Application of Wide Bandgap Devices in Renewable Energy Systems – Benefits and Challenges

Jiangbiao He[1], Tiefu Zhao[2], Xin Jing[3], and Nabeel A.O. Demerdash[1]

[1]Electrical Machines and Drives Lab
Marquette University
Milwaukee, WI, 53233

[2]Corporate Research & Technology
Eaton Corporation
Menomonee Falls, WI, 53051

[3]Global Vehicle Engineering
General Motors Corporation
Pontiac, MI, 48340

Abstract—**The rapid development of renewable energy systems (RES), especially photovoltaic (PV) energy and wind energy, poses increasing requirements for high-power, low-loss, fast-switching, and reliable semiconductor devices to improve system power capacity, efficiency, power density and reliability. The recent commercialization of wide bandgap (WBG) devices, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, provides very promising opportunities for meeting such requirements with their attractive features of high voltage blocking capability, ultra-low switching losses, fast switching speed, and high allowable operating temperatures. This paper analyzed the performance benefits and application challenges of using SiC or GaN devices in both PV and wind energy conversion systems. Solutions to these challenges of using WBG devices in various RES were reviewed and proposed, and the benefits of using such emerging devices were confirmed in simulation based on a 250 kW commercial-scale PV inverter and a 250 kW doubly fed induction generator wind turbine system.**

Keywords-wide bandgap device; PV inverter; wind turbine power converter; efficiency, EMI, high dv/dt

I. Introduction

Efficiency and power density of renewable energy conversion systems (RES) have been two important factors for improving their market competiveness. The recent commercialization of wide bandgap (WBG) switching devices enable much improvement in both efficiency and power density of power converters in RES. Specifically, commercially available wide bandgap devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, exhibit much lower switching losses, higher breakdown voltages, faster switching speed, and higher allowable operating temperatures than their Si counterparts, which are very suitable for being applied in RES.

However, there are some challenges with the application of WBG devices in RES. First, the fast switching speed of WBG devices will incur increased electro-magnetic interference (EMI) to RES if WBG-based power converters are not properly designed. Such increased EMI will degrade system performance and may pose challenges on the RES's compliance to meet the industrial standard of electro-magnetic compatibility (EMC). Second, the high change rate of converter output voltages (dv/dt) and currents (di/dt) as well as the associated overvoltage on load terminals will occur if stray capacitance and inductance in the power circuits are not minimized. Third, improvements of RES performance by extensively using WBG devices is counter to reducing system cost due to the presently high market price of WBG devices.

Considering that system cost is one of the most important factors for the market competiveness of commercial photovoltaic (PV) and wind power converters, massive utilization of WBG devices for efficiency and power density improvement of power converters would be unrealistic in practice with present market price of WBG devices. Therefore, a novel low-cost hybrid power module paralleling major Si devices and minor SiC devices is proposed in this paper. On one hand, the positive temperature coefficients of these Si and SiC devices enable the possibility of paralleling these devices to configure high-power modules; On the other hand, such hybrid power modules can achieve quasi soft-switching and therefore be able to significantly improve converter efficiency at light-load or medium-load conditions. The efficiency advantages of the proposed hybrid power module for RES power converters will be verified via simulations in this paper.

The content of this paper is organized as follows. In Section II, applications of WBG devices in both commercial and laboratorial photovoltaic (PV) converters are reviewed. Aiming at the application in commercial-scale PV inverters (100-250 kW), a novel low-cost and high-efficiency hybrid device module based on paralleling "SiC+Si" devices for a 250 kW PV inverter is presented and investigated in simulation in Section III. In Section IV, several cases of using WBG devices in different types of wind turbine power converters are reviewed. In Section V, investigations of efficiency improvement by replacing Si IGBTs with hybrid devices ("SiC MOSFET + Si IGBTs)" in a 250 kW double fed induction generator (DFIG) were carried out in Simulation. In Section VI, Potential challenges of using WBG devices in both PV and wind converters are discussed and their respective solutions are recommended. Finally, a few conclusions summarizing the benefits and challenges of using WBG devices in RES are given in Section VI.

II. Application of WBG Devices in PV Converters

PV energy sources have gained widespread acceptance with an impressive global jump of 39.8 GW PV cell production in 2013 [1]. PV inverters can be classified by power levels into

Table-1 PV system classification by power levels [1]

PV Inverter Ratings	Grid Connection	Application Scale of PV Inverters	DC Voltage Range
<10 kW	Single-phase or split phase	Residential and small commercial scale	200-400 VDC
10-100 kW	Three-phase 208VAC	Small commercial scale	300-600 VDC floating or grounded
100-250 kW	Three-phase 480VAC/600VAC	Commercial and large commercial scale	600 VDC mostly grounded
250 kW-1 MW	Three-Phase 300 to 600 VAC	Utility scale	1000 VDC floating

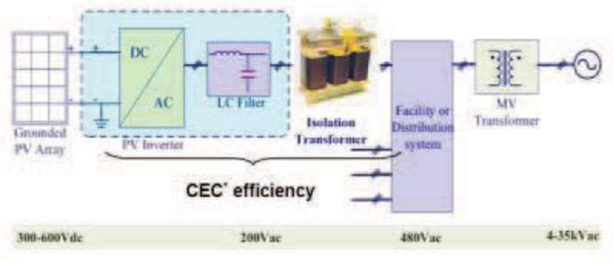

Fig. 1 Typical U.S. commercial scale PV inverter system

residential (<10kW), small commercial (10-100kW), large commercial (100-250kW) and utility applications (250kW-1MW), as shown in Table. 1. A typical commercial scale PV inverter system in the U.S. is shown in Fig. 1, in which the dc/ac inverter and the output passive filter play a dominant role in the system efficiency and power density, which can be much improved by using WBG devices.

The commercially available WBG devices in the current market include SiC MOSFETs from device manufacturers such as Cree and Rohm, SiC JFETs from Infineon and USC; SiC transistors from GeneSiC; GaN devices from EPC, Transform, and GaN Systems. Most of the SiC devices are rated at 1.2 kV or 1.7kV, and GaN devices are rated no more than 600V. Due to the power ratings of these devices, the most straightforward advantages yielded from using such WBG devices are for low-rated PV systems, namely, microinverters and small string inverters, for residential and commercial solar installations. It has been reported in [2] that the efficiency of a 200W dual-stage PV microinverter based on an interleaved flyback converter and an H4 inverter can be improved by up to 4% if replacing Si transistors with GaN HEMT. In reference [3], it demonstrated that with the utilization of SiC devices in an SMA 20 kW transformerless solar inverters have achieved 99% on the California Energy Commission (CEC) weighted efficiency scale.

There are numerous publications focusing on new topologies and applying SiC and GaN devices to PV inverters in residential systems. Several topologies such as H5, HERIC, half bridge NPC, full bridge with bypass topologies using SiC devices were respectively proposed in [4-7] to improve system efficiency and reduce common mode voltage. However, there are very few reported works on using SiC devices in three-phase transformerless PV inverters for large commercial-scale systems (100kW-250kW). As the emergence of SiC modules rating up to 1.7kV/200A, high-efficiency medium and large commercial-scale PV inverters with SiC devices are gaining more and more attention. Therefore, it is of great importance to develop a high-efficiency and cost-effective three-phase inverter solution to meet this market challenge and requirement, which will be elaborated in the following section.

III. High-Efficiency Commercial-Scale PV Inverters Based on "SiC+Si" Hybrid Devices

Considering the large power ratings of three-phase transformerless PV inverters in commercial-scale solar systems, one major challenge of using SiC devices in PV inverters is the high cost. However, such challenge can be solved by using hybrid devices, which consist of SiC and Si devices parallel connected together to gain better efficiency at light-load or medium-load conditions, which also reduce the required SiC ratings to decrease device cost. The basic structure of a 400A/1.2kV hybrid module in shown in Fig. 2, from which one can see the module is composed of one SiC MOSFET (100A/1.2kV) and three Si IGBTs (100A/1.2kV). The switching pattern for such hybrid devices is given in Fig. 3. As illustrated in Fig. 3, for turning-on of the hybrid devices, SiC MOSFET is turned on earlier to achieve quasi zero-voltage switching (ZVS) for the subsequent switching-on of IGBTs; For turning-off of the hybrid devices, SiC MOSFETs are turned off later to achieve quasi ZVS for the prior switching-off of IGBTs. The time setting of the turn-on delay and turn-off delay should be shorter than deadtime between complimentary switches and longer than turn-on/turn-off time of the specific devices from the manufacture datasheet. It should be noted that all the load current flows through SiC MOSFET during the turn-on delay and turn-off delay, which may cause device reliability issues under heavy load conditions. Therefore, this switching pattern is only recommended to be used in light load or medium load conditions. The methodology on how to determine the critical load points for using such switching pattern will be detailed in future work.

A 250 kW commercial-scale PV inverter using "SiC+Si" hybrid devices has been simulated in PLECS environment. The SiC MOSFET used is CREE CAS100H12AM1 (100A/1.2kV) [8], and the Si IGBTs used are Infineon 100R12YT3 [9], with the same ratings as the SiC MOSFETs. The topology of the PV inverter is a three-phase three-level neutral-point-clamped (NPC) inverter, which is shown in Fig. 4. Four power points, namely, 25%, 50%, 75%, and 100% of rated power were simulated in PLECS. Simulation results demonstrate that the CEC efficiency of the 250 kW PV inverter can be improved by up to 2% if conventional Si devices are replaced with hybrid devices, as shown in Fig. 5.

IV. Application of WBG Devices in Wind Turbine Power Converters

In addition to the promising applications of WBG devices in PV converters, wind turbine power conversion is another attractive area for the application of WBG devices. Variable speed wind turbine generators have been playing a dominant role in wind power generation market, and more than 75% of presently sold wind turbines require control by power converters [10]. Such large market share provides a very promising application prospect for WBG devices owing to the efficiency and power density improvement of solid-state power conversion unit, including power converters, passive filters,

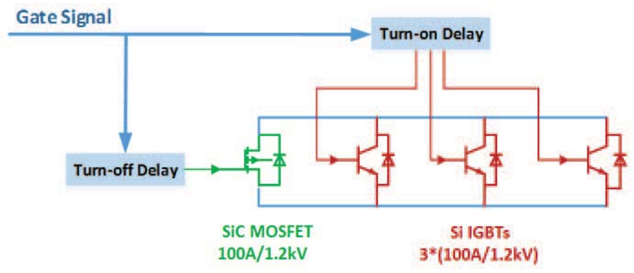

Fig. 2 Structure of a 400A/1.2kV "SiC+Si" hybrid device

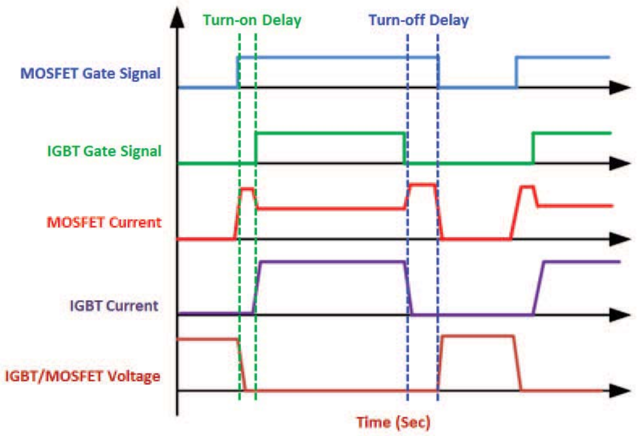

Fig. 3 Switching pattern for the "SiC MOSFET + Si IGBTs" hybrid device

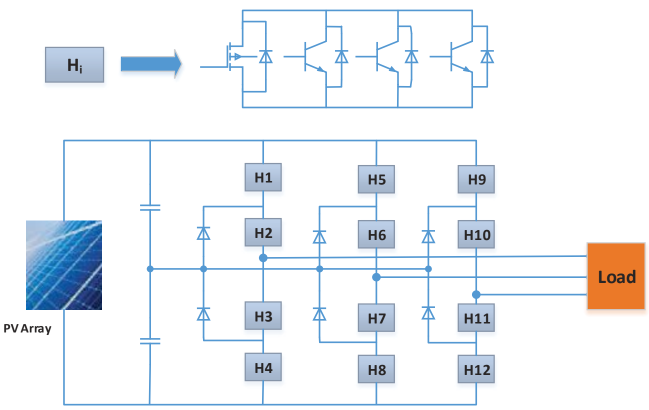

Fig. 4 A 250 kW NPC PV inverter based on 400A/1.2kV hybrid devices

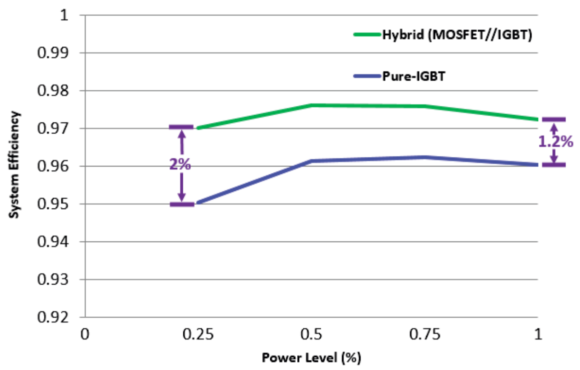

Fig. 5 Efficiency comparison between using hybrid devices and pure-Si devices in a 250 kW three-phase three-level NPC inverter

and cooling systems. Currently, the largest demand for switching devices for variable-speed wind turbines is 1.7 kV and 1.2 kV devices, in which the 1.7 kV devices are mainly used for full-scale power converters in direct-driven permanent magnet wind generators, while the 1.2 kV devices are used for partial-scale power converters in doubly fed induction generators [11]. The advantages in these devices with lower voltage classes compared to those of higher voltages (e.g., 3.3 kV) are lower system losses and system cost [11]. Among various WBG devices, SiC MOSFET and JFET are the most technically mature and suitable devices for wind turbine applications due to the high power ratings available. However, the present SiC MOSFETs or JFETs are only commercially available at 1.2 kV and 1.7kV voltage ratings or below.

In reference [12], application of SiC MOSFETs and Schottky diodes has been investigated in a full-scale two-level back-to-back power converter for a 1.5 MW permanent magnet wind turbine generator. The ratings of SiC MOSFETs were upward scaled from 1.2 kV/10A to 1.7 kV/1.2 kA based on curve fitting of test results. Simulation results show that, at switching frequency of 3 kHz, the average efficiency of SiC-based power converter reached 97.8%, which is an increase by 4.3% compared to the average efficiency of Si-based power converters (93.5%). In addition, at a switching frequency of 20 kHz, the efficiency gain of the power converter by using SiC devices can be increased by 12.8%, rising from 73.1% to 85.9%.

In reference [13], a small generator-side two-level power converter (<40 kW) based on SiC devices (JFETs and Schottky diodes) was investigated in an experimental setup with a three-phase squirrel cage induction generator (SCIG), in which the benefits of low switching losses and small passive filter were justified because of the high switching frequency (>100 kHz) used in the power converter.

It can be seen that all these aforementioned applications of WBG devices in wind turbine power converters are based on pure SiC devices, which will largely increase the system cost due to high market price of SiC devices at present. Thus, hybrid devices based on major Si IGBTs and minor SiC MOSFET/JFET will be a more cost-effective solution to boost the efficiency of wind turbine power converters. A simulation of a two-level back-to-back power converters based on "SiC+Si" hybrid devices for a 250 kW DFIG system has been carried out and will be detailed in Section V.

V. HIGH-EFFICIENCY WIND TURBINE POWER CONVERTERS BASED ON "SIC+SI" HYBRID DEVICES

Simulation of a two-level back-to-back power converter based on hybrid devices in a 250 kW DFIG system has been carried out in MATLAB Simulink and PLECS Blockset environment, the block diagram of which is shown in Fig. 6. The basic parameters of the DFIG system are tabulated in Table-2. The topology of the back-to-back power converter is a two-level back-to-back converter based on "SiC+Si" hybrid devices, which was given in Fig. 7. The ratings of the hybrid devices used in generator-side converter are 350A/1.2 kV per module, which are composed of one SiC MOSFET and one Si IGBT. The ratings of the switching devices used in grid-side converter are 900A/1.2kV per module, which are configured by

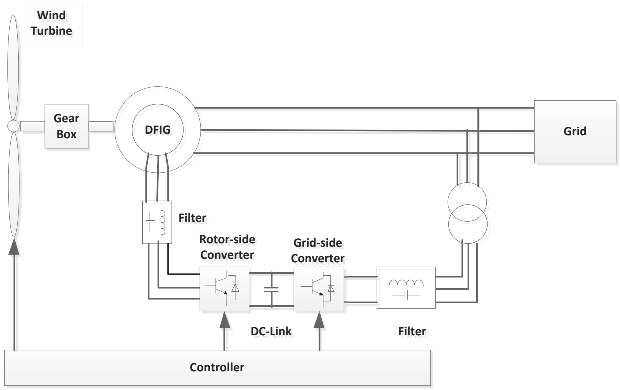

Fig. 6 Block diagram of the 250 kW DFIG wind turbine system

Table 2 Parameters of the 250 kW DFIG system

Parameters	Value	Units
Wind Turbine Rotor radius	91.2	Meters
Pole Number	6	/
Rated Power	250	kW
Rated Voltage	575	Volts
Stator Resistance	0.023	Ω
Rotor Resistance	0.016	Ω
Stator Inductance	0.18	H
Rotor Inductance	0.16	H
Magnetizing Inductance	2.9	H

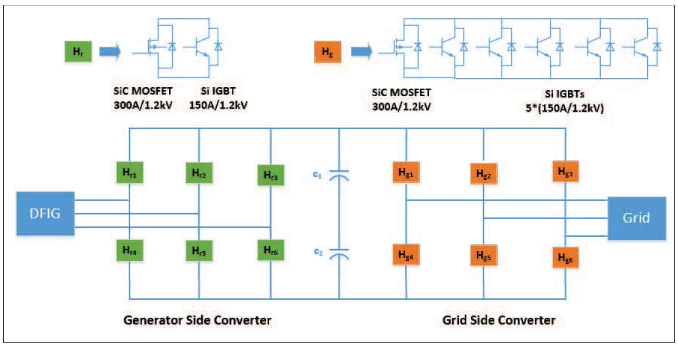

Fig. 7 A two-level back-to-back converter based on "SiC+Si" hybrid devices

Table 3 Switching device selection for the back-to-back power converters in the 250 kW DFIG system

	Generator-side converter		Grid-side converter	
Device Ratings	350A/1.2kV		900A/1.2kV	
Hybrid Device Configuration (Parallel)	1*SiC MOSFET[1]	1*IGBT[2]	1*SiC MOSFET[1]	5*IGBT[2]
	300A/ 1.2kV	150A/ 1.2kV	300A/ 1.2kV	750A/ 1.2kV

[1] SiC MOSFET, CREE, CAS300M12BM2.
[2] Si IGBT, Infineon, FF150R12YT3.

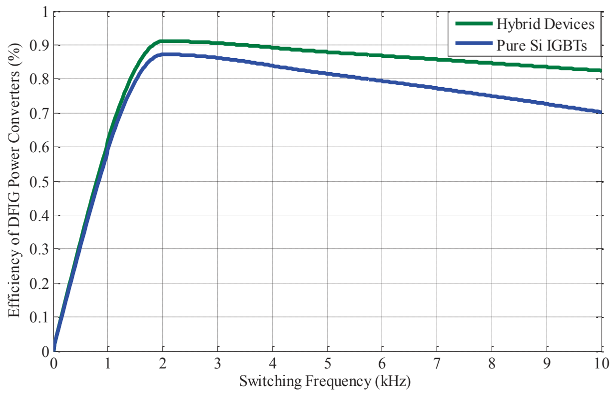

Fig. 8 Efficiency comparisons of DFIG power converters between using hybrid devices and Si IGBTs (under rated wind speed 12 m/s, $T_j = 125$℃)

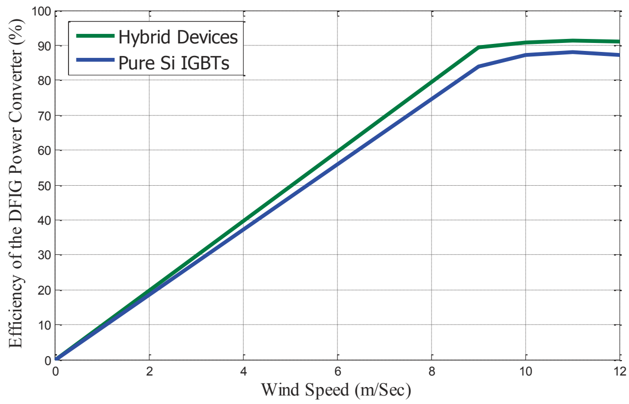

Fig. 9 Efficiency comparisons of DFIG power converters at various wind speed between using "SiC+Si" hybrid devices and Si-IGBTs ($T_j = 125$℃)

one SiC MOSFET and five Si IGBTs per module. The parameters and module number of all these devices are given in Table 3. The efficiency comparisons of power converters using "SiC+Si" hybrid devices versus that using Si IGBTs at various switching frequencies and under rated wind speed (12 m/sec) are shown in Fig. 8. As one can see, as the switching frequency increases, the efficiency advantage of power converters using hybrid devices increases. At switching frequency of 2 kHz, the converter efficiency increases from 87.2% to 91.1% if replacing all Si IGBT and diodes with their counterparts of hybrid devices. When the switching frequency is set at 10 kHz, the converter efficiency improves dramatically from 70.2% to 82.4% if replacing all Si devices with hybrid ones, yielding an efficiency advantage of nearly 12.2%. Moreover, the efficiency comparison of power converters at various wind speed between using hybrid devices and Si IGBTs are shown in Fig. 9, from which one can observe that DFIG converters have higher efficiency than Si-based counterparts, and the efficiency gain is as much as 3.9% under maximum power point tracking control.

VI. Challenges of Using WBG Devices in Renewable Energy Power Converters

According to the analysis and discussion above, it can be seen that the performance of renewable energy conversion systems can be much improved if utilizing WBG devices in power converters. However, such applications of WBG devices also causes challenges in practice. According to the literature review [14-22], three main challenges, namely, increased EMI, high dv/dt and high di/dt, as well as high device cost, have been limiting the broad application of WBG devices. Some recommended solutions to these three challenges are reviewed and commented-on in this section.

A. Increased EMI

According to the analysis and discussion above, one can see the numerous benefits from using WBG devices in RES. However, one potential penalty associated with these benefits is the increased EMI caused by the fast voltage and current switching transients in WBG-based power converters, which will pose great challenges with regard to compliance to EMC standard (IEC61800-3-C2) for future commercial RES using WBG devices. For instance, capacitive coupling existing in WBG-based power circuits becomes more prominent, because such coupling creates loops for high frequency noise propagation generated with fast switching due to WBG devices. It was shown in [14] that the use of SiC diode in a dc-dc boost converter has great influence on the radiated EMI, while the use of SiC MOSFET combined with Si diode reduces the radiated and conducted EMI generated by the converter. Two methods for mitigating the EMI noise emission due to capacitive coupling are proposed in [15], in which one method is based on using separate substrate for SiC power devices and the other one is to use broadband modeling to identify the most effective EMI filter design.

B. High di/dt and dv/dt

The high change rate of current (di/dt) and voltage (dv/dt) will become another severe issue due to using WBG devices in RES because of the much faster switching speed of such devices. To be specific, high di/dt mainly occurs in low-voltage high-current applications (e.g., the power converters for the resistance control in wounded rotor induction generator systems), which can generate pronounced overvoltage when the WBG devices switch off while parasitic inductances in the power circuits are high. As a results, WBG devices with higher voltage ratings must be used to meet the overvoltage requirement, which will cause additional cost and losses. Moreover, high di/dt generates induced high electric filed in the proximity of WBG-based power converter, which is reflected as radiated emission. Therefore, low-parasitic design should be considered both in the packaging of WBG modules and external power circuits. Also, passive filters such as LC filters can be used to mitigate the high di/dt in the converters.

Moreover, large dv/dt can also occur in medium and high voltage power converters, such as full-scale back-to-back converters used in MW wind turbine generators. Such high dv/dt will generate high displacement current through parasitic capacitances of the module and the converter load. More seriously, since power converters in wind turbine systems are typically installed at the bottom of the mast for maintenance convenience, which are far away from the wind generators installed in the nacelle of the mast as shown in Fig. 10, therefore, overvoltage would be as much as twice or three times that of the rated voltages at the generator terminals and inter-connecting cables between power converters and generators are long enough to introduce successive reflection issues in the presence of short rise time of WBG devices. In such scenarios, dv/dt filters will be strongly recommended for overvoltage mitigation. The mechanisms of such overvoltage phenomenon was reported in [16], and recommended solutions to mitigate such overvoltage due to high dv/dt in high switching frequency power electronic systems were given in [17].

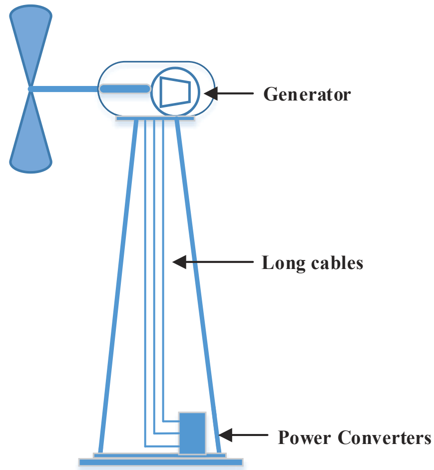

Fig. 10 Basic structure of a wind power station

C. Increased System Cost

Currently, the market price of WBG devices is still much higher than that of their Si counterparts. Therefore, system cost will become unacceptable if one entirely relies on using WBG devices in RES power converters to achieve high performance. Under such scenario, compromise methods based on the hybrid combination of both Si and SiC devices would be a very promising solution to improve the system efficiency with an acceptable cost rise, such as the hybrid devices introduced in Section III and Section V.

In addition to the hybrid paralleling of Si and SiC active devices introduced above, hybrid co-pack modules based on paralleling Si IGBTs and SiC Schottky diodes were also proposed for MW applications, as introduced in [18], which can achieve a reduction of up to 40% of the total switching losses and allowing a three to five fold increase in operating frequency without derating of the output power capability. Similar concepts of hybrid devices at different voltage levels were also reported in [19-21].

Another way to reduce RES cost while using WBG devices is replacing the Si-based three-level NPC converter topologies with WBG-based two-level converter topologies. Nowadays, many commercial PV or wind power converters based on three-level NPC topologies have been developed to obtain a typical efficiency up to 98% due to low switching losses of 600V Si IGBTs or MOSFETs and reduced filter core losses. However, two-level converters based on 1.2kV SiC devices can achieve a higher efficiency with just half number of switching devices and gate drivers. It was reported in [23] that a SiC-based two-level full-bridge inverter is more cost-effective than a Si-based three-level NPC inverter for +10kW range of three-phase PV inverters.

VII. CONCLUSIONS

This paper discussed the performance benefits of applying WBG devices to renewable energy conversion systems. The utilization of SiC and GaN devices in both commercial and laboratorial power converters for PV and wind power converters were reviewed and analyzed. Aiming at large rated power converters used in RES, a novel type of low-cost high-efficiency hybrid device paralleling major Si IGBTs and minor SiC devices were proposed. Simulation of a 250 kW commercial-scale three-level NPC PV inverter and a two-level back-to-back DFIG power converter based on “SiC+Si” hybrid devices were carried out. The efficiency improvements by using such hybrid devices were verified, which provides a cost-effective solution to high-efficiency power converters used in large PV and wind systems.

In addition, associated challenges of using WBG devices in RES were discussed, which include increased EMI, high di/dt and dv/dt, as well as high system cost. The corresponding solutions to these potential challenges were reviewed and commented, which will be helpful for future industrial users and researchers in related areas.

ACKNOWLEDGMENT

The authors would like to express thanks to the U.S. National Science Foundation (NSF) for financial support of the work in this paper through NSF-GOALI Grant No. 1028348. Sincere appreciation is given to Plexim GmbH U.S. Office for donating the PLECS Blockset licenses which have been used in the simulation analysis in this paper.

REFERENCES

[1] Solar PV Market IMS Research Report, 2011.

[2] L.G. Rodriguez, et al, “Design of a GaN-based microinverter for photovoltaic systems,” *IEEE power electronics for distributed generation systems (PEDG)*, pp. 1-6, June 2014, Galway, Ireland.

[3] “The inverter with a plus”, Photon Magazine, pp. 140-147, Jan 2012.

[4] R. Gonzalez, E. Gubia, J. Lopez, and L. Marroyo, “Transformerless single-phase multilevel-based photovoltaic inverter,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2694–2702, Jul. 2008.

[5] T. Kerekes, P. Rodríguez, G. Vázquez and E. Aldabas, “A New High-Efficiency Single-Phase Transformerless PV Inverter Topology,” *IEEE Trans. Ind. Electron.*, vol. 58, no.12, pp. 184-191, Jun. 2009.

[6] T. Kerekes, R. Teodorescu and U. Borup, “Transformerless Photovoltaic Inverters Connected to the Grid,” *in Proc. IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2007, pp. 1733-1737.

[7] Ideal Power Converters. [Online]. Available: http://www.idealpowerconverters.com/pdf/IPC_ICSET_2008_Solar_Inverter.pdf.

[8] Cree Inc. [Online]. Available: http://www.cree.com/.

[9] Infineon Technologies. Available: http://www.infineon.com/.

[10] A. D. Hansen, F. Iov, F. Blaabjerg, L. H. Hansen, “Review of contemporary wind turbine concepts and their market penetration,” *Journal of Wind Engineering*, Vol. 28, No. 3, 2004, pp. 247-263.

[11] Power Electronics in Wind. [Online]. Available: http://www.infineon.com/.

[12] H. Zhang, and L. M. Tolbert, “Efficiency impact of silicon carbide power electronics for modern wind turbine full scale frequency converter,” *IEEE Transactions on industrial electronics*, vol. 58, no. 1, Jan. 2011.

[13] M. Adamowicz, et al, “Evaluation of SiC JFETS and SiC Schottky diodes for wind generation systems,” *in Proc. IEEE International Symposium on Industrial Electronics (ISIE)*, Gdansk, 2011.

[14] P. B. Franco, and J. B. Sendra, “EMI Comparison between Si and SiC technology in a boost converter,” *International Symposium on Electromagnetic Compatibility (EMC Europe)*, 2012, Rome.

[15] X. Gong, “Conducted EMI in inverters with SiC Transistors,” *Ph.D. dissertation*, TU Delft, Netherlands, 2013.

[16] E. Persson, “Transient effects in application of PWM inverters to induction motors,” *IEEE Transactions on Industrial Applications*, vol. 28, no. 5, pp. 1095-1110, Sep./Oct. 1992.

[17] J. He, G. Y. Sizov, P. Zhang, and N. Demerdash, “A review of mitigation methods for overvoltage in long-cable-fed PWM AC drives,” *in Proc. IEEE Energy Conversion Congress and Exposition*, 2011, pp. 2160-2166.

[18] T. Miyanagi, and M. Nakazawa, “Newly developed hybrid module by Si-IGBT and SiC SBD,” *Power Conversion Intelligent Motion (PCIM)*, 2011, Nuremberg.

[19] L. Nistor, M. Rahimo, L. Storasta, C. Corvasce, and A. Mihaila, “Opportunities and challenges for wide bandgap power devices in megawatt PE applications,” *in Proc. Power Conversion Intelligent Motion (PCIM)*, 2012, Nuremberg.

[20] G. Skibinski, D. Braun, D. Kirschnik, and R. Lukaszewski, “Developments in hybrid Si-SiC Power Modules,” *Material Science Forum*, 527-529, 1141.

[21] J. Lai, W. Yu, P. Sun, etc “A hybrid switch based soft-switching inverter for ultrahigh efficiency traction motor drives,” *IEEE Transactions* on *Industry Applications*, Issue 99, 2013.

[22] C. Sintamarean, E. Eni, F. Blaabjerg, R. Teodorescu, and H. Wang, “Wide-band gap devices in PV systems – opportunities and challenges,” *in Proc. International Power Electronics Conference (IPEC)*, Hiroshima, Japan, 2014, pp. 1912-1919.