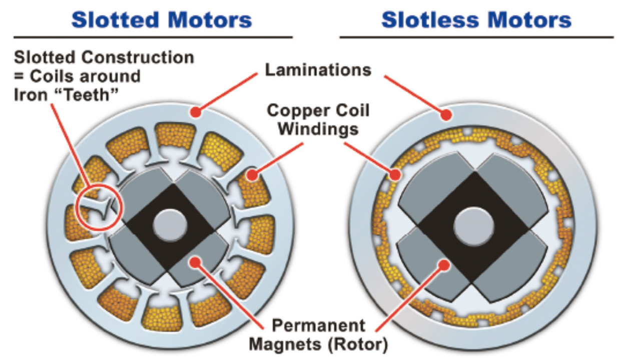

Fig. 3. Slotted and slotless motors [32].

B. Low Voltage, High speed Motors

Motors supplied with a low voltage have fewer number of turns and hence a low inductance. Traction motors used in battery or fuel cell powered vehicles are good examples of such motors. The maximum speed at which a given motor will run while providing sufficient torque is directly related to the bus voltage and the back EMF constant, K_b. In general, a low-leakage inductance induction machine design allows a constant power mode operation over a range of speeds in excess of 3 times the base speed of the machine. This is highly desirable in applications such as traction motors [19].

III. WBG DEVICES FOR HIGH SPEED MOTORS

High-speed electric machines are gaining popularity in industry due to their high power density [24]. The worldwide push for electrification of transportation systems is also fueling the advance of high-speed machine technologies. Another benefit of high speed machines in certain applications is the elimination of the intermediate gear box (direct-drives), which can improve the reliability of the system. The fundamental frequency required by high-speed machines can be multiple kilo-Hertz (kHz). Traditional high-speed machines are dominantly two-pole due to switching frequency limitation of devices. Two-pole design requires a minimum fundamental frequency excitation at a given speed, but designing high-speed machines with a larger number of poles can reduce the weight and volume. The higher switching frequency capability of WBG devices can reduce rotor losses in high speed machines with either slotted or slotless stators by reducing the asynchronous harmonics in the air gap flux, which induce eddy current losses in the rotor. Reducing the losses is important to prevent the permanent magnets on rotors of PM machines from demagnetizing due to elevated temperatures. These rotor losses can be decreased by increasing the inverter switching frequency [40], [41].

MW level (>1000 HP), high speed (10,000-20,000 rpm) motors are used in petroleum refining industries, natural gas infrastructure, and other industrial applications. Deployment of MV VSDs in these MW class motors has the potential for significant energy savings of up to 0.7% to 1.8% of total U.S. electricity consumption [25]. The Si based Variable Frequency Drive (VFD) integrated with a standard 60 Hz motor operates at 1800 or 3600 rpm while the compressor runs at 15-20 krpm. This VFD is integrated into the compressor through a gear box to increase speed. The high frequency capability of SiC MOSFET allows the motor to run at the same speed as compressor with an increased fundamental frequency [24]. For example, the speed of 18 krpm can be obtained with a 4-pole motor supplied at a 600 Hz fundamental frequency. As a rule of thumb, for a VFD to be able to synthesize this frequency, minimum switching frequency should be an order of magnitude higher than the fundamental electrical frequency. A switching frequency of at least 6 kHz will be required for 600 Hz fundamental frequency. In [42], the design and experimental results of a Medium Voltage (MV), 2 level converter based on 10 kV/10 A SiC MOSFETs have been presented. A converter efficiency of 96% was achieved at a fundamental frequency of 1 kHz and a switching frequency of 20 kHz. In [43], a SiC based high-speed electric drive has been presented for a more electric engine. The converter is able to supply a SMPM motor with currents with fundamental frequency of up to 4 kHz. Experimental results for SiC based inverters for high speed Permanent Magnet Synchronous Machines (PMSM) have been presented [44], [45]. In [44], the inverter is tested at high switching frequency up to 500 kHz. The target switching frequency for the high speed PMSM is 100 kHz in order to allow a good sinusoidal modulation of the current fundamental at 4 kHz. Integrating the SiC based MV-VSD with MW class high speed, direct-drive motors will result in significant reductions in the volume and weight of the integrated system by utilizing higher switching frequencies and junction temperatures, as well as the inherent higher voltage capabilities of WBG devices. SiC MOSFETs are available at a voltage rating of up to 15 kV [46]. Multiple chips can be paralleled inside the module to obtain a higher current capability, which depends on advanced packaging technology. General industrial applications that will benefit from MV motor drives include Electrical Submersible Pumps (ESPs), drilling and hoist motors, HVAC systems and industrial compressors, marine electrified propulsion systems, all electric underground mining vehicles, etc. High-speed machines are mainly used in electric vehicles, more electric engines, flywheel energy storage systems, high speed spindle applications, gas compressors, industrial air compressors and air blowers, etc. [24].

The performance of and need for GaN devices for high speed motor drives has been discussed, and its advantages are highlighted in [47]. In [48], performance improvement of a single phase brushless DC (BLDC) high-speed GaN based motor drive has been investigated. The authors found that the efficiency of the motor drive was improved by 4% by utilizing GaN devices. These motors are being widely used in many low-power applications such as blower motors, computer disk spindle motors, and vacuum cleaner motors. In all speed ranges, the GaN-based motor drive shows better efficiencies than the Si-based drives because of its significantly lower conduction and switching losses. In [40], performance of a GaN Gate-Injection-Transistor (GIT) and a Si IGBT has been compared for high-speed drive applications.

IV. High Temperature Application

The maximum operating temperature of a semiconductor material is determined by its bandgap. Therefore, semiconductors with a wider bandgap can operate at higher temperatures. SiC can produce devices with a practical temperature limit of 600 °C as opposed to Si with a temperature limit of 225 °C. Additionally, SiC has a higher thermal conductivity compared to Si, so SiC devices can theoretically operate at much higher power densities than Si devices. GaN transistors are capable of operating at temperatures as high as 300 °C. 300 V GaN FETs rated for 150 °C are available.

A. Integrated motor drive (IMD)

With the increased demand for high efficiency, high power density, and high-temperature capabilities in aerospace and automotive applications, IMDs offer a promising solution. The trend toward higher levels of power electronics integration is appearing in a wide variety of equipment and applications. IMDs also offer direct replacement for inefficient direct on-line motors. An IMD is the functional and structural integration of the power electronic converter and the machine into single unit, taking into consideration the electrical, structural, and thermal impacts that the two components have on each other and the system as a whole [49]. However, close physical integration of the converter and the machine results in a temperature increase in the associated power electronic components. Until recently, at power levels beyond 7.5 kW, the effect of the build-up of heat from both the machine and the drive imposed a practical limit in manufacturing higher power IMDs [50]. The motor can sustain peak temperatures around 180 ℃, but the maximum safe operation temperature for Si based power electronics was limited to 150 ℃ [51]. WBG devices with their high temperature capability make

IMDs feasible for higher power levels. Power electronics integration can be divided into three major categories, namely surface mount integration, end plate mount integration, and stator iron mount integration. The size of WBG devices is smaller than Si devices for a given voltage rating. Operation at a high frequency allows a reduction of DC link capacitor size, which further reduces the system size. The high junction temperature operation of WBG devices enables the integration of the converter with the motor as a higher junction temperature allows operation in high temperature environment with reduced cooling requirements. The European-Union funded project COSIVU's [52] objective is to develop a new system architecture for vehicle drivetrains by developing a smart, compact, and durable single-wheel drive unit integrating an electric motor, the full SiC power electronics, and an advanced ultra-compact cooling solution. The main goals of COSIVU is to increase performance, flexibility, and safety and reliability. With integrated systems, the effort for electromagnetic compatibility (EMC), the High Voltage (HV)-harness, and the cooling systems can be reduced significantly. Integrated Modular Motor Drive (IMMD) design with GaN devices is presented in [53]. The main goals are to increase performance and flexibility, as well as safety and reliability. An IMMD is shown in Fig. 4.

B. *WBG Devices for Hybrid and Fully-Electric Vehicle*

For a typical driving cycle on the Hybrid Electric Vehicle (HEV), the drivetrain is lightly loaded for a majority of the time. Therefore, the vehicle-level fuel efficiency is significantly reduced by the silicon IGBT losses. Si IGBT inverter losses consume 4~10% of the total engine output energy depending on the drive cycle. SiC MOSFETs with lower losses can greatly improve the fuel economy of HEVs [54]. In [54], it is shown that mild drive cycles like EPA-City get the most benefit from adopting SiC devices. The EPA metro-highway cycle fuel economy could be improved up to 5% by replacing Si devices with SiC MOSFETs. In 2014, Toyota, in conjunction with Denso, introduced a prototype SiC power control unit (PCU) for its Prius hybrid vehicles, demonstrating a 5% improvement in fuel economy over the standard JC08 Japanese drive cycle [55]. The Electric Drive Technologies (EDT) subprogram within the US DOE's Vehicle Technologies Office (VTO) provides support and guidance for many cutting-edge automotive technologies now under development; one of these areas is the development of inverter technologies involving advanced WBG devices. The DOE's 2020 traction inverter power density target is 13.4 kW/L and the specific power target is 14.1 kW/kg with a target cost of less than \$3.30/kW for quantities of 100,000 units while maintaining a 15-year reliability. Ambient operating temperature is from • 40 to +140 °C [56]. Fig. 5 shows the 2022 electric drive system target set by the DOE Advanced Power Electronics and Electric Motor (APEEM) R&D Program [57]. SiC modules have also been developed for power levels of up to 88 kW for automotive inverters using new 900 V SiC MOSFET technology [58], [59]. The first 650 V, 420 A enhancement-mode GaN High Electron Mobility Transistor (HEMT)-based power module for the world's most compact 55 kW all-GaN vehicle traction inverter is under development [56]. A 650 V/150 A enhancement-mode GaN-based half-bridge power module has already been developed as a part of this project [60]. Reliability and performance studies of GaN have been performed by EPC for high temperature applications [61]. In [62], the advantages and challenges of using GaN for electric vehicles have been discussed. WBG devices can operate at higher junction temperatures, which allows the use of hotter coolant and smaller heat sinks and can potentially help facilitate air cooling without sacrificing performance. SiC increases the overall efficiency of the drive system, reduces the size of passive components, such as DC link capacitors and filter components, due to its high frequency operation, and reduces thermal requirements [63]-[67].

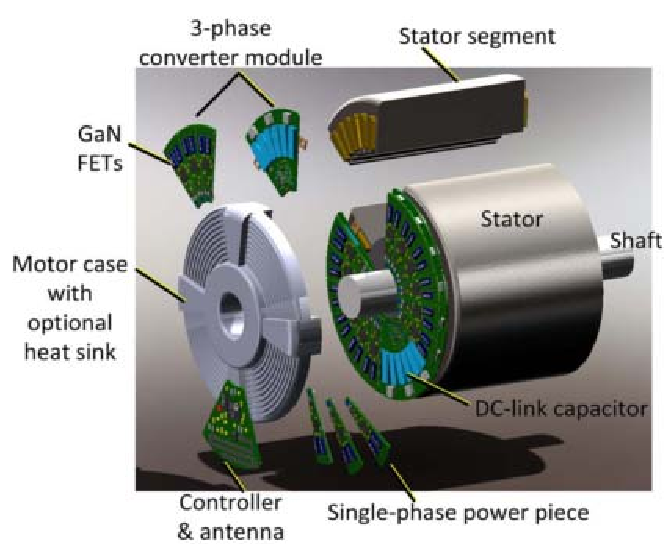

Fig. 4. Three-dimensional illustration of the Integrated Modular Motor Drive (IMMD) [53]

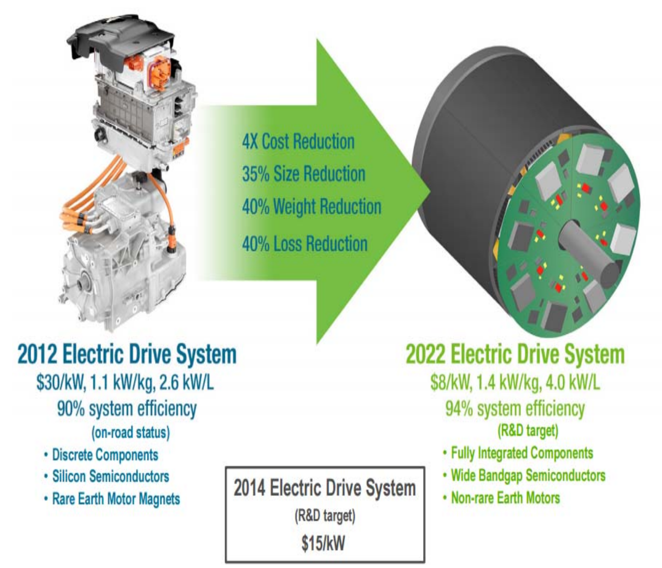

Fig. 5. US DOE 2022 electric drive system target for electric vehicle [57]

C. Reliability and Performance of SiC MOSFETs for High Temperature

The reliability and stability of SiC devices with high temperatures, thermal cycling, surge currents, and repetitive pulsed overcurrent conditions has been investigated thoroughly [68]-[73].

In [68], it has been concluded that SiC MOSFETs have a long device lifetime, based on the results of accelerated lifetime testing, such as High Temperature Reverse-Bias (HTRB) and Time-Dependent Dielectric Breakdown (TDDB). HTRB characterization is used to monitor the drain-source leakage current (I_{DSS}) through the built-in body diode of the power MOSFET. TDDB is done to test gate oxide quality. Both of these tests are performed under accelerated conditions, above the device operation specifications.

In [69], the reliability and high-performance of SiC MOSFETs rated at 1.2 kV voltage and 200 ℃ junction temperature (T_j) is investigated. These reliability assessments were performed in accordance with AEC-Q101 automotive qualification standard. The tests performed are HRTB and High Temperature Gate-Bias (HTGB). The HTGB characterization method is commonly employed to monitor the threshold voltage (V_{TH}) and on-state resistance ($R_{DS(on)}$) variations of power MOSFET devices. SiC MOSFETs display parametric stability when subjected to industry standard qualification tests such as 1000 hour/200 ℃. SiC MOSFETs also demonstrate superior performance over wide temperature ranges spanning from T_j=25 ℃ to T_j=200 ℃.

EVs frequently operate in acceleration, deceleration, and low speed driving in urban traffic. Therefore, the extreme operating conditions also must be considered in addition to the rated operation condition. In [73], the variations of the junction temperature of SiC MOSFETs and Si IGBT in an EV inverter at different operation conditions are studied using an electro-thermal coupling model. Simulation results show that the maximum junction temperatures and junction temperature fluctuations of SiC MOSFETs are much lower than that of Si IGBTs in all test conditions, as shown in Fig. 6 where the heatsink temperature was assumed constant at 40 ℃.

D. Reliability and Performance of GaN Devices for High Temperature

The stable high-temperature dynamic on-state resistance (R_{dson}) is the key to reliability of WBG power devices. With their proprietary and innovative designs, Onsemi semiconductor has developed cascode GaN power devices which shows robust performance and reliability [74].

EPC has published reliability reports covering all released products [61]. EPC's eGaN® FETs were subjected to a wide variety of stress tests: HTRB, HTGB, High Temperature Storage (HTS), in which parts are subjected to heat at the maximum rated temperature, Temperature Cycling (TC), in which parts are subjected to alternating high- and low-temperature extremes, and Intermittent Operating Life (IOL), in which parts are subjected to an on/off cyclic DC power pulse which heats the device junction to a predefined temperature and subsequently to an off state junction temperature. These tests prove reliability over a wide operating temperature range. The stability of the devices is verified with DC electrical tests after stress biasing. A combined total of over 8 million device-hours have been accumulated with zero failures. In [75], a 600 V GaN based GIT has been evaluated for high temperature and high efficiency applications. Across the full operation temperature range, the GaN-GIT's on-resistance has a positive temperature coefficient, and the threshold voltage has a small negative temperature coefficient.

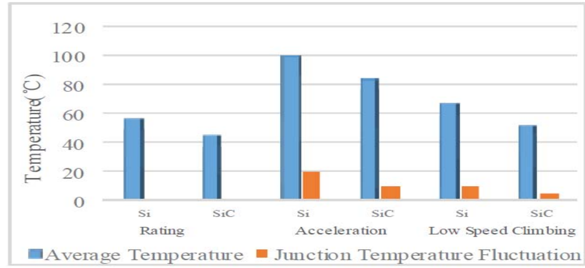

Fig. 6 .Junction temperature comparisons for Si and SiC during different driving scenarios [73]

V. CONCLUSION

The benefits of WBG devices for low inductance motors, high speed motors, and electric drives operating in high temperature environments have been explored and discussed. WBG devices are enabling technologies for emerging motor drive applications. This paper explores various electric drive applications that can benefit significantly from WBG devices in terms of power density, reliability, dynamic response, and energy efficiency. WBG device based converters have a high power density and reduced cooling requirements, which results in a compact system. GaN has reached cost parity with Si and is ready for widespread adoption in the low voltage range. On the other hand, the system level benefits and energy savings due to the high efficiency obtained using SiC devices can offset their high cost, especially in high voltage applications. WBG devices are key technologies for vehicle electrification as well and will make electric vehicles more efficient and economical in near future. Finally, WBG devices are reliable in high temperature applications.

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