Chinese Journal of Electrical Engineering, Vol.3, No.1, June 2017

A Novel Boost Four-Leg Converter for Electric Vehicle Applications

Xiaoyu Jia[1], *Huaibao Wang*[1], *Baocheng Wang*[1], *Xiaoqiang Guo*[1]*, *and Xiaoyu Wang*[2]

(1. Department of Electrical Engineering, Yanshan University, Qinhuangdao, 066004, China
2. Department of Electronics, Carleton University, Ottawa, Canada)

Abstract: Integrating the electric vehicle into grid or microgrid has been receiving more and more attention in recent years. Typically, the electric vehicle (EV) chargers with their power batteries have been developed for vehicle-to-home(V2H) applications, acting as a backup generation to supply emergency power directly to a home. Traditional EV chargers in V2H applications mainly consist of DC/DC and DC/AC stages, which complicate the control algorithm and result in low conversion efficiency. In order to solve this problem, a novel EV charger is proposed for V2H applications. It can boost the battery voltage and output AC voltage with only one-stage power conversion. Also, the DC, 1-phase and 3-phase loads can be fed with the proposed single-stage EV charger. The system control strategy is also provided to deal with versatile load variations. Finally, the performance evaluation results verify the effectiveness of the proposed solution.

Keywords: Electric vehicle, boost converter, four-leg converter, V2H mode.

1 Introduction

In recent years, electric vehicles(EVs) have attracted more and more attention for their enormous potential[1-3]. Utilizing bi-directional power electronics can allow a vehicle to not only charge its batteries from the electric utility grid during charging, but also can provide power back to the grid during discharging. The possible uses of V2G vehicles for distributed energy applications are to provide power to the microgrid[4-6], regulate voltage and frequency, offer spinning reserves, and enable electrical demand management. Electric, plug-in hybrid and V2G vehicles will have the potential to absorb excess electricity produced by renewable energy sources (e.g., wind or photovoltaics) when the microgrid is operated at low load conditions, as shown in Fig.1.

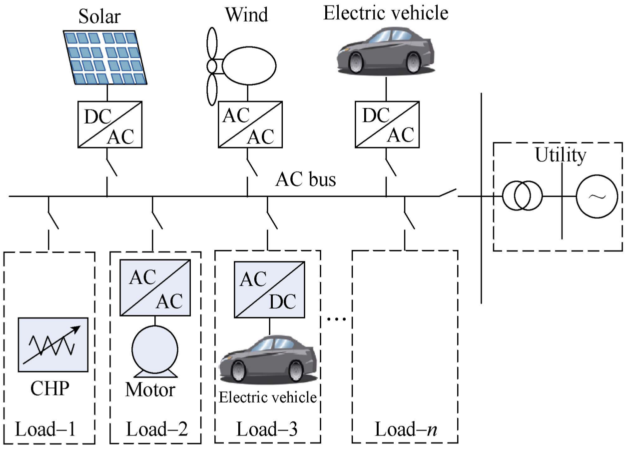


Fig.1 Microgrid integrated with electric vehicles

In general, bi-directional power converters have been applied and the EV charger mainly operates in the grid-to-vehicles(G2V) or vehicles-to-grid(V2G) mode. Also, it is able to operate in the vehicle-to-home(V2H) mode as a backup generation to supply the emergency power directly to a home[7-8].

The traditional EV battery charger in V2H applications mainly consists of DC/DC and DC/AC stages[9]. The DC/AC stage which is usually an inverter is mainly to change the DC energy from the battery to AC energy for various loads. A DC/DC converter acting as the DC/DC stage is used to boost the voltage towards the desired level. The double-stage system needs more semiconductors and complex multiple-loop control structures, resulting in a more complicated design, low power density and lower conversion efficiency as well[10-11].

Meanwhile, if burdened with some 1-phase home appliances, the EV charger which employs 3-phase inverters is problematic with the 3-phase unbalanced condition. So the traditional EV charger is not able to satisfy all the requirements for 1-phase, 3-phase and DC loads simultaneously which are common for home applications[12]. Ray, et al proposed a three-phase boost-derived hybrid converter[13], which can handle the dc and ac loads simultaneously. But for ensuring the neutral point voltage constant, the dc link must use two bulky capacitors in series, which will increase the cost, size and decrease the reliability of the system.

In order to solve the problem, a novel bidirectional EV battery charger is proposed for V2H applications in this paper. It can boost the battery voltage and output DC/AC voltages with no need of two-stage power conversion. Also, the DC, 1-phase and 3-phase loads can be fed with the proposed single-stage EV battery charger. In addition, the fourth leg of the topology provides a path for zero-sequence current and makes the inverter have the

---

* Corresponding Author, E-mail: yeduming@163.com.

Supported by Hebei Province Natural Science Foundation (E2015203407) and Young Scholars Research Project of Yanshan University (15LGB011).

ability of handling unbalanced loads. It can decrease the system cost, volume and increase the power density of the system. The step-by-step design guideline is provided for controlling the proposed single-stage EV battery charger to deal with versatile load variations. Finally, the time-domain performance tests of a Level-2 EV battery charger are carried out, and the test results verify the effectiveness of the proposed solution.

2 Topology and control scheme

The proposed EV charger is shown in Fig.2. It can feed 1-phase, 3-phase and DC loads with a single-stage converter only, which decrease the system cost, volume and increase the power density of the system. Different from the conventional EV charger, the proposed one does not have the problem of the shoot-through breakdown, so the system reliability is enhanced. The 4-leg of the topology provides a path for zero-sequence current and makes the inverter capable of handling unbalanced loads.

Different from the conventional 3-phase inverter, the proposed converter has the shoot-through operating mode. By regulating the duty of D_{st}, the duration of one leg turning on, the DC output will change. There will be energy storage for inductor in shoot- through mode. In active vectors operating mode, the diode conduct and the dc output voltage acts as the input to the 3-phase four-leg inverter.

In continuous conduction operation mode, the DC output voltage and the peak value of AC output voltage can be expressed as

$$V_{\mathrm{dcout}}=\frac{1}{1-D_{\mathrm{st}}}V_{\mathrm{dcin}} \tag{1}$$

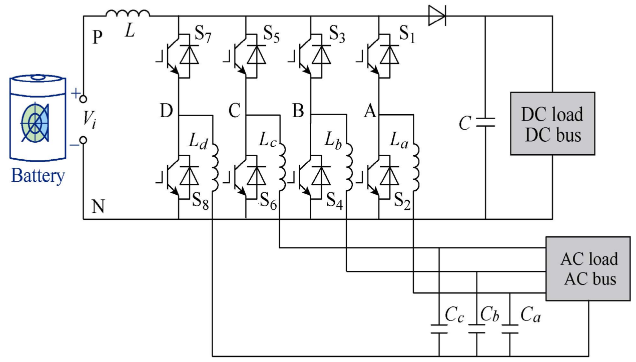


Fig.2 The proposed EV charger

$$V_{\mathrm{acout}}=\frac{M}{2(1-D_{\mathrm{st}})}V_{\mathrm{dcin}} \tag{2}$$

where M is the modulation index, V_{dcin} is the DC input voltage, V_{dcout} is the DC output voltage, V_{acout} is the AC output voltage.

The expressions for DC and AC output power are

$$P_{\mathrm{dc}}=\frac{V_{\mathrm{dcin}}^2}{R_{\mathrm{dc}}\left(1-D_{\mathrm{st}}\right)^2} \tag{3}$$

$$P_{\mathrm{ac}}=\frac{3M^2V_{\mathrm{dcin}}^2}{4R_{\mathrm{ac}}\left(1-D_{\mathrm{st}}\right)^2} \tag{4}$$

The limit between the DC and AC output power is

$$\frac{P_{\mathrm{dc}}}{P_{\mathrm{ac}}}=\frac{4R_{\mathrm{ac}}}{3M^2R_{\mathrm{dc}}} \tag{5}$$

Fig.3 shows the modulation strategy for the proposed EV charger, In order to reduce the switching loss and conducting loss of IGBT, one-leg shoot-through method was adopted in modulation strategy. V_0 is the zero-sequence signal modulated the switches S_7 and S_8.

$$V_0=-\frac{1}{2}\left[\max(V_a,V_b,V_c)+\min(V_a,V_b,V_c)\right] \tag{6}$$

To control the DC and AC output dependently, there is a limit for the sum of D_{st} and M

$$D_{\mathrm{st}}+M\leqslant 1.15 \tag{7}$$

The system control strategy is presented, as shown in Fig.4, to deal with versatile load variations.

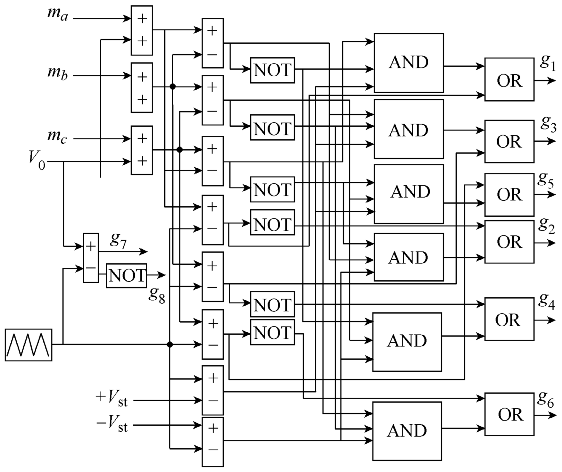


Fig.3 Modulation strategy for EV charger

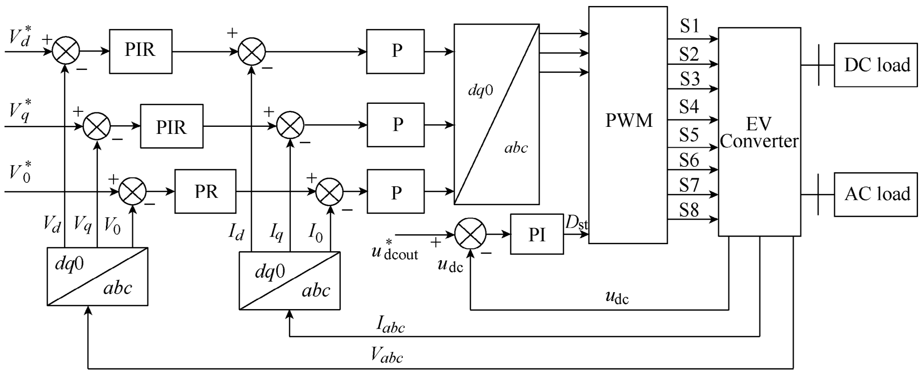


Fig.4 Control strategy for EV charger

The current is unbalanced for unbalanced load systems, which can be divided into positive sequence, negative sequence and zero sequence components. Under two- phase rotating d-q coordinate, the d axis and q axis components include dc components and twice frequency of the fundamental components, independently. The zero axis components include fundamental component. A PI controller is designed to regulate dc output, the AC output control consists of an inner current loop and an outer voltage loop, aPIR controller is designed for d-axis and q-axis voltage loop to ensure zero steady-state error, while the PR controller[14-15] is designed for zero-axis voltage loop and a P controller is adopted for inner current loop.

The controllers for the voltage loop are expressed as follows.

$$G_{\mathrm{PIR}}(s)=K_{\mathrm{P}}+\frac{K_{\mathrm{I}}}{s}+\frac{K_{\mathrm{R}}s}{s^2+4\omega_0^2} \tag{8}$$

$$G_{\mathrm{PR}}(s)=K_{\mathrm{p}}+\frac{K_{\mathrm{r}}s}{s^2+\omega_0^2} \tag{9}$$

where $G_{\mathrm{PIR}}(s)$ is the d-axis and q-axis voltage loop controller, while $G_{\mathrm{PR}}(s)$ is the zero-axis voltage loop controller, ω_0 is the fundamental frequency.

3 Simulation results and discussion

In order to validate the proposed solution, a Level-2 EV charger model with versatile loads is developed with Matlab/Simulink. The system parameters are listed in Table 1.

3.1 DC and 3-phase loads

Firstly, the simulation test is carried on with 3-phase load (rated 3kW) and DC load (rated 1.6kW). The simulation results are shown in the Fig.4.

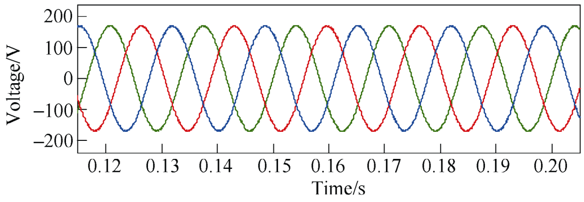
From Fig.5, it can be seen that the 3-phase AC output voltage of the charger is sinusoidal and the DC output voltage is around 400V, which verifies the effectiveness of the proposed charger under both DC and 3-phase loads.

3.2 DC, 1-phase and 3-phase loads

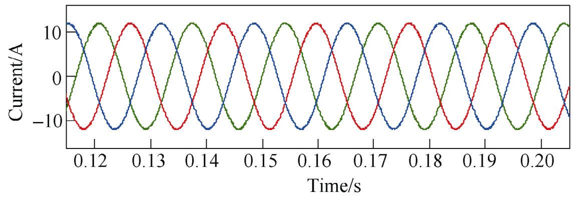
In case of V2H application, single-phase loads are generally involved. In the following test, initially, the charger is connected with DC load (rated 1.6kW) and 3-phase load (rated 3kW). The single- phase load(rated 1kW) is then connected to phase-C at 0.13s.

Table 1 Simulation parameters

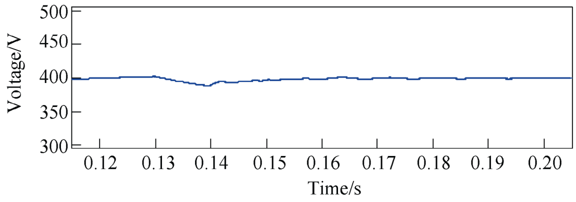
	Parameters	Value
Battery	Nominal voltage/ V	250
	Fully charged voltage/ V	291
	Rated capacity/(Ah)	50
	Internal resistance/ Ω	0.04
	Nominal voltage/ V	250
Charger	L/ mH	1
	C/μF	940
	L_x (x=a,b,c,d)/mH	3
	C_x (x=a,b,c,d)/μF	10
AC output	Single phase voltage/	120V/60Hz
	Three phase voltage	208V/60Hz
DC output	DC Voltage/ V	400



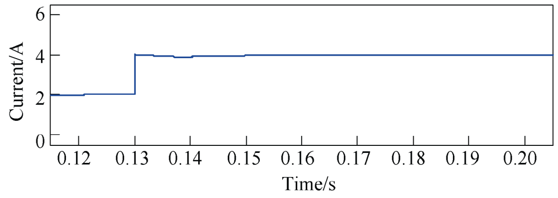
(a) AC output voltage



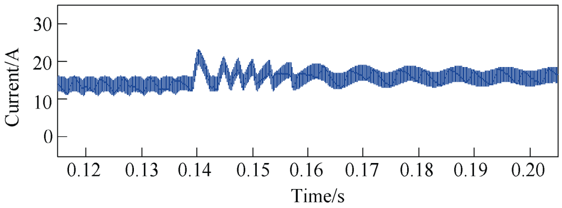
(b) AC output current



(c) DC output voltage



(d) DC output current



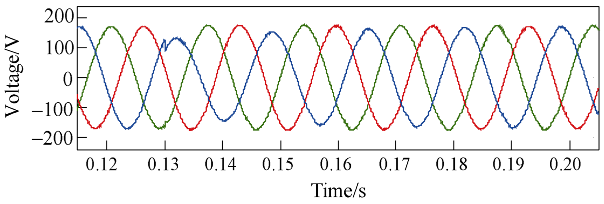
(e) Battery current

Fig.5 Simulation results in case of DC and 3-phase loads

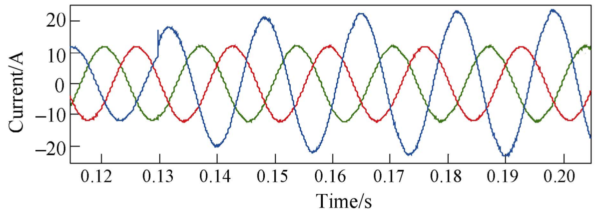
The simulation results are shown in Fig.6, from which it can be observed that 3-phase AC output voltage of the charger is sinusoidal even under both single and three-phase loads. Aside from that, and the DC output voltage is well regulated around 400V, which verify the effectiveness of the proposed charger under single/three-phase and DC loads.

3.3 DC load

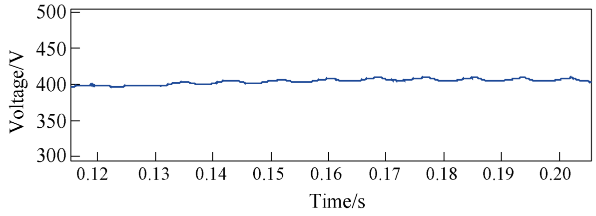
When the vehicles only supply electricity for DC load, the converter plays the role of a boost circuit. The DC voltage is controlled by a closed-loop method, and only the fourth leg switches S7 and S8 are modulated. The simulation test is carried on with DC load (rated 1.6kW). The simulation results are shown in the Fig.7. It can be seen that the DC output voltage is around 400V, which verifies the effectiveness of the closed-loop control. In this case, the AC voltage and current is zero.



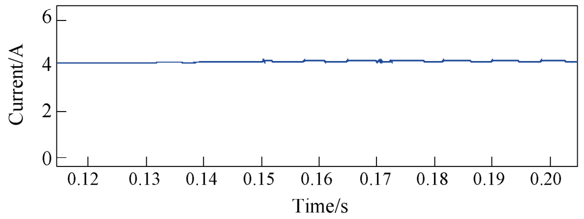
(a) AC output voltage



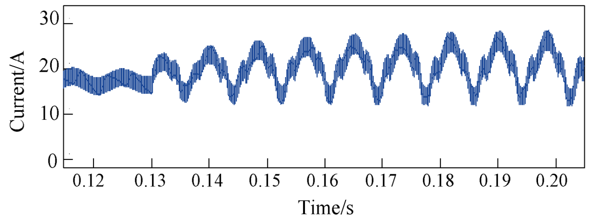
(b) AC output current



(c) DC output voltage

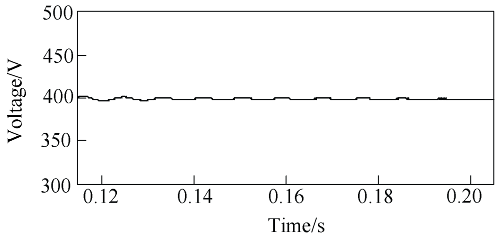


(d) DC output current

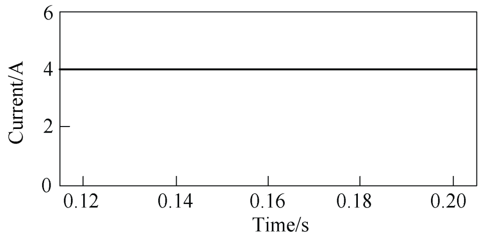


(e) Battery current

Fig.6 Simulation results in case of DC, 1-phase and 3-phase loads



(a) DC output voltage



(b) DC output current

Fig.7 Simulation results in case of DC loads

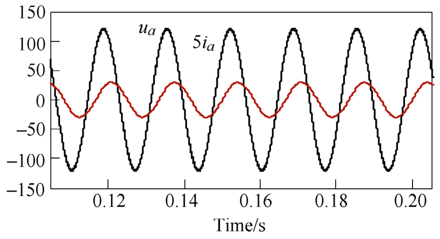


Fig.8 Simulation results with resistance-inductance loads

3.4 Resistance-inductance loads

In case of V2H application, resistance-inductance loads are generally involved. In the following test, the charger is connected with AC load. The active power is rated 1.5kW and the inductive reactive power is rated 1.5kvar, the simulation result is shown in fig.8. It can be seen that the AC current and voltage are not in-phase, and the current lags behind the voltage 45 degrees.

4 Conclusion

This paper has presented the analysis and evaluation of a novel boost four-leg converter for electric vehicle applications. The results reveal that the proposed EV charger can boost the battery voltage and output 3-phase AC voltage. Also, 1-phase, 3-phase and DC loads can be fed with one stage conversion only. The test results verify the effectiveness of the proposed solution.

References

[1] L. Hua, J. Wang, and C. Zhou, "Adaptive electric vehicle charging coordination on distribution network," *IEEE Trans. Smart Grid*, vol. 5, no.6, pp.2666-3675, Nov. 2014.

[2] X. Li, L. A. C. Lopes, and S. S. Williamson, "On the suitability of plug-in hybrid electric vehicle (PHEV) charging infrastructures based on wind and solar energy," *Proc. IEEE Power & Energy Society General Meeting*(PES '09), pp. 1-8.

[3] C. Liu, K. T. Chau, Diyun Wu, and S. Gao, "Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies," *Proc. of the IEEE*, vol. 101, no. 11, pp.2409-2427, Nov. 2013.

[4] C. Chen, and S. Duan, “Microgrid economic operation considering plug-in hybrid electric vehicles integration", *Journal of Modern Power Systems and Clean Energy*, vol. 3, pp. 221-231, 2015.

[5] J. Cai, C. Chen, P. Liu, and S. Duan, "Centralized control of parallel connected power conditioning system in electric vehicle charge–discharge and storage integration station," *Journal of Modern Power Systems and Clean Energy*, vol. 3, no.2, pp. 269-276, 2015.

[6] L. Liu, F. Kong, X. Liu, Y. Peng, and Q. Wang, "A review on electric vehicles interacting with renewable energy in smart grid," *Renewable and Sustainable Energy Reviews*, no. 51, pp. 648-661, 2015.

[7] J. G. Pinto, V. Monteiro, H. Gonçalves, B. Exposto, D. Pedrosa, C. Couto, and J. L. Afonso, "Bidirectional battery charger with grid-to-vehicle, vehicle-to-grid and vehicle-to-home technologies," Proc. of IEEE 39th Annual Conference IECON, pp. 5934-5939, 2013.

[8] F. Berthold, A. Ravey, B. Blunier, D. Bouquain, S. Williamson, and A. Miraoui, "Design and development of a smart control strategy for plug-in hybrid vehicles including vehicle-to-home functionality," *IEEE Trans. on Transportation Electrification*, vol. 1, no. 2, pp.168-177, Aug. 2015.

[9] M. Yilmaz, and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for

plug-in electric and hybrid vehicles," *IEEE Trans. on Power Electronics*, vol. 28, no. 5, pp. 2151-2169, May 2012.

[10] A. Khaligh, S. Dusmez, "Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles," *IEEE Trans. Vehicular Technology*, vol. 61, no. 8, pp. 3475 -3489, Oct. 2012.

[11] S. F. Tie, C. W. Tan,"A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 20, no.4, pp.82-102, 2013.

[12] K. Ma, W. Chen, M. Liserre, F. Blaabjerg, "Power controllability of a three-phase converter with an unbalanced AC source," *IEEE Trans. Power Electronics*, vol.30, no.3, pp.1591-1604, Mar. 2015.

[13] O. Ray, V. Dharmarajan, S. Mishra, R. Adda, and P. Enjeti, "Analysis and PWM control of three-phase boost-derived hybrid converter," *Proc. of IEEE Energy Conversion Congress and Exposition(ECCE)*, pp. 402-408, Nov. 2014.

[14] W. Wu, M. Huang, X. Wang, H. Wang, F. Blaabjerg, M. Liserre, and H. S. Chung, “A robust passive damping method for LLCL-filter-based grid-tied inverters to minimize the effect of grid harmonic voltages,” *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3279-3289, Jul. 2014.

[15] W. Wu, Y. He, and F. Blaabjerg, “A new design method for the passive damped LCL- and LLCL-filter based single-phase grid-tied inverter,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 10, pp. 4339-4350, Oct. 2013.

Xiaoyu Jia received the B.S. degree in electrical engineering from Yanshan University, Qinhuangdao, China, in 2014, where she is currently working toward the M.S. degree in power electronics.

Her current research interests include modulation and control technology of photovoltaic grid-connected inverter.

Huaibao Wang is an associated researcher at Department of Electrical Engineering, Yanshan University. His research interests include renewable energy systems.

Baocheng Wang is a professor at Department of Electrical Engineering, Yanshan University. His research interests include renewable energy systems.

Xiaoqiang Guo (M' 10-SM' 14) received the B.S. and Ph.D. degrees in electrical engineering from Yanshan University, Qinhuangdao, China, in 2003 and 2009, respectively.

He has been a Postdoctoral Fellow with the Laboratory for Electrical Drive Applications and Research (LEDAR), Ryerson University, Toronto, ON, Canada. He is currently an associate professor with the Department of Electrical Engineering, Yanshan University, China. He has authored/coauthored more than fifty technical papers, in addition to nine patents. His current research interests include high-power converters and ac drives, electric vehicle charging station, and renewable energy power conversion systems.

Dr. Guo is a Senior Member of the IEEE Power Electronics Society and IEEE Industrial Electronics Society. He is an active Referee for IEEE Transactions on Industrial Electronics and IEEE Transactions on Power Electronics.

Xiaoyu Wang (M’08-SM’13) received the B.Sc. and M.Sc. degrees from Tsinghua University, Beijing, China, in 2000 and 2003, respectively, and the

Ph.D. degree from the University of Alberta, Edmonton, AB, Canada, in 2008.

He is currently an Associate Professor with the Department of Electronics, Faculty of Engineering and Design, Carleton University, Ottawa, ON, Canada.

His research interests include the integration of distributed energy resources and power quality.