

Overview of Silicon Carbide Technology: Device, Converter, System, and Application

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Abstract—This paper overviews the silicon carbide (SiC) technology. The focus is on the benefits of SiC based power electronics for converters and systems, as well as their ability in enabling new applications. The challenges and research trends on the design and application of SiC power electronics are also discussed

Index Terms—SiC power semiconductors, SiC based converters.

I. INTRODUCTION

At the heart of modern power electronics converters are power semiconductor switching devices. Today's power semiconductor devices are dominated by the mature and well established silicon (Si) technology. Since the advent of Si thyristors in 1957, many Si based switching devices have been developed to meet different application and performance needs. The most popular Si switching devices are insulated-gate bipolar transistors (IGBT) and power metal-oxide-field-effect transistors (MOSFET), with IGBT for high voltage, high power, and low frequency applications, and MOSFET for low voltage, low power and high frequency applications. Thyristors and their derivatives such as integrated-gate-commutated thyristors (IGCT) are still used in special high power applications.

Si power semiconductor devices have gone through many generations of development in the last 50 years and are approaching material theoretical limitations in terms of blocking voltage, operation temperature, and conduction and switching characteristics. Due to limited performance, the highest voltage rating of the state-of-art commercial Si IGBT has been 6.5 kV for the last 15 years. There are no commercial Si based devices with junction temperature capability above 175 °C. These intrinsic physical limits become a barrier to achieving higher performance power conversion.

The emergence of wide bandgap (WBG) semiconductor devices promises to revolutionize next-generation power

electronics converters. Compared with Si devices, WBG devices feature high breakdown electric field, low specific on-resistance, fast switching speed and high junction temperature capability. All of these characteristics are beneficial for the efficiency, power density, specific power, and/or reliability of power electronics converters. The WBG devices under rapid development and commercialization include silicon carbide (SiC) and gallium nitride (GaN) devices, with SiC mainly targeting high voltage high power (600 V, kilowatts or above) applications, and GaN for low voltage low power (600 V, kilowatts or below) applications [1]. This paper focuses on SiC technology.

SiC devices can improve and impact power electronics in several ways [2]: 1) At converter level, through substituting Si devices directly or simplifying circuit topologies, SiC devices can improve converter efficiency, reduce cooling needs, and reduce active and passive component numbers and size, with their high voltage, low loss and fast switching capabilities; 2) At system level, SiC based converters can have better dynamic performance and more system functionalities as a result of their high frequency capability and high control bandwidth enabled by fast switching speed, and 3) SiC can enable new applications, such as high-efficiency high-density solid-state transformers (SST) and high speed motor drives. A number of commercial and research prototype converters using SiC devices have been developed with promising results on significantly improved efficiency and power density [3]–[49].

The extremely fast switching and other superior characteristics of SiC devices have nonetheless also posed severe challenges to their applications. Pervasive dv/dt and di/dt slew rates of up to 100 V/ns and 10 A/ns, augmented electromagnetic interference (EMI) emissions, single-device blocking voltages as high as tens of kV with corresponding insulation requirements, switching frequencies in the 100s of kHz range, and junction temperatures surpassing 200 °C, have called for a comprehensive reformulation of design procedures developed for Si-based power electronics. Addressing these design and application issues are critical to the adoption and success of SiC power electronics.

This paper overviews the SiC technology and recent advances on devices, converters, systems, and applications. The focus is on the benefits of SiC based power electronics for converters and systems, as well as their ability in enabling new applications. The challenges and research trends on the design and application of SiC power electronics are also discussed.

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II. SiC POWER SEMICONDUCTOR DEVICES AND MODULES

The discussion in this section focuses on the characteristics of SiC devices versus their Si counterparts, status of SiC power semiconductors as well as SiC version of the intelligent power modules.

A. Introduction of SiC in Comparison to Si

WBG refers to electronic energy band gaps significantly larger than one electron-volt (eV). SiC materials have several characteristics that make them attractive compared to narrow bandgap Si for power electronics converters. Fig. 1 highlights some key material properties of SiC semiconductor candidates as compared to traditional Si [50]. Generally speaking, for SiC material, the energy gap, breakdown electric field, thermal conductivity, melting point, and electron velocity are all significantly higher. These characteristics allow SiC semiconductor based power devices to operate at much higher voltage, switching frequency and temperature than Si [1], [51], [52].

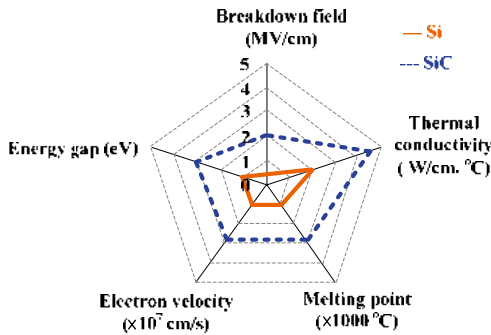


Fig. 1. Summary of Si and SiC relevant material properties [50].

For example, with the breakdown field higher than that of Si, a thinner drift layer with a higher doping concentration can be used for SiC power devices at the same blocking voltage. For unipolar device such as Schottky diodes and MOSFETs, the combination of thinner blocking layer and higher doping concentration yields a lower specific on-resistance compared with Si majority carrier devices.

The fast switching-speed capability of SiC devices can be expected due to higher breakdown field and electron velocity. First, with lower on-resistance at the same breakdown voltage, a reduced chip size is achieved in SiC unipolar devices such as MOSFET. Considering the tradeoff between thinner drift region and smaller chip size, the junction capacitance of SiC MOSFETs is still lower than that of the Si counterparts, therefore the switching speed becomes faster. Second, minority carriers are swept out of the depletion region at the saturated drift velocity during the turn-off transient. The electron saturated drift velocity of SiC is higher than that of Si, leading to an increased switching speed of SiC devices.

Additionally, the excellent thermal conductivity allows SiC dissipated heat to be readily extracted from the device.

Hence, a larger power can be handled by the device at a given junction temperature. Also, higher thermal conductivity together with wide bandgap makes it possible for SiC devices to work at high temperature.

In summary, SiC based power devices offer low specific on-state resistance, fast switching speed, and high operating temperature and voltage capabilities.

B. Status of SiC Devices

This subsection summarizes available information on SiC power devices, including device types, voltage/current ratings, status of commercialization, as well as the latest trend of SiC device development. Note that the hybrid power modules consisting of Si active switches and SiC Schottky barrier diodes (SBDs), which have been commercially available, are not focused in the following discussion.

The availability of high quality SiC wafers allows a reasonable yield of large-area SiC power devices. Currently, 150 mm or 6 inch SiC wafers are commercially available [53]. Fig. 2 summarizes the status of SiC based power devices, including Schottky diodes, PIN diodes, MOSFETs, junction gate FETs (JFETs), IGBTs, bipolar junction transistors (BJTs), and thyristors with the voltage range from 400 V to 22.6 kV. It is observed that the low voltage (from 400 V to 1700V) SiC devices are becoming commercially available. Among them, the current rating per die approaches up to 100 A, and with multiple dies in parallel, state-of-art SiC power modules on market can deliver hundreds of amperes current. On the other hand, the high voltage SiC (referred here as 3.3 kV and above) are generally in developmental stages with limited commercial availability and small current rating per die [54].

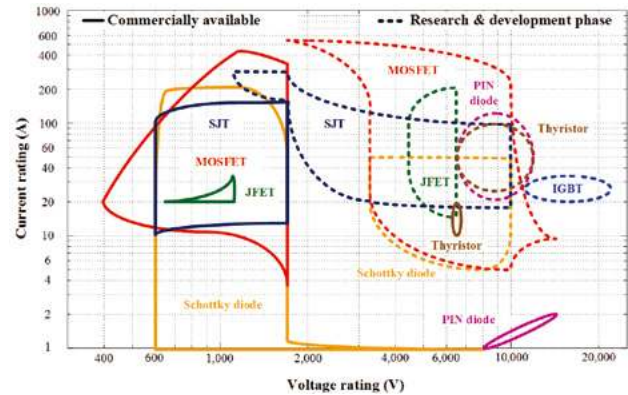


Fig. 2. Summary of status of SiC power devices [55]-[65].

Currently SiC MOSFETs are the most developed active switches, with some JFETs, IGBTs, BJTs, and thyristors also available. For SiC diodes, at low breakdown voltage (< 1700 V), SBDs are popular since they show extremely high switching speed and low on-state loss. But high leakage current and low blocking voltage limit their utilization in high voltage applications. PIN diodes and Junction Barrier Schottky (JBS) diodes are preferred in high voltage applications. Compared with PIN diodes, JBS diodes have

excellent reverse recovery characteristic but poor static performance, making them suitable as anti-parallel diodes of active switches.

SiC power devices are developing rapidly. Compared with the data summarized in [2] a year ago, a few updates are highlighted as follows

1) Increased Current Ratings and More Available Voltage Ratings

Current ratings have been significantly improved at both die level and power module level under wide voltage ratings. For example, 650 V/ 17 mΩ discrete SiC MOSFET has been released with the current rating of 118 A at room temperature [55], which is comparable with the current rating of the state-of-the-art 650-V C7 Si CoolMOS on the market. Also, at medium voltage (MV) level, several large current power modules have been developed and demonstrated, including but not limited to 1.7 kV/ 550A, 3.3 kV/180 A, 10 kV/ 240 A SiC MOSFETs based phase-leg power modules, and 6.5 kV/ 200 A SiC JFETs based phase-leg power modules [66], [67].

More voltage ratings are available mainly due to the application orientated consideration. One example is that a 1000 V SiC MOSFET has been released recently targeting the electric vehicle application. Compared with 900 V and 1200 V voltage ratings, which are typical values for traditional Si devices, a dedicated 1000 V SiC MOSFET is developed to achieve better tradeoff between performance (e.g. switching and conduction loss) and reliability (e.g. adequate voltage margin) [61]. As expected, with the acceleration of acceptance and adoption of SiC devices in industrial products, SiC manufacturers may be willing to develop more dedicated power semiconductors to best serve specific markets.

2) Improved Packaging Techniques

Advanced packaging techniques have been adopted for SiC devices for parasitic minimization, weight/size reduction, and high temperature operation.

For example, TO-247-4 pin package with separated Kelvin source has been utilized for discrete SiC MOSFETs at 1000 V and 1200 V levels [56], [61]. Thanks to the Kelvin source connection and its resultant lower common source inductance, the switching performance can be greatly improved with fast switching and low loss. Also, power modules with < 5nH parasitic inductance are developed for 1200-1700 V power modules with more than 400 A current capability [61], [65]. Additionally, ultra-light SiC power modules based on Easy1B PressFIT package are available for high density power conversion system [56]. Furthermore, high temperature packaging techniques are employed so as to allow commercially available SiC devices (e.g. Schottky diodes and super junction transistors) to operate up to 210 °C [57].

3) Availability of More Power Module Configuration

In addition to the phase-leg power module, more options with respect to the configuration of power modules are

available, such as boost chopper, buck chopper, full bridge, three-level neutral point clamped (NPC), three-level T-type, triple phase-leg [59]. With this, users are able to more conveniently develop high performance power electronics circuits based on different topologies for various applications.

4) Enhanced Short-circuit Withstand Capability

Short circuit withstand capability is challenging for tiny and fast SiC devices [68]-[71]. Compared with traditional Si devices with > 10 μs short circuit withstand time, the typical short circuit withstand time of SiC MOSFETs is on the order of 1 μs. Recently, an enhanced short circuit capability SiC MOSFETs has been developed at MV level (> 3.3 kV). It is demonstrated that these new devices are capable of sustaining short circuit current up to 13 μs, which significantly benefits the reliable operation of SiC MOSFETs for voltage source based high power conversion system [66].

5) Better SiC MOSFET's Body Diode Performance and Trend of Eliminating SBDs in Power Modules

The body diode of the SiC MOSFET is structurally similar to the p-n junction diode formed in the body of a Si MOSFET. The lifetime of minority carriers in SiC is shorter than Si, so the reverse recovery charge is reduced.

To mitigate the reverse recovery induced by MOSFET's body diode, a dedicated SiC SBD is generally added. However, considering the charging of SBD junction capacitance, employing an SBD in parallel does not necessarily result in low total switching energy loss. Specifically, at room temperature, the charging of SBD junction capacitance is greater than reverse recovery charge introduced by MOSFET's body diode [72]. Under elevated temperature, reverse recovery charge was observed to increase significantly; as a result, the switching energy loss may be higher as compared to that with SBD case. Recently, it is demonstrated that for the latest generation Wolfspeed SiC MOSFETs, at 150 °C, the total switching energy loss without SBD does not exceed the loss with employing SBD [72]. Therefore, under wide operating range, the excellent switching performance can be achieved by SiC MOSFET without the extra SBD. Regarding the conduction loss, the channel of SiC MOSFETs, instead of its body diode, can efficiently conduct reverse current. In the end, the penalty without antiparallel SBD with respect to efficiency is limited.

Furthermore, reduced size and cost due to the lack of SBDs in power module can improve the power density and cost of overall power conversion system. Accordingly, it is observed that there is a trend of eliminating SBDs in SiC based power modules [65].

C. SiC Intelligent Power Module

Intelligent power modules (IPMs) are advanced power conversion units that combine power semiconductor chips with optimized gate drive and protection circuitry, such as

over-current (OC), short-circuit (SC), over temperature (OT), and under voltage lock out (UVLO). The compact, easily assembled IPMs can be beneficial to reducing system size/weight, cost, and time to market, and have been successfully applied for Si based high power conversion system [73].

A similar concept is being leveraged to SiC power semiconductors by different approaches. By replacing Si devices with SiC, SiC based IPMs are starting to be commercially available [74]. Also, several gate drives optimized for the commercial-off-the-shelf SiC modules

were developed and released recently [75], [76]. Although gate drive is not packaged with power module in an integrated fashion, the basic function of the IPMs defined above can be achieved. More versions of SiC based power module integrated with gate drive have been investigated and demonstrated [77]-[80]. They are generally in developmental stages.

TABLE I summarizes the state-of-the-art SiC IPMs. Note that the direct replacement of Si devices by SiC offers limited improvements in actual power electronics circuit as

TABLE I
STATUS OF THE STATE-OF-THE-ART SiC IPMS

No.	Manufacturer/Model	Description	Circuit	Special consideration for SiC
1	Powerex [74] PMF75CL1A120	SiC six pack IPM	Three-phase	Short-circuit protection, soft shutdown
2	Cree (now Infineon) [75] CGD15HB62LP	Gate drive board optimized for SiC modules	Phase-leg	High common mode (CM) transient immunity
3	Agile Switch [76] EDEM3	Gate drive board optimized for SiC modules	Phase-leg	2-level turn-off driving, multi-level shutdown
4	Univ. of Tennessee [77] Research & development	Power module integrated with gate drive in board level	Phase-leg	High temperature, low parasitics and fast switching, fast short-circuit protection
5	Virginia Tech [78] Research & development	Power module integrated with gate drive in board level	Phase-leg	High temperature, decoupling capacitor built in, low parasitic and fast switching
6	North Carolina State Univ [79] Research & development	Power module integrated with gate drive in module level	Phase-leg	Decoupling capacitor built in, low parasitics and fast switching
7	Fraunhofer [80] Research & development	Device chips integrated with gate drive in board level	Phase-leg	Decoupling capacitor built in, low parasitics and fast switching, high CM transient immunity

compared to the inherent capability offered by SiC materials. Therefore, special design considerations of SiC IPMs have to be given, which are highlighted in TABLE I as well.

III. SiC BASED POWER ELECTRONICS AND THEIR BENEFITS

Thanks to superior characteristics offered by SiC at power semiconductor device and module level, SiC based power electronics can be significantly beneficial from converter level and system level. More importantly, with much enhanced capability, SiC based power electronics are able to replace or enhance conventional functions performed by electromagnetic or electromechanical devices, leading to SiC enabled new applications.

This section focuses on the benefits achieved by utilizing SiC in power electronics converters from different aspects along with several examples for effectiveness demonstration.

A. Converter Level Benefits

Converter level benefits mainly include improved efficiency, smaller size and lighter weight, enhanced reliability, and reduced cost. They can be realized mainly in the following three ways

1) Substitution of Si PIN Diodes with SiC Schottky Diodes

Without any other modification to power converters, the

excellent reverse recovery characteristics of SiC Schottky diodes lead to less switching loss. It is reported that the substitutions of Si PIN diodes with SiC Schottky diodes in applications using 600 V and 1200 V devices enabled more than 50% switching loss reduction [81]. As a result, improved efficiency and reduced cooling requirement can be achieved. For example, based on a 55-kW three-phase inverter in motor drives, test results show that, by merely replacing Si PIN diodes with their SiC Schottky diode counterparts, the losses of an inverter decrease up to 10.7% under motoring mode and 12.7% under regeneration mode [82].

Alternatively, with the given loss budget, increased switching frequency and reduced passive components need can also be realized. Since 2001 when SiC SBDs became commercially available, they have been successfully employed in many products and demonstrated the expected performance in terms of improved efficiency and reliability [1]. Also, hybrid power modules consisting of Si IGBTs or MOSFETs with SiC SBDs are commercially available by multiple suppliers on the market [56], [60].

2) Substitution of Si Active Switches with SiC Devices

In addition to the mitigated reverse recovery, low on-state resistance and fast switching-speed capability of SiC active switches can further reduce power loss, therefore improve power conversion efficiency. Together with high

operating temperature of SiC devices, they can also lead to reduced cooling requirement. Moreover, they can lead to high switching frequency and therefore reduced passive components need. In the end, converter power efficiency, power density, and/or temperature capability can be improved.

For example, in the data center power supply system, a 7.5 kW all-SiC three-phase buck rectifier was developed and demonstrated with 98.54% efficiency tested at full load, approximately 70% less loss than Si IGBT based converter. Moreover, SiC version is 10% lighter and 4% smaller [49]. Recently, General Electric has released megawatt level photovoltaic (PV) inverter utilizing SiC MOSFETs with CEC efficiency approaching 99% [14]. Also note that more and more all SiC based power modules with increased current capability become commercially available, which will accelerate the adoption of SiC active devices in commercial products.

3) Topology Simplification with High Voltage (HV) SiC Devices

Limited by the voltage and frequency capabilities of Si devices, today's MV drives typically employ complicated multi-level topologies, such as three-level NPC topologies and cascaded H-bridge (CHB) topologies. High voltage and fast switching SiC devices offer an opportunity to achieve the same functions and performance with the simple two-level voltage source converter. The number of active and passive components can be reduced. Therefore, complexity of converter design and operation is reduced, resulting in higher density, higher reliability and lower cost.

It was investigated that in MV motor drive application, high voltage SiC based two-level voltage source inverter exhibited the most promising performance as compared to Si, Si/SiC hybrid, all SiC based three-level NPC inverter, with the fewest number of components, lowest power loss, and smallest cooling system size/weight [83]. Recently the U.S. Department of Energy (DOE) initiated the Next Generation Electric Machines program. One of the main research and development efforts is to leverage recent SiC technology advancements in power electronics of MV megawatt (MW) drive systems for a wide variety of critical energy applications. Using high voltage SiC power semiconductor devices with simplified topology is one of the promising approaches to improve the density by the factor of 3 along with 50% reduction of loss for MV MW level power electronics converter [84]. Also, DOE targets the Technology Readiness Levels (TRL) will improve to 6 or beyond at the end of the program as compared to current TRL of 4 or below. Therefore, it can be expected the commercial product based on this technology will be ready in the near future. Furthermore, SiC device manufacturers have taken the initiative to develop high voltage large current SiC power module to support this effort. It is reported that 10 kV/ 240 A SiC MOSFETs based phase-leg power modules, and 6.5 kV/ 200 A SiC JFETs based phase-leg power modules have been developing with some promising demonstrations [66], [67].

B. System Level Benefits

In addition to power converters themselves, SiC devices also bring benefits at system level as a result of the high switching frequency capability and high control bandwidth, especially for the system where the high controllability is required. One example focusing on the distribution energy resource interface converters in microgrid system is presented here.

A microgrid may contain a number of distribution energy resources (DER), such as photovoltaic (PV), battery energy storage system (BESS), wind turbine generator, etc. Considering the characteristics are similar for grid-interface power electronics converters for different kinds of DER, a PV system and a BESS system are selected as representatives of DERs in this case study. Fig. 3 illustrates the configuration of the 1 MW microgrid with the DER interface converters highlighted. In the following analysis, comparisons based on simulation between Si based interface converter with 3 kHz switching frequency and SiC based one with 10 kHz switching frequency are conducted from different aspects.

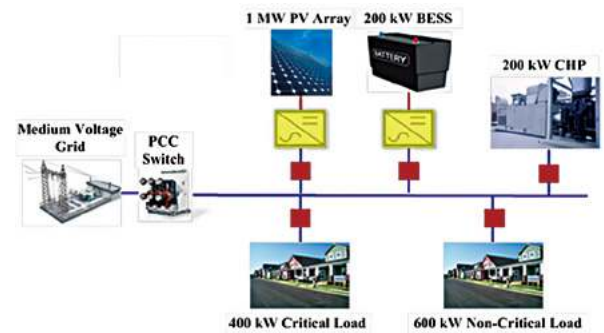


Fig. 3. Configuration of microgrid system.

1) Power Quality Improvement

The growing use of electronic equipment produces a large amount of harmonics in the power distribution systems because of non-sinusoidal currents consumed by non-linear loads. Traditionally, harmonic distortion in power distribution systems can be suppressed using passive and/or active filters. Thanks to the high voltage high frequency SiC devices, the harmonic compensation function can be integrated into the SiC based DER interface converter. In other words, no dedicated filters are needed.

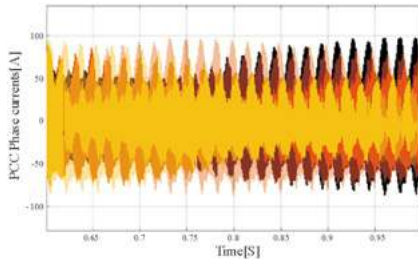
A simulation study was carried out based on configuration in Fig. 3 at 1 MW power rating with six-pulse uncontrolled rectifier as the representative of the non-linear load. It shows that to maintain the Total Demand Distortion (TDD) of the Point of Common Coupling (PCC) on grid side smaller than 5%, in Si based solution with 3 kHz switching frequency, a dedicated active power filter (APF) is required, then the total current rating of the power converter equals the sum of the rms value of the PV output current and the APF output current. In SiC version with 10 kHz switching frequency, the total current rating is almost the same as the rms value of the

PV output current. The simulation results show that in a wide range of grid impedance from 0.01 p.u. to 0.15 p.u., Si version design needs an extra 150 kVA (15% more) converter for APF while the impact on SiC based converter rating is minimal (~1%). By eliminating the dedicated active filters, the SiC based approach saves about 14% converter rating.

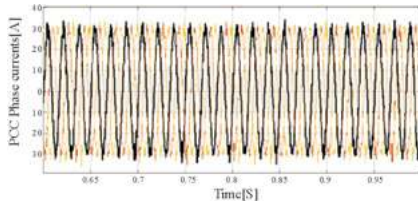
2) System Stability Enhancement

Multiple renewable energy and energy storage interface converters in microgrids, connected to relatively weak grids, can lead to harmonic resonance and stability issues [85], [86]. SiC-based converters, with their switching frequency and high control bandwidth, can help damp the resonance/oscillation and enhance stability.

To investigate the benefits of SiC-based interface converters on the system stability, two cases based on Si and SiC are set up and compared. Specifically, Si based interface converter has lower switching frequency (3 kHz) and limited current control bandwidth (300 Hz) while SiC based converter is with higher switching frequency (10 kHz) and current control bandwidth (1 kHz). As shown in Fig. 4, under the weak grid condition where the grid impedance is 0.1 p.u., integration of Si based interface converter into the microgrid system becomes unstable with the resonance of about 1 kHz while SiC based interface converter is able to ensure the system stability. Due to the advantage of a higher switching frequency and a smaller time delay in the control loop, the SiC-based converter possesses a non-passive range in the higher frequency range, compared with that of the Si-based converter. Therefore, when connecting to a weak grid, the SiC-based converter has a smaller destabilization effect on the system stability, compared with the Si-based converter. In other words, weak grids with SiC-based converters have better stability than those with Si-based converters.



(a) PCC phase current with Si based interface converter.



(b) PCC phase current with SiC based interface converter.

Fig. 4. Simulation results comparison when the grid impedance is 0.1 p.u..

C. Enabled Emerging Applications

SiC based converters, with much enhanced capability can

replace or enhance conventional configurations or functions that cannot be achieved by traditional Si based converters with limited capability. This is also an active area of research. Three examples are highlighted here.

1) High-Speed Motor Drive System

The high switching frequency can enable high speed motor which will have higher power density and smaller footprint. The system impact of high speed motors depends on applications.

One example is for the natural high speed loads like compressors, the gearbox can be eliminated for reduced maintenance, high reliability, and potentially lower system cost. The footprint of the high-speed direct-coupled system can be only 41% of the traditional low-speed system with gearbox, and the power density can increase to 2.5 times [83]. Note that there are Si based high speed motor drives available commercially. They either involve de-rating at the high speeds or involve special complex topologies (e.g. multi-level, interleaving).

2) High Performance Solid-state Transformer

Another attractive application of SiC devices is in the replacement of bulky line-frequency 50 or 60 Hz transformers with solid-state alternatives based on high frequency link transformers especially in MV applications, such as distribution grid, shipboard power systems, high-speed train traction drives [87]. A significant size and weight reduction can be achieved for the transformer since the magnetic core size is, as a first order approximation, inversely proportional to its operating frequency, as shown in Fig. 5.

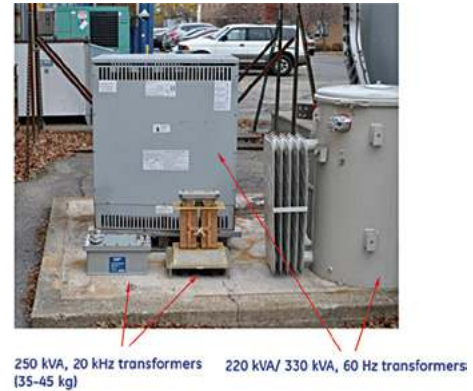
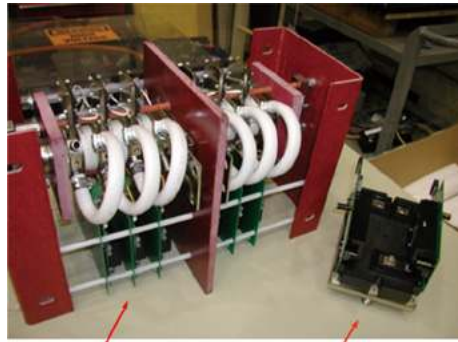


Fig. 5. High frequency vs line frequency transformers.

To realize high frequency (e.g. 20 kHz as in Fig. 5) link for a MV transformer, it would take a large number of low voltage high frequency Si IGBT devices or converters to series, or high voltage low frequency Si IGBT devices or converters to parallel. In contrast, high voltage SiC MOSFETs with their faster switching speed enable power modules with decreased size and weight, and high switching frequency operation (20-40 kHz). Fig. 6 shows the reduction in size achievable with a single high voltage SiC device instead of a stack of lower voltage silicon IGBTs as well as the key static and dynamic characteristics comparison.



Si IGBT stack, 10 kV, 160 amps
(3x 4.5 kV devices in series)
• Conduction drop > 10 V
• Switching time > 3 μ s

SiC Module, 10 kV, 120 amps
• Conduction drop < 6 V
• Switching time < 100 ns

Fig. 6. SiC 10 kV modules vs Si IGBT stack.

Fig. 7 shows a prototype SST based on 10-kV, 120-A SiC MOSFETs phase-leg power module, a 1-MW, 4160-V three-phase ac to 1000-V dc converter with a 40 kHz isolation transformer. This unit has a weight of 900 kg, which is approximately 10% of the 60 Hz transformer-rectifier unit used currently. The volume is also reduced to a third of the existing unit.



Fig. 7. Prototype 1 MW, 4160-V ac/1000-V dc converter.

3) Solid-state Fault Current Limiter and Circuit Breaker

Substitution of fuses and circuit breakers (CBs) with SiC based fault current limiters for short-circuit protection is another promising application. Fuses and CBs are proven and reliable protection equipment. However, fuses are single-use devices, which have to be manually replaced and cause prolonged service interruptions; CBs with high-current interrupting capabilities are bulky and expensive electromechanical systems. More importantly, electromechanical CBs are relatively slow and cannot break dc current. Furthermore, due to the increasing power demand in modern electric power system, the higher fault currents are expected. This increased fault current levels may in the future exceed the interrupting capability of existing CBs [88].

Solid-state fault current limiter (SSFCL) and solid-state circuit breaker (SSCB) have been proposed as a new device to limit and/or interrupt fault currents before their first maximum peaks are reached through fast isolating faulted sections. Similar to SSTs, SSFCLs and SSCBs can be realized by both Si and SiC devices. With higher

blocking voltages, greater current densities, higher operating temperatures, and faster switching speeds, SiC based SSFCLs and SSCBs can achieve better protection while also have smaller size and high reliability, and eventually lower and acceptable cost. Recently, several MV SiC based SSFCLs have been designed and installed in electric power distribution systems which have successfully demonstrated their functionality and feasibility [6], [89].

IV. SiC BASED APPLICATIONS

This section summarizes the applications where SiC power devices have been adopted or have potentials to be beneficial and commercialized. It includes but should not be limited to electric utility grid, transportation, industrial motor drive, and power supply. For each example in a given application, specifications, performance and/or benefits with employing SiC are highlighted. Also, the specific realization approaches (e.g. replacement of diode and/or active switch, modification of topology) are presented.

Note that SiC based power conversion systems and applications have been extensively investigated for years and are still active area of research. It is hardly possible to cover all SiC related research activities and product development. The purpose here is to present a few examples to highlight the existing and potential applications for SiC devices along with the benefits due to SiC devices. The resources summarized as follows are mainly from U.S. with some other countries included as well.

A. Utility Grid

TABLE II summarizes the selected SiC power converters in utility application, including renewable energy (e.g. PV, wind), distribution grid (e.g. SST), energy storage (e.g. flywheel, BESS), protection (e.g. SSFCL, SSCB), Flexible AC Transmission System (FACTS), and High Voltage Direct Current (HVDC) system.

Efficiency is a key consideration for utility application by adopting SiC based solution. The reduced cooling and passive requirements and the resultant cost reduction and reliability enhancement are also important. Furthermore, the fast dynamics and high control bandwidth as discussed in Section III introduces further benefits.

Also note that some equipment, such as SST, SSFCL, and SSCB, are not limited to utility application but can be leveraged to any applications with electric power system, such as shipboard, electrified train.

B. Transportation

TABLE III summarizes several examples of SiC based transportation application, including hybrid electric vehicle (HEV) and electric vehicle (EV), train (including metro), more electric aircraft (MEA). Also, as discussed above, SiC based converter, such as SST, are being developed for shipboard and train as well.

TABLE II
SUMMARY OF SELECTED SiC POWER CONVERSION SYSTEMS IN UTILITY APPLICATIONS

Application	Commercial or R&D, Year	Researcher/ Developer	Specifications, Performance and/ or Benefits by Employing SiC	Realization Approach
PV [16]	R&D, 2016	Technical University of Denmark, Denmark	T-type inverter for Grid-Tie application, 800 Vdc, reduced semiconductor losses by more than 50% , increased converter efficiency up to 1% at light load and more than 60% reduction of cooling requirement with 16 kHz switching frequency, up to 192 kHz switching frequency at 1.5 kW with reduced magnetic size	Substitution of Si IGBTs with SiC MOSFETs
PV [15]	R&D, 2014	Infineon Technologies, Germany	17 kW, 650 Vdc, reduced semiconductor losses in the converter, which maintains electrical performance at high switching frequency and then lowering costs. In the end, achieve up to 20% system cost reduction	Substitution of Si IGBTs with SiC JFETs & topology simplification (3 level to 2 level)
PV [14]	Commercial Product, 2016	General Electric, U.S.	MW class, 1500Vdc, 99% CEC efficiency	Substitution of Si IGBTs with SiC MOSFETs
PV [13]	R&D, 2016	Florida State University, U.S.	T-type inverter, 50 kW, 50 kHz switching frequency, natural convection, 99.1% peak efficiency, 22.7 W/in ³ volumetric power density, 2.5 kW/kg specific power, improved power density by a factor of 3 vs Si based state-of-the-art product	Substitution of Si IGBTs with SiC MOSFETs
Wind [12]	R&D, 2006	Peregrine Power LLC, U.S.	Multi-megawatt rating, 30%-50% switching loss reduction and 15%-25% total loss reduction by Substitution of Si diode with SiC SBD, leading to 0.4% increase in average efficiency and energy production. Expected to employ SiC active devices for wind turbine with nominal voltage from 690 to 4,160 Vac	Substitution of Si diodes with SiC Schottky diodes
Wind [11]	R&D, 2011	Tuskegee Univ. / Univ. of Tennessee, U.S.	1.5MW, 690Vac, 1.1 kVdc, improved wind system power conversion efficiency and reduce the system size and cost due to increasing the switching frequency from 3 kHz by Si IGBT to 50kHz by SiC MOSFET with high temperature properties	Substitution of Si IGBTs with SiC MOSFETs
SST [10]	R&D, 2011	Cree, GE, Powerex Inc., NIST, U.S.	10 kV SiC MOSFETs with low switching and conduction losses leads to 75% reduction in weight, 50% reduction in size, 97.1% efficiency, and cooler operation. Note that in addition to utility, SST can be used in other power distribution systems, such as shipboard power system, railway traction system	SiC enabled new application
SST [9]	R&D, 2015	North Carolina State Univ., U.S.	13.8 kV to 480 V grid-interfaced three-phase SST using 15 kV SiC n-IGBT, 96.75% efficiency for transformer-less intelligent power substation	SiC enabled new application
Flywheel ESS [8]	R&D, 2015	Sanken Electric Co. / Nagaoka Power Elec. Co., Japan	Matrix converter, 5 kW, 200 Vac, 25 kHz switching frequency, 98% efficiency, increased lifetime over 20 years, reduced maintenance time and cost by eliminating low lifetime components in the system.	Substitution of Si devices with SiC MOSFETs & topology modification
Battery ESS [7]	R&D, 2016	Univ. of Cambridge/ Univ. of Warwick, UK	1-10 kW converter application range where battery storage is applied, 50.8% loss reduction at 20 kHz by SiC MOSFET vs Si IGBT, 98.8% efficiency at 40kHz by using SiC MOSFETs and 98.6% by using SiC BJT	Substitution of Si IGBTs with SiC active devices
SSFCL [6]	R&D, 2014	Univ. of Arkansas, U.S.	4.16 kV SiC super gate turn-off thyristor based solid state fault current limiter successfully blocked an overcurrent within 40 μ s.	SiC enabled new application
SSCB [5]	R&D, 2016	Wolfspeed, U.S.	SiC module based solid state circuit breaker handles a 250A fault in 10us and a 450A fault in 70us on a 270 VDC bus, reduced space and weight, higher power density, longer lifetime due to absence of mechanical parts	SiC enabled new application
FACTS [4]	R&D, 2014	Central Queensland University, Australia	30 kVA dSTATCOM, reduced power loss, increased allowable environment temperature by using SiC devices, fast switching frequency can lower required DC bus capacitance, which is beneficial to cost and failure rate in power conversion system	Substitution of Si devices with SiC active devices
HVDC [3]	R&D, 2015	SuperGrid Institute / University of Toulouse, France	Insulated dc-dc converter for off-shore wind application, 735 kVA, 20 kVdc output voltage, 10 kHz switching frequency, 99% efficiency by using 10 kV SiC MOSFET	Topology modification

TABLE III
SUMMARY OF SELECTED SiC POWER CONVERSION SYSTEMS IN TRANSPORTATION APPLICATIONS

Application	Commercial or R&D, Year	Researcher/ Developer	Specifications, Performance and/or Benefits by Employing SiC	Realization Approach
HEV [35]	R&D, 2011	Univ. of Tennessee, U.S.	Inverter efficiency up from 74.3% to 89.1 %, system efficiency up from 32.9% to 37.3%	Substitution of Si IGBTs with SiC JFETs
HEV [33]	Commercial product, 2014	Toyota, Japan	5% higher fuel efficiency, 80% reduction in size	Substitution of Si with SiC devices
HEV [31]	R&D, 2013	Nissan research center, Japan	25 kVA, 600 Vdc, 8 kHz switching frequency, 70 kVA/L air-cooled inverter module, 98.8% efficiency with 15 kW-class induction motor	Substitution of Si devices with SiC JFETs
HEV [27]	Commercial product	McLaren Technology Centre, UK	Motor control unit (MCU) -500 used in McLaren P1 road car, 120 kW, > 20 kW/kg specific power	Substitution of Si devices with SiC MOSFETs
HEV [32]	R&D, 2016	North Carolina State Univ., U.S.	Up to 55 kW, 2% higher efficiency, 12.1 kW/L power density	Substitution of Si devices with SiC MOSFETs
HEV [30]	R&D, 2008	National Technical Univ. of Athens, Greece, Lund Institute of Tech., Sweden	5 kW, Efficiency higher than 98%, smaller size, less cooling requirement, 130 °C operation	Substitution of Si devices with SiC BJT
EV [29]	Commercial product, 2014	Mitsubishi Electric, Japan	60 kW/14.1 L	Substitution of Si with SiC devices
EV [26]	R&D, 2016	Siemens / Porsche, Germany	40 kHz switching frequency, 140 kW, 450~850 Vdc, High switching frequency/lower loss, smaller size	Substitution of Si devices with SiC MOSFETs
EV [25]	R&D, 2014	University of Padova, Italy	80 kW, 20 kHz switching frequency, 100 kJ energy saving per driving cycle (5% longer range)	Substitution of Si IGBTs with SiC MOSFETs
EV [24]	R&D, 2014	Fraunhofer IISB, Germany, Swerea IVF, Sweden	290 kVA, 800 Vdc, up to 175 °C operating temperature, smaller size	Substitution of Si IGBTs with SiC BJTs
EV [23]	R&D, 2014	Leibniz University of Hanover, Germany	10 kHz switching frequency, up to 70% loss reduction in energy loss and 66% reduction in chip area	Substitution of Si devices with SiC devices.
EV [28]	Commercial product	Venturi Automobiles, Monaco McLaren, UK	Venturi VM200, up to 200 kW, over 19,000 rpm and over 150 Nm torque peak performance, more competitive to win the FIA Formula-E Championship	Substitution of Si devices with SiC devices.
Metro [17], [18]	Commercial product, 2013	Mitsubishi Electric, Japan	140 kVA, 600 Vdc, Natural air-cooling, installed in Tokyo Metro's Tozai Line subway, 30% less power loss, 20% smaller, 15% lighter, reduced transformer noise by 4dB due to a 35% improvement in the distortion rate of output voltage waveforms, 51% energy regeneration compared to 22.7% of Si based	Substitution of Si IGBTs with SiC devices
MEA [22]	R&D, 2007	ETH Zurich, Switzerland	1.5 kW continuous output power, 5 kW peak output power, 115 Vrms input voltage, 94% efficiency, 1.5 kW/L volumetric power density	Substitution of Si devices with SiC JFET in cascode structure
MEA [21]	R&D, 2016	Microsemi, Ireland University of Nottingham, UK	5 kVA, 540 Vdc, 40 °C lower skin temperature, continued SiC based module operation for 150,000 flight hours	Substitution of Si IGBTs with SiC MOSFETs
MEA [19]	R&D, 2010	Virginia Tech, Boeing, U.S.	10 kW, 70 kHz switching frequency, 3.59 kW/kg specific power, 3.03 kW/L volumetric power density, 95.4% efficiency at 5.1 kW load	Substitution of Si devices with SiC JFETs
MEA [20]	R&D, 2010	Virginia Tech, Boeing, U.S.	15 kW, 650 Vdc, 70 kHz switching frequency, 6.3 kW/L volumetric power density, 2.78 kW/lb specific power, up to 250 °C device operating temperature	Substitution of Si devices with SiC JFETs

In general, high density is a key goal for the SiC based converter in transportation application. High temperature capability may also be important in this application since the ambient temperature of transportation system is usually higher than room temperature. Also, by elevating the device junction operating temperature, less cooling requirement and high density can be realized.

C. Industrial Motor Drive

TABLE IV summarizes the selected SiC power converters in industrial motor drive application.

In general, high efficiency, low cost, as well as small volume/footprint are main objectives for SiC based motor drives. For special cases, such as compressors applied in oil

TABLE IV
SUMMARY OF SELECTED SiC POWER CONVERSION SYSTEMS IN INDUSTRIAL MOTOR DRIVE APPLICATIONS

Application	Commercial or R&D, Year	Researcher/ Developer	Specifications, Performance and/or Benefits by Employing SiC	Realization Approach
MV Drive [36]	R&D, 2016	North Carolina State Univ., U.S.	Medium voltage two-level converter using 10 kV SiC MOSFETs, 20 kVA, 6 kVdc, estimated 96.64% efficiency at 20 kHz switching frequency, 4.11 W/inch ³ volumetric power density	Topology Simplification with 10 kV SiC MOSFETs
Motor Drive [39]	R&D, 2015	Danfoss Drives, Denmark	18.5 kW, 16 kHz switching frequency, 3% efficiency increase across wide power range (6-17kW) over Si IGBTs	Substitution of Si IGBTs with SiC MOSFETs and SBDs
Motor Drive [38]	R&D, 2007	Cree/ North Carolina State Univ., U.S.	60 kW, 600 Vdc, 10 kHz switching frequency, 68% reduction in conduction loss, 78% reduction in switching loss, 99.1% efficiency with 2% overall increase, and 75% size reduction of heat sink by using SiC vs Si	Substitution of Si IGBTs with SiC MOSFETs
Motor Drive [37]	R&D, 2014	KTH Royal Institute of Technology, Sweden	312 kVA, 550 Vdc, 20 kHz switching frequency 99.3% efficiency over entire load range	Substitution of Si IGBTs with SiC MOSFETs

and gas industry, high temperature capability is also critical. Moreover, compared with low voltage motor drives, medium voltage application is more suitable to fully utilize the advantages of SiC devices, especially with the consideration of integrating high speed medium voltage motors. Then, the high voltage high frequency SiC devices offer a unique opportunity to achieve highly efficient ultra-dense medium voltage integrated motor drive system with relatively simple topology and control.

D. Power Supply

TABLE V summarizes several examples of SiC based power converters for power supply, including data center power system, battery charger, and power factor correction (PFC).

In general, efficiency and volume/weight are the main focuses for SiC based power supply. More soft switching topologies with hundreds of kHz up to MHz switching frequency can be observed in this application. As a result, the passive need is significantly reduced, and the small size along with high efficiency can be achieved.

V. CHALLENGES FOR SiC BASED POWER CONVERSION SYSTEM

Superior characteristics of SiC devices promise to significantly improve today's power conversion system. In the meanwhile, these small and fast devices also pose new design challenges. Special considerations must be given to the converter design with SiC devices in order to utilize them effectively and reliably. The SiC based converter design is still an active area for research. Several key topics are highlighted here.

A. Power Module and Packaging

Packaging device dies into power modules involve electrical,

thermal, and mechanical design. The key considerations for SiC based power module packaging are summarized here.

Parasitic minimization: In general, parasitic electrical parameters involved in the switching loop can be categorized as either power device related internal parasitics or interconnection related external parasitics. The internal parasitics include gate-source capacitance, drain-source capacitance, Miller capacitance, and internal gate resistance; the external parasitics mainly include parasitic inductances, such as gate loop inductance, power loop inductance, and common source inductance. All these parasitics can significantly impact the switching performance of power devices, especially for the fast switching SiC devices [90], [91].

For the device module design, we have to accept the internal parasitics, and try to avoid adding extra parasitics to these parameters externally. At the same time, interconnection related external parasitics should be minimized. Some of the effective parasitic minimization techniques include magnetic field cancellation technique and P-cell and N-cell concept [92], [93].

Also, there is a trend to utilize 3D packaging technique to further reduce the power loop inductance inside the module [94]-[97]. With 3D designs, the commutation loop area can be effectively reduced by restricting the commutation loop in the thickness level of the device. Some existing designs revealed significant reductions of power loop inductance due to package [94]-[97].

High temperature packaging: High temperature operation of power modules reduces the cost of power electronics systems through less semiconductor use and/or lower cooling need. As SiC power devices offer higher temperature capability, high temperature packaging becomes critical. New materials and optimized thermo-mechanical design are necessary to prevent the accelerated degradation of the power modules due to high temperature or temperature excursion [98]. The high temperature technologies cover almost all aspects of the packaging: die attach, substrate,

TABLE V
SUMMARY OF SELECTED SiC POWER CONVERSION SYSTEMS IN POWER SUPPLY APPLICATIONS

Application	Commercial or R&D, Year	Researcher/ Developer	Specifications, Performance and/or Benefits by Employing SiC	Realization Approach
Data Center [49]	R&D, 2012	Univ. of Tennessee, U.S.	Three-phase buck rectifier, 7.5 kW, 400 Vdc, 28 kHz switching frequency, 98.54% efficiency, >70% more efficient than Si IGBTs, 10% lighter and 4% smaller than Si	Substitution of Si IGBTs with SiC MOSFETs and SBDs
Data Center [43]	R&D, 2016	ETH Zurich / ABB Switzerland	Three-phase buck-type rectifier, 8 kW, 380 Vdc, 27 kHz switching frequency, 99% efficiency, 4 kW/dm ³ volumetric power density	Substitution of Si devices with SiC MOSFETs
Battery Charger [48]	R&D, 2006	Univ. of Tennessee / Oak Ridge National Lab, U.S.	Utility interface for battery system, three-phase voltage source inverter, 3.1% efficiency increase during discharging vs Si; 5.4% efficiency increase during charging vs Si	Substitution of Si IGBTs with SiC JFETs and SBDs
Battery Charger [45]	Near commercially available, 2016	ABB Switzerland	Train application, 10x smaller (1 kW/liter), 80% weight reduction (1 kW/kg), more efficient compared to previous generations	Substitution of Si devices with SiC active devices
Battery Charger [44]	R&D, 2014	Global Power Electronics, U.S.	On-board vehicle battery charger, 3.3 kW, 200 kHz switching frequency, 97.7% peak efficiency and 94.7% overall efficiency, > 1 kW/L volumetric power density	Substitution of Si Super Junction MOSFETs with SiC MOSFETs
Battery Charger [40]	R&D, 2013	APEI, U.S.	On-board vehicle battery charger, phase-shifted full-bridge converter, 6.06 kW, 93.4% efficiency at 500 kHz and 96.5% efficiency at 200 kHz, 12.0 kW/L volumetric power density and 9.1 kW/kg specific power	Substitution of Si devices with SiC active devices
Battery Charger [42]	R&D, 2014	Ikerlan Technological Research Center, Spain	HEV, railway applications, 2.5 kW, 540 Vdc, 100 kHz switching frequency, 97.4% global efficiency, 53.54% reduction in volume of magnetic elements, reduced semiconductor operating temperature	Substitution of Si devices with SiC MOSFETs and SBDs
Battery Charger [41]	R&D, 2016	North Carolina State Univ., U.S.	EV fast charger, single phase medium voltage rectifier, 50 kW, up to 50 kHz, > 96% efficiency at 25 kHz, 0.81 kW/dm ³ volumetric power density	Substitution of Si devices with SiC MOSFETs and SBDs
PFC [47]	R&D, 2003	Virginia Tech, U.S.	Single-phase PFC with Si CoolMOS and SiC SBD, 1 kW, 400 kHz, 0.5% efficiency increase at full power, 11W/in ³ volumetric power density	Direct SiC SBD placement
PFC [46]	R&D, 2007	North Carolina State Univ./ CREE, U.S.	250 W, up to 1 MHz switching frequency, 2% efficiency increase and 33% smaller heat sink (SiC MOSFET vs. Si CoolMOS)	Substitution of Si CoolMOS with SiC MOSFETs

encapsulant, and interconnection structure.

Device paralleling: Today, due to the limited current rating of single die of SiC device, development of SiC based power module with multiple dies in parallel is necessary for high power conversion system. The positive coefficient of on-state resistance of most SiC devices allows each paralleled device to achieve current sharing naturally. However, special attention must be paid to the dynamic current sharing during fast switching transient since the switching behavior of SiC devices is highly sensitive to the mismatch of parasitics in the switching loop (e.g. gate loop inductance). Accordingly, parasitics of each die should be carefully controlled via packaging and layout design to ensure good dynamic current sharing.

Capacitive coupling effect: Inside the power module, a layer of insulating material is used to separate the SiC devices from the electrically conductive baseplate. Thus, a chip to baseplate capacitance is formed [99]. Via the baseplate of power module, this coupling capacitance is

paralleled with SiC devices, which increases their equivalent output capacitance, and worsens the switching behavior. Additionally, the chip to baseplate capacitance together with high dv/dt during fast switching transient will generate large CM current (37.5 A in three-phase voltage source inverter reported in [100]), causing severe EMI issue.

B. Gate Drive

As the interface between the micro-controller and power semiconductor devices, gate driver is a key component to achieve the optimal performance of devices in actual power converters. To fully utilize the potential benefits of SiC devices in actual converters, specifically the fast switching speed, the gate driver design is critical. Fig. 8 displays the components of gate driver circuits in the phase-leg configuration. Generally, gate driver mainly consists of driver integrated circuit (IC), signal isolator, and isolated power supply.

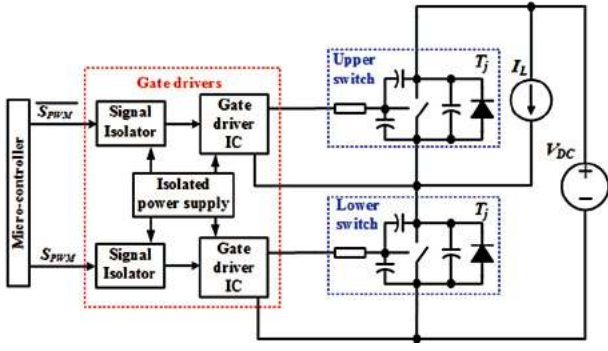


Fig. 8. Gate driver circuits in a phase-leg configuration.

Special attention needs to be paid to gate driver IC, since it directly interfaces with the gate terminals of power devices and is a key component to switching performance of power devices. There are three critical parameters for a gate driver IC that determine the gate driving capability, including pull-up (-down) resistance of gate driver, rise (fall) time, and amplitude of gate driver output voltage. For SiC MOSFETs, considering the modest transconductance and relatively high Miller voltage as compared to the Si counterparts, the amplitude of gate driver output voltage plays a significant role on the switching behavior [101]. Based on this, an intelligent gate driver for SiC was proposed via actively tuning gate voltage during switching transient to enhance the gate driving capability to best serve SiC MOSFETs [102].

Additionally, signal isolator and isolated power supply can also become the limitations of the switching speed if the fast switching transient causes them to operate abnormally. In a phase-leg configuration, the ground of the secondary side of signal isolator and isolated power supply for the upper switch associated gate driver circuit swings from dc bus voltage to 0 when the states of power devices are changing. Therefore, the primary and secondary sides of isolation components suffer high dv/dt during the switching transient. Meanwhile, the input-to-output parasitic capacitance offers a path to conduct CM noise induced by dv/dt [103], [104]. In the end, pulse-width-modulation (PWM) signals from micro-controller will be interfered; and the output voltage quality of the isolated power supply will be affected. For SiC devices with high dv/dt during fast switching, high CM noise immunity capability or low input-to-output parasitic capacitance is a critical selection criterion of signal isolator and isolated power supply.

To fully utilize the high operating temperature capability of SiC devices, their neighboring components must be capable of enduring high temperature. Considering that the gate driver circuits are preferred to be near the power devices for parasitic minimization, high temperature gate driver is an important design consideration. Currently, several gate drivers based on silicon on insulator (SOI) technology have been developed to operate at high temperature (e.g. $> 200^\circ\text{C}$). However, they are generally bulky and expensive [105], [106].

Furthermore, SiC gate drive design also faces several

unique challenges due to the inherent properties of these emerging power devices. For example, for normally-off SiC JFETs, the gate is not insulated from the channel by an oxide as MOSFETs, but forms a pn-junction with drain and source terminals, it is therefore required to inject hundreds of milliamps gate-source current during the on-state. On the other hand, during the switching transient, the gate drive should sink or source several amperes peak gate current to achieve fast switching [107]. To meet the different requirements for turn-on and turn-off switching transients on one hand and the steady on-state on the other hand, a gate driver with multiple driving stages should be designed [108].

C. Protection

Considering their intrinsic properties, SiC devices pose two unique challenges that can threaten the reliable operation of the power converters. One is the cross-talk among devices in a converter, e.g. between two devices in a voltage source converter (VSC) phase-leg, and the other is the limited overcurrent capability [109].

High dv/dt during a fast switching transient of one device will affect the operating behavior of its complementary device in the same phase leg. This interaction between two switches is cross-talk. Specifically, during the turn-on transient of the lower switch, as can be observed in Fig. 9(a), the positive charge stored in the Miller capacitance of the upper switch is transferred via its gate loop, inducing a positive spurious gate voltage. Thus, the upper switch may be partially turned on; and a shoot-through current will be generated, leading to additional switching losses in both switches and even shoot-through failure. On the other hand, during the turn-off transient of the lower switch, as shown in Fig. 9(b), the negative spurious voltage induced at the gate-source terminals of the upper switch may overstress the power device if its magnitude exceeds the maximum allowable negative gate voltage acceptable to the semiconductor device. With low threshold voltage, large internal gate resistance, and fast switching-speed, cross-talk is a clear hazard for safe operation of SiC devices in the VSC. Often, to avoid cross-talk, the high switching-speed capability of SiC devices has to be compromised. To suppress cross-talk without sacrificing fast switching, several gate assist circuits were developed [102], [110]-[114]. Some are all transistor-based, which can be conveniently integrated with conventional gate driver IC [115], [116]. In the end, there is no extra complexity for end users.

Additionally, compared with Si devices, the short circuit protection of SiC MOSFETs is more challenging in several aspects. From thermal standpoint, SiC MOSFETs tend to have lower short circuit withstand capability, compared with Si IGBTs and MOSFETs, due to smaller chip area and higher current density [68]-[71]. The lower short circuit withstand capability requires a faster response time of the protection circuit to guarantee SiC MOSFETs operating within the safe operating areas (SOA). In addition to thermal breakdown, an overcurrent condition also has negative

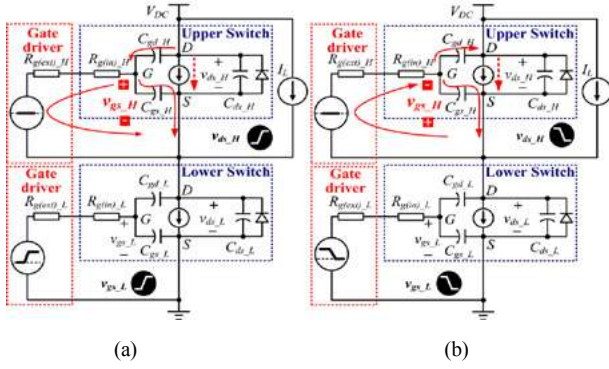


Fig. 9. Mechanisms causing cross-talk: (a) Turn-on transient; and (b) Turn-off transient.

impact on the long term stability of SiC MOSFETs, which had in the past suffered gate oxide reliability issues caused by poor interface quality [117]. Under high di/dt and dv/dt condition, it is difficult for a short circuit protection scheme to achieve fast response time and strong noise immunity simultaneously. Currently, no IEEE standards or published work exists on the allowable response time for protection of WBG devices. A faster fault response time is always desirable to avoid device damage and/or degradation, as long as sufficient noise immunity can be guaranteed. To cope with this issue, a desaturation technique suitable for WBG devices was proposed to provide fast detection. It can help to clear a short-circuit fault within 200 ns [118]. Also note that several latest generation SiC MOSFETs with enhanced short-circuit withstand capability have been developed and demonstrated with more than 10 μ s short-circuit sustaining time. But currently these devices are only available at medium voltage level. Also, to enhance the short-circuit withstand capability, device's switching performance often has to be compromised. Therefore, to maximize the benefits of SiC devices, the fast response short-circuit protection with strong noise immunity capability is always preferred.

Voltage spikes during switching transients can cause device breakdown. SiC devices with high switching-speed capability and small on-state resistance exacerbate the problem. Note also that compared with the overvoltage of the operating switch during the turn-off transient, which has been extensively investigated for Si devices, the voltage spikes of the non-operating switch in the same phase leg during the turn-on transient can be more severe for SiC devices [119]. Advanced packaging techniques and optimal layout design for parasitics minimization can relieve the overvoltage.

D. Interaction with Loads

High switching-speed of SiC devices leads to low switching loss and enables high switching frequency. However, high di/dt and dv/dt during the fast switching transient worsens the electromagnetic environment of loads. In the meantime, fast switching makes the switching performance of SiC devices significantly susceptible to the loads' parasitics. In the end, the interaction between converter and load due to fast switching

SiC devices challenges the performance and reliability of the whole system.

First, voltage pulses with fast rise time generated by PWM switching of power devices can cause serious non-uniform voltage distribution in motor windings, and voltage doubling effect at motor terminals for motor loads with long power cables. The phenomenon is detrimental to motor insulation, and would require dedicated filter or special motor to mitigate. This is a well-known issue with Si device based PWM drives, and becomes more severe when SiC devices are utilized. Moreover, high dv/dt induced by SiC devices can cause larger shaft voltage and bearing current in motor loads, detrimental to motor reliability.

Furthermore, high switching-speed performance of SiC devices will be affected by parasitics of loads. Fig. 10 depicts the impedance of 7.5-kW induction motor plus 2-meter power cable with the frequency range from 10 kHz to 100 MHz. It can be observed that the motor load is no longer inductive in the switching-related frequency range which is determined by the switching speed and typically at several MHz to tens of MHz for SiC devices considering switching intervals of tens of nanoseconds [120]. The load and cable parasitic impedances worsen the SiC devices' switching performance. It is reported that due to parasitics of the inductive load in Fig. 10, the tested switching time of SiC MOSFETs increases up to 42% during turn-on, and doubles during turn-off; an additional 32% of energy loss is dissipated during the switching transient. Also, for the higher power rating induction motor with longer power cable, the associated impedance at high frequency is even lower [121]. One solution to address this issue is to insert an auxiliary filter between converter and load to reshape the high frequency impedance of load such that parasitics of the load will "not be seen" or be masked from the converter side during the switching transient [122].

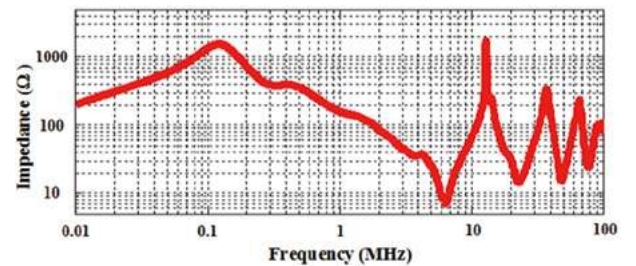


Fig. 10. High frequency impedance of 7.5-kW induction motor plus 2-meter power cable.

E. EMI Filter

SiC devices with high switching frequency operation provide the opportunity to shrink the size of passive EMI filters. However, electromagnetic noise will also trend to concentrate in the high frequency range and increase filter design difficulties due to the non-ideal behaviors of passive components at high frequencies. When switching frequency is in the EMI standard range, the non-ideality of the passive filter, i.e. the equivalent parallel capacitance (EPC) of

inductors and the equivalent series inductance (ESL) of capacitors and related self-resonant frequency, will present significant impact on filter insertion gain. This challenges the filter component design. Better winding schemes to reduce the EPC and better filter scheme to reduce inductance/capacitance values and filter size to further reduce EPC and ESL, may be needed. Also, high frequency has more to do with the non-ideality of core material property, e.g. the widely used nanocrystalline core for CM choke has fast permeability drop above hundreds of kHz. Better solution on choke design may be needed, such as combination of core materials associated with different frequency properties [123], combination of active and passive filters to cancel the lower frequency CM noise via active filter and reduce the needed value/size of passive filter to enhance its high frequency performance [124].

At high frequencies, the coupling effect of filter components through capacitive path and inductive path also becomes worse. In low switching frequency converters, though coupling exists, converter noise can be already attenuated considerably at the typical coupling frequency range. Whereas, in high switching frequency converters, since the main noise spectrum is in or closer to the range of coupling frequency, filter attenuation will be significantly degraded. Careful filter layout and component placement to mitigate the coupling, coupling cancellation schemes [125], or filter approaches that can avoid component coupling are desired.

F. Thermal Management

Generally, due to the highly-efficient SiC based power conversion system, less cooling is required. However, similar to the capacitive coupling effect within the power module, usually a thin layer of insulating material is used to separate the SiC devices from the electrically conductive heat sink. Thus, a parasitic capacitance is formed between the drain base plate of the SiC devices and the common heat sink plate, as shown in Fig. 11 [99]. In the end, this capacitance is paralleled with devices, which increases their effective output capacitance, and then negatively affects the switching speed.

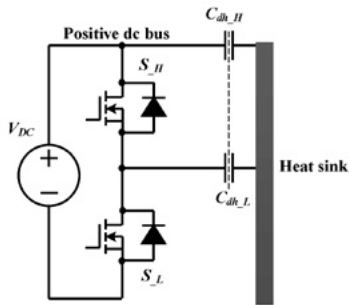


Fig. 11. Capacitive coupling between devices and heat sink.

The key reason for the capacitive coupling effect is the existence of a common heat sink for the upper and lower switches in the phase-leg. One approach to cancel the effect

of capacitive coupling is to decouple the lower and upper switches to separate heat sinks, i.e. one heat sink is used for all upper switches and the other for all lower switches in the phase-leg [99]. The method is effective only if two heat sinks can have different potentials.

G. Control

Control is an essential part of the power electronics converter system. There are many levels of controls. A suitable control architecture, based on the layered hierarchical control for high power converters, is recommended in [126] and illustrated in Fig. 12. There are many levels of controls, including hardware control layer, switching control layer, converter control layer, application control layer, and system control layer. Compared with the traditional Si based power conversion system, fast switching SiC devices pose several challenges, which are highlighted in Fig. 12 as well.

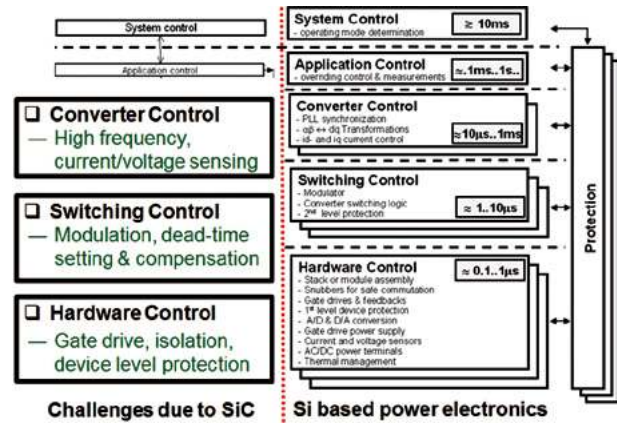


Fig. 12. Control architecture based on Si power electronics converter and challenges due to SiC.

Hardware control layer: Manages everything specific to the power devices, such as gate drives and it may consist of multiple modules depending on the power requirements. For SiC devices, gate drive, isolation, and device level protection are challenging. Details are discussed in Parts B and C in this section. Also note that compared with Si devices with 0.1 -1 μs control time in hardware control layer, fast switching SiC devices shorten it by a factor of 10 in the range of 0.01-0.1 μs.

Switching control layer: Enables the power electronics to behave as a switch-mode controlled source and includes modulation control and pulse generation. For SiC, modulation, especially considering the impact of dead-time for high frequency converter, is critical. More details are discussed as follows. Similar as the hardware control layer, the allowable control time for SiC devices becomes shorter.

Converter control layer: Enables the application control layer to perform its mission by implementing many of the functions common to all converters such as synchronous timing (phase-locked-loop), current and voltage filtering, measurements, and feedback control calculations. This layer will include the current control loop, which is independent of the application. Fast switching SiC enables higher switching

frequency and control bandwidth, in the meantime, shortens the control algorithm execution time and challenges the computing capability of micro-controller. For 100s of kHz to MHz switching frequency application, depending on the complexity of the control strategy, probably, the duty cycle (i.e. comparator value) of the PWM signal has to be updated per several switching cycles. Additionally, current/voltage sensing becomes highly susceptible to the noise introduced by high speed devices operating at high frequency. Detailed discussion of current/voltage sensing is presented as follows.

System and application control layers: System control layer covers all functions involved in the determination of the system mission and thus the duties of the power electronics system or their mode of operation. And application control layer dictates the operation of the power electronic system in order to meet the mission determined by the system control. Impact of SiC devices on these two control layers includes added functionalities as discussed in Section III.

Two unique challenges due to SiC devices with respect to control are highlighted as follows. It includes modulation with the consideration of dead-time effect and current/voltage sensing.

1) Dead-Time Setting and Compensation

Modulation with the consideration of finite switching interval and associated dead-time effect significantly affect the performance of high frequency power conversion system. For example, turn-off time of SiC devices is highly sensitive to the operating conditions. As can be observed in Fig. 13, based on 1200-V/20 A SiC MOSFETs, compared to the tested turn-off time at the operating current of 20 A, turn-off time at 5 A increases by a factor of 5 [102]. Thus, the traditional fixed dead-time depending on turn-off time at the worst operating point (i.e. 600-V/20-A in Fig. 13) is not suitable for SiC based voltage source converter. Also, for the SiC MOSFETs without SBD in parallel, the reverse conduction induced extra energy loss during the superfluous dead-time is significantly higher than the loss dissipated in the switch channel. Moreover, this reverse conduction loss is dissipated during each switching cycle and comparable to the switching loss [127]. Accordingly, dead-time setting for SiC devices is more critical as compared to the traditional Si counterparts. Adaptive dead-time regulation has been investigated to achieve the satisfactory tradeoff between efficiency and reliability [127].

Also, fast speed switching intensifies the impact of parasitics on switching commutation, and affects the power quality of the power converter. For example, when SiC based ac/dc converter is operated at high switching frequency, non-ideal voltage commutation becomes a key distortion factor for power quality control especially around each current zero crossing region. Also note that the parasitics of inductive load in practice significantly affect the switching commutation. Fig. 14 illustrates that under the same operating condition, turn-off time with the motor load is doubled as compared to that when an optimally-designed inductor load is employed [128]. This voltage ramping

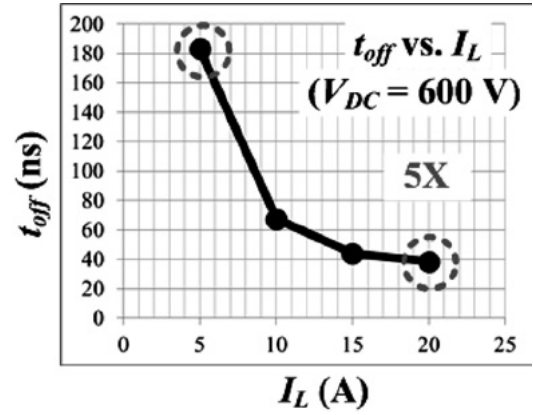


Fig. 13. Turn off time dependence on inductive load current.

introduces voltage loss compared to the ideal PWM voltage, leading to even harmonics for single phase ac/dc and $6k \pm 1$ order harmonics for three phase converter [129]. The higher the switching frequency is, the more severe voltage loss in a shorter switching period becomes. This effect shows the worst distortion in switch-diode configured converters such as Vienna-type rectifier, and it can also be accompanied with dead time effect or overlap time effect in phase-leg configured voltage source converters or current source converters. Compensation methods from voltage-second equivalence by adjusting duty cycle in each switching cycle [130] or by modulation compensation [129], [131], to feedback control [132]-[135] have been studied in recent years.

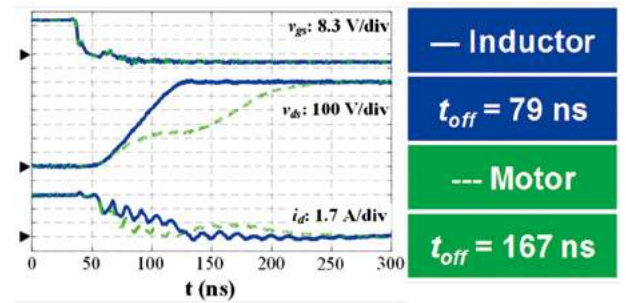


Fig. 14. Turn-off commutation time dependence on different inductive loads.

2) Current/Voltage Sensing

The integrity of current and voltage sensing signals is the basis for feedback control. However, a current sensor works normally at low switching speed in a typical Si based converter might be severely distorted under high-frequency high-speed conditions when SiC devices are adopted. It is found that for current sensors, the capacitive coupling due to high dv/dt and magnetic coupling due to high di/dt from the SiC device switching node and loop, have impeded the effective control of current quality. Different approaches have been considered to mitigate these two distortion effects, such as better arrangement of sensor location (e.g. instead of placing the current sensor to the terminal of the converter, one can put it on the other side of the inductor), selection of

sensor with built-in capacitive shielding or applying proper exterior shielding, di/dt decoupling solutions, and etc.

VI. CONCLUSIONS AND FUTURE TRENDS

This paper overviews the wide bandgap SiC technology. The focus is on the benefits, opportunities, and challenges with SiC based power electronics. The following observations and conclusions can be made and drawn from this paper:

- 1) With smaller size, lower loss, faster switching, and higher temperature capability, SiC devices can improve power conversion systems in several ways: by direct substitution of Si devices in existing circuits for improved efficiency and power density, by simplifying the circuit topology for reduced complexity and further enhanced power density, and by enabling system configuration modification for overall system power density improvement and lower cost.
- 2) In addition to the converter level benefits, SiC power electronics can further introduce system-level benefits as a result of fast switching capability and high available control bandwidth. The examples of system-level benefits include integrated harmonic filtering and stabilizer functions of the SiC based DER interface converters in a distribution grid or a microgrid.
- 3) SiC can also enable new power electronics applications that were previously not feasible with Si technology due to performance, cost, efficiency, reliability or density concerns. Examples include high-speed motor drive, SST, SSCB, and SSFCL. More emerging applications can be expected with SiC as a key enabling technology.
- 4) With faster switching, higher temperature, and smaller size, SiC also raise new design and application challenges. Gate drive and protection need to be faster and more adaptive. Loads can interfere with converter switching, therefore may require additional filters. High temperature and fast switching also demands better device packaging. Other challenges include thermal management, EMI filters, sensors and control. Many solutions have been and are being developed. However, the design and application methodology for SiC power electronics will remain an active research area for the foreseeable future.

Many of the advances presented in this paper are not yet mature and under rapid development. It is expected that SiC devices and related technologies will become mature, resulting in devices with lower cost, higher current ratings, better reliability, better gate drive and protection technologies, and more robust high temperature package. Consequently, they will be applied in more commercial power electronics converters.

One key to overcome adoption barrier of SiC and other WBG technologies is to train a new generation of engineers in the area of WBG power electronics. The U.S. DOE sponsored WBG Traineeship Program at University of Tennessee and Virginia Tech is a step in the right direction.

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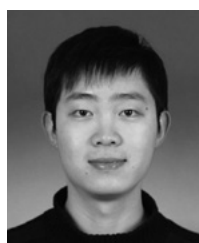


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