from 310V to 225V at 400ms when the gain of the ES is 0.05. As shown in Fig. 16(a), the current is significantly reduced from 10A to 6A, which implies that the active power is reduced from 1550W to 675W. When the gain of the ES is 0.2, as shown in Fig. 16(b), V_l drops from 310V to 281V at 600ms, and the current drops from

Fig. 15. Photograph of the AC/AC Buck converter.

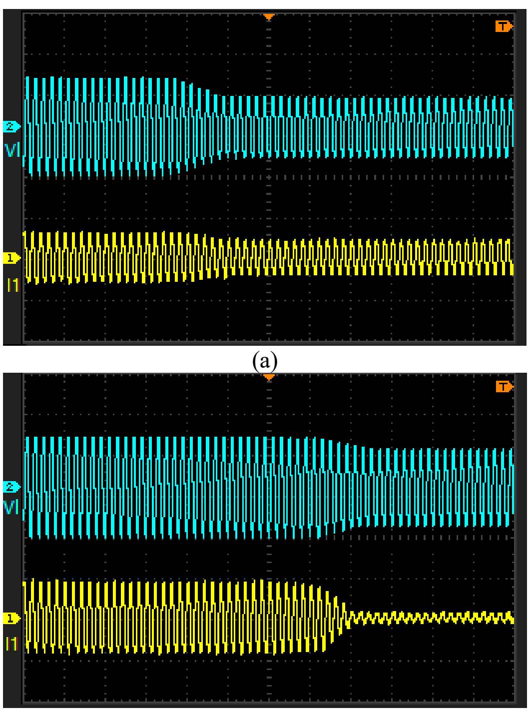

Fig. 16. Voltage and current curves of a smart load: (a) the ES gain is 0.05, CH1- I_l 15A/Div., CH2- V_l 150V/Div., Time Base 100ms/Div; (b) the ES gain is 0.2, CH1- I_l10A/Div., CH2- V_l 150V/Div., Time Base 100ms/Div.

10A to 1.9A. This implies that the active power is shed from 1550W to 267W. This result shows that the resistive ES performs well in shedding power when the mains voltage drops.

C. Test c): Operation of the Proposed Power Flow Controller in a Subnetwork with an Intermittent Wind Power Injection

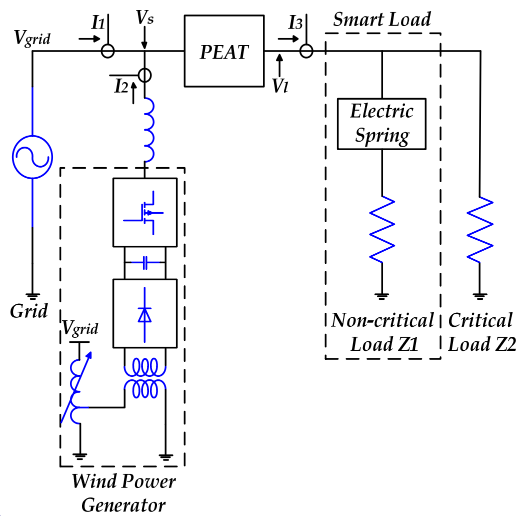

Fig. 17. Experiment setup schematic.

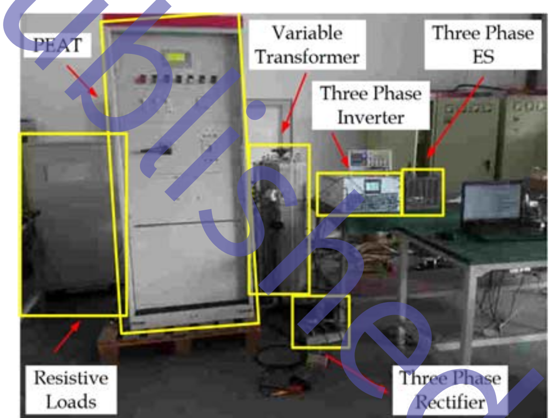

Fig. 18. Photograph of the practical experiment setup.

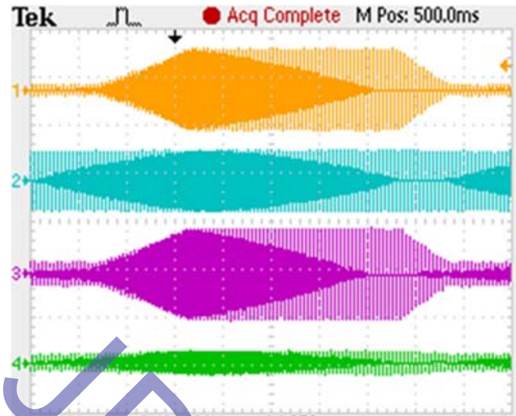

Fig. 19. Measured waveforms where CH1 - wind power generator current I_2 50A/Div., CH2 - Line voltage V_l 500V/Div., CH3 - Line current I_3 50A/Div., CH4 - Grid current I_1 50A/Div., Time Base 250ms/Div.

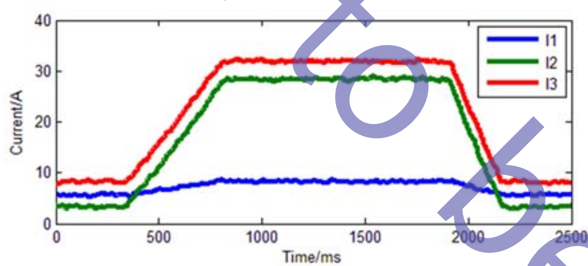

Fig. 20. RMS values of the currents with the grid current I_1, wind power generator current I_2 and line current I_3.

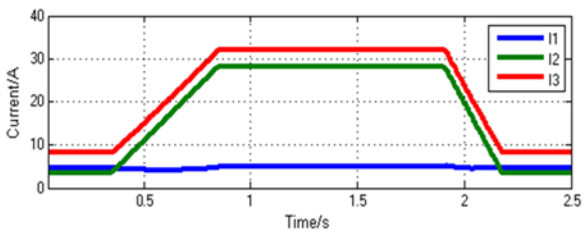

Fig. 21. Simulated RMS values of the currents with the grid current I_1, wind power generator current I_2 and line current I_3.

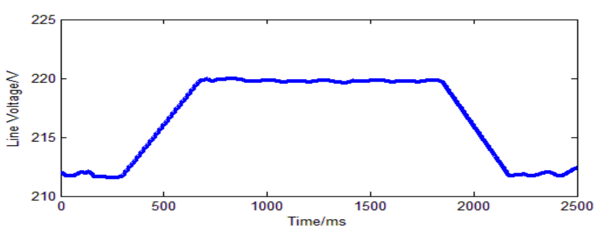

Fig. 22. RMS values of the line voltage.

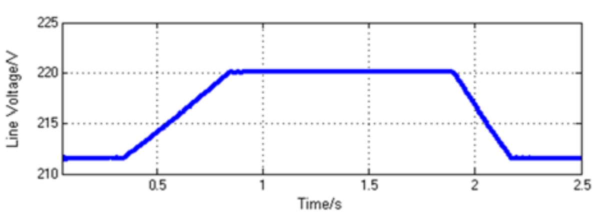

Fig. 23. Simulated RMS values of the line voltage.

A subnetwork system is built and the experimental setup schematic is shown in Fig. 17. The system includes a wind power generator, a PEAT, a smart load and a critical load.

The wind power generator applies a variable transformer to simulate intermittent wind power. The variable transformer varies the voltage by moving the tap changer, and then voltage is applied to the isolation transformer to isolate the voltage from the grid for protection purposes. The isolation transformer output voltage is regulated through a grid connected inverter to simulate intermittent wind power. The PEAT controller regulates the total load power to be balanced with wind power, which is the second power controller in Section V. The smart load automatically sheds the load power. Both the smart load and critical load are connected to the subnetwork. Waveforms of the power source voltage V_s, line voltage V_l, grid current I_1, wind power generator current I_2 and line current I_3 are measured. Fig. 16 shows a photograph of the practical experiment setup. The test conditions are the grid phase voltage V_{grid} = 220Vac, non-critical load Z_1 = 8.2 ohm, critical load Z_2 = 43ohm, G (the gain of the ES) = 31, P (the proportional gain of the power flow controller) = 8 and I (the integral gain of the power flow controller) = 2.

The power flow controller is activated and works throughout the experiment. The purpose of the experiment is to check the performance of power flow controller when wind energy changes. In the beginning, the wind power generator current I_2 is around 3.5A as shown in Fig. 20. It then begins to increase to 28.2A to inject more power into the system, which is simulated in this experiment by changing the tap-changer of the variable transformer of the wind power generator in Fig. 17. The wind power generator current I_2 then decreases to 3.5A again. The experiment result in Fig. 20 show that the line current I_3 increases from 8.2A to 32.0A when the wind power generator injects more power, and decreases to 8.2A when the wind power generator decreases the injected power. This implies that the total load power follows the wind power and that the power flow controller performs well. The grid current only changes slightly when the wind power changes, which shows that the total load power is balanced with the wind power and that the impact of the intermittent nature of the wind power generator on the grid is significantly reduced. Fig. 22 shows that the line voltage is increased by the PEAT and ES of the power flow controller when the wind power increases. As a result, more power is consumed by the load. Fig. 19 shows measured waveforms of the wind power generator current I_2, line voltage V_l, line current I_3 and grid current I_1. It shows that the line current follows the trend of the wind generator current and that the grid current only changes slightly when the wind generator current changes.

Fig. 21 shows MATLAB simulation results of the RMS values of the grid current I_1, wind power generator current I_2, line current I_3 and line voltage. Comparisons between Fig. 20

and Fig. 21 and between Fig. 22 and Fig. 23 show that the practical experiment results follow the simulation experiment results.

The obtained experiment results validate the function of the proposed power flow controller, which applies the second power controller in Section V. The total load power is balanced with the wind power and the impact of changes in the wind power have a slight impact on grid.

VIII. Conclusions

A novel power flow controller comprising a resistive ES and a PEAT has been developed. The principle behind the control strategy has been described in detail, and a stability analysis performed on the derived mathematical model for the controller shows that it is stable. Simulations carried out for different test cases on this model indicate the effectiveness of the proposed controller in shaping the power flow. An experimental setup is made, and it is shown that the obtained experimental results closely follow the simulation results, indicating that the model of the power flow controller is valid. In addition, the stability analysis and effectiveness of the proposed power flow controller can be extended to actual realization.

The obtained results show that the PEAT plays the role of a global controller and the ES plays the role of a local controller. The combination of these two controllers makes the power flow control complete in terms of controlling the RES power to supply non-critical loads and grid power to supply critical loads. This way, the critical loads, which require a stable and reliable power supply, are guaranteed to be provided with power through the grid, and the non-critical loads can be supplied power through an intermittent but cheaper RES when it is available. If the RES produces abundant power, the critical loads can be supplied power through it instead of the grid.

It can be concluded that the proposed power flow controller is a promising and realizable way to mitigate the effect of the intermittent availability of the RES in the future grid and to ease the tension of the grid power supply to meet sudden changes in electricity demand.

Appendix

TABLE I

System Stability Analysis Test Data

k_{es}	V_l (V)	I_1(A)	I_2(A)	V_{es} (V)	V_l(V)	λ_1	λ_2
0.5	206.0549	199.0824	206.0549	6.9725	199.0824	-1514.8+177.8i	-1514.8-177.8i
1	206.1834	192.3667	206.1834	13.8166	192.3667	-1.1675e3	-1.18626e3
2	206.4274	179.2823	206.4274	27.1452	179.2823	-0.8476e3	-2.3597e3
5	207.0713	142.4275	207.0713	64.6437	142.4275	-0.4773e3	-3.8784e3
10	207.9175	87.0926	207.9175	120.8249	87.0926	-0.2762e3	-7.0481e3
20	209.0533	-9.8798	209.0533	218.9332	-9.8798	-0.0148e3	-1.7656e3
30	209.7082	-99.0452	209.7082	308.7534	-99.0452	-0.0100e3	-4.4733e3

TABLE II

Case Studies Results

		Part1(1~5min)	Part2(6~9min)	Part3(10~13min)
Case 1)	Average Power Upstream(kW)	30.1	0.2	0.2
	Critical load power(kW)	6.5	6.8	11.4
	Non-critical load power(kW)	48.2	19.1	16.0
	Wind power(kW)	25.1	25.1	25.1
	Critical load voltage(V)	207.5	213.8	213.3
Case 2)	Average Power Upstream(kW)	30.1	7.1	11.7
	Critical load power(kW)	6.5	6.9	11.6
	Non-critical load power(kW)	48.2	25.3	25.1
	Wind power(kW)	25.1	25.1	25.1
	Critical load voltage(V)	207.5	214.5	214.6
Case 3)	Average Power Upstream(kW)	30.1	0.2	0.3
	Critical load power(kW)	6.5	6.9	11.4
	Non-critical load power(kW)	48.2	17.9	16.5
	Wind power(kW)	25.1	25.1	25.1
	Critical load voltage(V)	207.5	213.9	213.3

REFERENCES

[1] S. R. Bull, "Renewable energy today and tomorrow," *Proceedings of the IEEE*, Vol. 89, No. 8, pp. 1216-1226, Aug. 2001.

[2] A. Tuladhar, H. Jin, and T. Unger, "Control of parallel inverters in distributed ac power system with consideration of line impedance effect," *IEEE Trans. Ind. Appl.*, Vol. 36, No. 1, pp. 131-138, Feb. 2000.

[3] Z. Liu, "An improved droop control based on complex virtual impedance in medium voltage micro-grid," *IEEE Power and Energy Engineering Conference (APPEEC)*, pp. 1-6, 2013.

[4] F. Shahnia, R. Majumder, and A. Ghosh, "Operation and control of a hybrid microgrid containing unbalanced and nonlinear loads," *Electric Power Systems Research*, Vol. 80, No. 8, pp. 954-965, Aug. 2010.

[5] T. L. Vandoom, J. D. M. De Kooning, and B. Meersman, "Automatic power-sharing modification of P/V droop controllers in low-voltage resistive microgrids," *IEEE Trans. Power Del.*, Vol. 27, No. 4, pp. 2318-2325, Sep. 2012.

[6] R. Majumder, B. Chaudhuri, and A. Ghosh, "Improvement of stability and load sharingin an autonomous microgrid using supplementary droop control loop," *lEEE Trans. Power Syst.*, Vol. 25, No. 2, pp. 796-808, Jul. 2010.

[7] E. Reihani, S. Sepasi, and L. R. Roose, "Energy management at the distribution grid using a battery energy storage system (BESS)," *International Journal of Electrical Power & Energy Systems*, Vol. 77, pp 337-344, May 2016.

[8] A. Subburaj, P. Kondur, and S. B. Bayne, "Analysis and review of grid connected battery in wind applications," *2014 Sixth Annual IEEE Green Technologies Conference*, pp. 1-6, 2014.

[9] B. Shaffer, B. Tarroja, and S. Samuelsen, "Dispatch of fuel cells as transmission integrated grid energy resources to support renewables and reduce emissions," *Applied Energy*, Vol. 148, pp. 178-186, Jun. 2015.

[10] S. Sichilalu, H. Tazvinga, and X. Xia, "Optimal control of a fuel cell/wind/PV/grid hybrid system with thermal heat pump load," *Solar Energy*, Vol. 135, pp. 59-69, Oct. 2016.

[11] W. Chen, Y. Han, and Q. Li, "Design of proton exchange membrane fuel cell grid-connected system based on resonant current controller," *International Journal of Hydrogen Energy*, Vol. 39, No. 26, pp. 14402-14410, Sep. 2014.

[12] M. G. Molina and P. E. Mercado, "Power flow stabilization and control of microgrid with wind generation by superconducting magnetic energy storage," *IEEE Trans. Power Electron.*, Vol. 26, No. 3, pp. 910-922, Dec. 2011.

[13] T. Asao, R. Takahashi, and T. Murata, "Evaluation method of power rating and energy capacity of Superconducting Magnetic Energy Storage system for output smoothing control of wind farm," *ICEM 2008. 18th International Conference on Electrical Machines*, pp. 1-6, 2008.

[14] M. G. Molina and P. E. Mercado, "Power flow control of microgrid with wind generation using a DSTATCOM-UCES," *IEEE International Conference on Industrial Technology (ICIT)*, pp. 955-960, 2010.

[15] I. Hadipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renewable Sustainable Energy Rev.*, Vol. 13, No. 6-7, pp. 1513-1522, Aug./Sep. 2009.

[16] A. S. Subburaj, B. N. Pushpakaran, and S. B. Bayne, "Overview of grid connected renewable energy based battery projects in USA," *Renewable and Sustainable Energy Reviews*, Vol. 45, pp. 219-234, May 2015.

[17] Balijepalli, V. S. K. M, Pradhan, and V. Khaparde, "Review of demand response under smart grid paradigm," *Innovative Smart Grid Technologies - India (ISGT India), 2011 IEEE PES*, pp. 236-243, Dec. 2011.

[18] P. Kienzle and G. Andersson, "Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty," *IEEE Trans. Sustain. Energy*, Vol. 2, No. 2, pp. 194-202, Jan. 2011.

[19] C. Zhao and Topcu, "Optimal load control via frequency measurement and neighborhood area communication," *IEEE Trans. Power Syst.*, Vol. 28, No. 4, pp. 3576-3587, May 2013.

[20] M. Shankar, J. Nutaro, and J. Stovall, "Evolution of communication and control for electric grid load management," *IEEE Power and Energy Society General Meeting*, pp. 1-7, Jul. 2010.

[21] C. K. Lee, B. Chaudhuri, and S. Y. Hui, "Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources," *IEEE J. Emerg. Sel. Topics Power Electron.*, Vol. 1, No. 1, pp. 18-27, May 2013.

[22] C. K. Lee, K. L. Cheng, and W. M. Ng, "Load characterization of electric spring," *IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 4665-4670, Sep. 2013.

[23] C. K. Lee, S. C. Tan, and F. F. Wu, "Use of Hooke's law for stabilizing future smart grid– the electric spring concept," *IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 5253-5257, Sep. 2013.

[24] J. Soni, K. R. Krishnanand, and S. K. Panda, "Load-side demand management in buildings using controlled electric springs," *Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE*, pp. 5376-5381, 2014.

[25] C. K. Lee and S. Y. Hui, "Reduction of energy storage requirements in future smart grid using electric springs," *IEEE Trans. Smart Grid*, Vol. 4, No. 3, pp. 1282-1288, Apr. 2013.

[26] C. K. Lee, N. R. Chaudhuri, and B.Chaudhuri, "Droop control of distributed electric springs for stabilizing future power grid," *IEEE Trans. Smart Grid*, Vol. 4, No. 3, pp. 1558-1566, Jul. 2015.

[27] Y. Shuo, S. C. Tan, and C. K. Lee, "Electric spring for power quality improvement," *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, pp. 2140-2147, 2014.

[28] X. Che, T. Wei, and Q. Huo, "A general comparative analysis of static synchronous compensator and electric spring," *2014 IEEE Conference and Expo on Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, pp. 1-5, 2014.

[29] X. Luo, Z. Akhtar, and C. K. Lee, "Distributed voltage control with electric springs: comparison with STATCOM," *IEEE Trans. Smart Grid*, Vol. 6, No. 1, pp. 209-219, Aug. 2014.

[30] R. Kabiri, G. Holmes, and B. McGrath, "LV grid voltage regulation using transformer electronic tap changing, with PV inverter reactive power injection," *IEEE J. Emerg. Sel. Topics Power Electron.*, Vol. 3, No. 4, pp. 1182-1192, Jun. 2015.

[31] C. R. Fuerte-Esquivel, E. Acha, and I. Ambriz-Perez, "Integrated SVC and step-down transformer model for Newton-Raphson load flow studies," *IEEE Power Eng. Rev.*, Vol. 20, No. 2, pp. 45-46, Feb. 2000.

[32] P. Melato, N. Mbuli, and J. Pretorius, "Serving low load levels by derating line voltage using step down transformers," *50th International Universities Power Engineering Conference (UPEC)*, pp. 1-5, 2015.

[33] R. Majumder, A. Ghosh, and G. Ledwich, "Power management and power flow control with back-to-back converters in a utility connected microgrid," *IEEE Trans. Power Syst.*, Vol. 25, No. 2, pp. 821-834, Nov. 2009.

[34] E. Martinez, I. Fernandez, and J. Canales, "Thyristor based solid state tap changer for distribution transformers," *2013 IEEE 11th International Workshop of Electronics, Control, Measurement, Signals and their application to Mechatronics (ECMSM)*, pp. 1-5, Jun. 2013.

[35] S. M. Garcia, J. Rodriguez, and J. Antonio, "Feasibility of electronic tap-changing stabilizers for medium voltage lines – Precedents and new configurations," *IEEE Trans. Power Del.*, Vol. 24, No. 3, pp. 1490-1503, Jun. 2009.

[36] H. Jiang, R. Shuttleworth, and B. Zahawi, "Fast response GTO assisted novel tap changer," *IEEE Trans. Power Del.*, Vol. 16, No. 1, pp. 111-115, Jan. 2001.

[37] J. Faiz and B. Siahkolah, "New solid-state onload tap-changers topology for distribution transformers," *IEEE Trans. Power Del.*, Vol. 18, No. 1, pp. 136-141, Jan. 2003.

[38] J. Faiz and B. Siahkolah, "Optimal configurations for taps of windings and power electronic switches in electronic tap-changers," *IEE Proceedings - Generation, Transmission and Distribution*, Vol. 149, No. 5, pp. 517-524, Dec. 2002.

[39] S. Bhowmik and R. Spee, "A guide to the application-oriented selection of AC/AC converter topologies," *IEEE Trans. Power Electron.*, Vol. 8, No. 2, pp. 156-163, Feb. 1993.

[40] C. Wang and C. Su, "A Novel Common-Neutral Single-Stage Single-Phase AC/DC/AC Converter with High Input Power Factor," *37th IEEE Power Electronics Specialists Conference, 2006. PESC '06*, pp. 1-5, 2006.

[41] The MathWorks Inc., SimPowerSystems™ *R2013b User's Guide (Second Generation)*, 2013.

[42] N. Vazquez, A. Velazquez, and C. Hernandez, "AC voltage regulator based on the AC-AC buck-boost converter," *IEEE International Symposium on Industrial Electronics*, pp. 533 - 537, Jun. 2007.

[43] IEEE Standard 141-1993.

[44] IEEE Standard 519-1992.

[45] W. Wangdee, "Reliability Impact of intermittent renewable energy source integration into power system," *2014 IEEE International Electrical Engineering Congress (iEECON)*, pp. 1-4, 2014

Kun Liu was born in Jiangxi, China. He received his B.S. degree in Electrical Engineering from Shanghai Jiao Tong University, Shanghai, China, in 2014, where he is presently working towards his M.S. degree in Electrical Engineering with a specialization in Power Electronics. His current research interests include DC-DC converters, contactless inductive power transfer, as well as the control and stability of microgrids and smart grids.

Muhammad Mansoor Khan was born in Lahore, Pakistan. He received his B.S. degree in Electronics from the NED University of Engineering and Technology, Karachi, Pakistan; his M.S. degree in System Engineering from Quaid-i-Azam University, Islamabad, Pakistan; and his Ph.D. degree from Shanghai Jiao Tong University, Shanghai, China, in 2002. He has been with the Department of Electrical Engineering for past 12 years, and is presently serving as an Associate Professor. He has coauthored more than 30 SCI papers. His current research interests include power electronic converters, power quality equipment, solar inverters, solid-state transformers, as well as the control and stability of microgrids and smart grids.

Ahmad Rana received his B.S. degree in Electrical Engineering (with honors) from the University of Engineering and Technology, Lahore, Pakistan; his M.S. degree in Systems Engineering with a specialization in Nuclear Instrumentation and Control from the Center for Nuclear Studies, Nilore, Pakistan; and his Ph.D. degree in Robotics from the University of Sheffield, Sheffield, ENG, UK. He is actively involved in applied research, and is a Research Associate at the Villanova Center for Analytics of Dynamic Systems of Villanova University, Villanova, PA, USA. He also runs a consultant firm offering services in industrial control. His current research interests include embedded control systems for power electronics, and telecommunication systems for distributed embedded control.

Dong Fei received his B.S. degree in Mechanical Engineering from Tongji University, Shanghai, China, in 2005; and his M.S. degree in Electrical Engineering from Shanghai Jiao Tong University, Shanghai, China, in 2012. From 2005 to 2010, he was with the State Grid Shanghai Municipal Electric Power Company, Shanghai, China. In 2010, he joined State Grid Shanghai Procurement Company, Shanghai, China. His current research interests include DC-DC converters, and PWM converter/inverter systems.