

Distributed Autonomous Voltage Balancing Control for A Modular IPOS DC Grid-Connected Renewable Power System

Xiaofeng Dong, Hongfei Wu,
Yangjun Lu, Haibing Hu
Center for More-Electric-Aircraft Power System
Nanjing University of Aeronautics and Astronautics
Nanjing, China
wuhongfei@nuaa.edu.cn

Kai Sun
Department of Electrical Engineering
Tsinghua University
Beijing China
sun-kai@mail.tsinghua.edu.cn

Abstract—A distributed autonomous voltage balancing control strategy for an input-parallel output-series (IPOS) modular DC grid-connected renewable power system is presented and analyzed in this paper. Autonomous voltage balancing of output voltages and distributed voltage regulation of low voltage DC bus of these IPOS DC-DC modules are achieved by introducing the output voltages of DC-DC modules into the input voltage reference of each module. The information of output voltages of these modules is shared through the low voltage DC bus. Therefore, fully distributed and automatic power balancing control and hot-swap can be realized without information exchange or central controller among these modules. Simple control, easy realization and high reliability can be ensured with the presented control strategy. Experimental results are provided to verify the effectiveness and feasibility of the IPOS system and its control strategy.

Keywords—Input-parallel output-series (IPOS); autonomous voltage balancing control; DC grid-connected; modular system

I. INTRODUCTION

Renewable energy power generation systems, like photovoltaic (PV) energy, have been known as an effective solution of severe environmental pollution and energy shortage problems [1]-[4]. For a long time, AC grid-connected system is a major technical approach of utilizing renewable energy. In comparison with a traditional AC grid-connected system, a DC grid-connected system is more promising because of its advantages of easier control, higher efficiency, more flexibility and stability [5]-[8]. However, it is difficult to meet the requirement of high voltage DC grid, e.g. a 10kV DC grid, using only one DC-DC converter due to the high voltage stresses of devices. In addition, the output voltage of PV modules is relatively low. In order to interface the low output voltage of the PV panels with a high voltage DC grid, multiple modular DC-DC converters with input-parallel output-series (IPOS) configuration can be used. IPOS systems have been widely used in high output power systems [9]-[11], but the operation and control of an IPOS system for DC grid-connected applications are much more different. One of the key problems in operation of modular IPOS systems is to

guarantee the balance of voltages among these modules. Although there have been some research results on equalizing control of series-parallel systems, these control strategies cannot be directly applied to a DC-grid connected power system, in which both low voltage DC bus and grid current should be regulated simultaneously[12]-[14]. Moreover, input of DC grid-connected PV system usually show constant power characteristics, and its output is a DC grid, whose voltage cannot be changed by the IPOS system. Therefore, the traditional voltage balancing control strategies can't directly apply to DC grid-connected PV system.

A modular DC grid-connected renewable power system with distributed automatic voltage balancing control strategy is presented in this paper. Distributed and autonomous low voltage DC-bus regulation and output voltage sharing control is achieved by using only one input voltage control loop of each DC-DC module in the IPOS system. Furthermore, hot-swap of DC-DC modules can be achieved to improve the reliability of whole DC grid-connected renewable power system.

II. SYSTEM ARCHITECTURE AND CONTROL STRATEGY

A. System Architecture

The architecture of modular DC grid-connected renewable power system is illustrated in Fig.1. The first stage is a modular

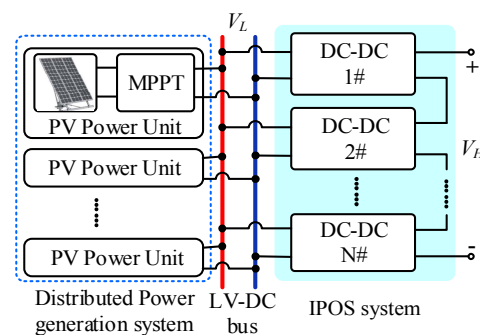


Fig. 1. Modular DC grid-connected PV system.

This work was supported by National Natural Science Foundation of China (51407092, 51577102), Six talent peaks project in Jiangsu Province (2016-XNYQC-008) and QingLan Project.

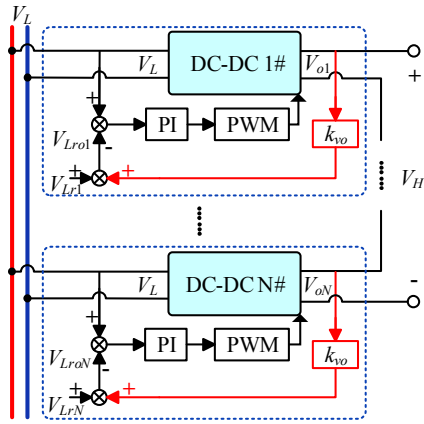


Fig. 2. Autonomous voltage balancing control of IPOS DC grid-connected system.

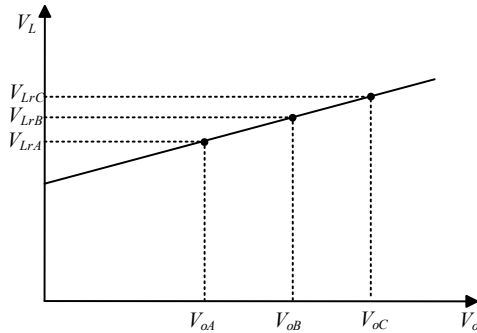


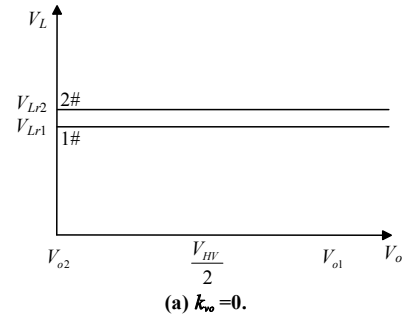
Fig. 3. Relation between input and output voltages.

distributed power generation system, which is responsible for distributed MPPT control of PV modules. The second stage is an IPOS DC grid-connected system, which is composed of multiple DC-DC power modules and the main focus of this paper. The inputs of these DC-DC grid-connected modules are connected in-parallel to the low-voltage (LV)-DC bus while outputs of these modules are connected in-series to the high-voltage (HV)-DC bus. Hence, voltage stress at output side and the current stress at input side of these modules can be reduced. In addition, in order to improve the reliability and stability of IPOS DC grid-connected system, it need to achieve output voltages balance of different modules.

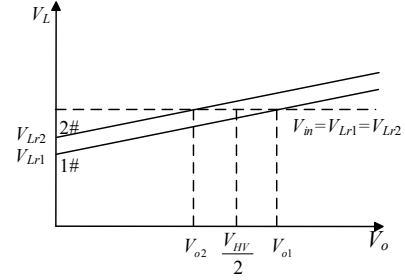
B. Control Strategy

According the intrinsic logical relationship of input voltage reference and output power in single module. Considering to build an autonomous regulation to rise input voltage reference when output power increases, and then lead to restrain output power's change. In addition, voltage balancing of IPOS system should be realized and output voltage of each module reflects its output power.

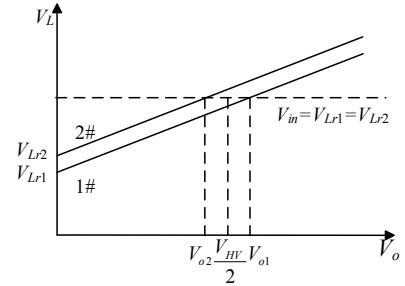
The control objectives of IPOS system include input and output voltages stability, grid-connected current adjustment and output voltages balancing. With presented distributed autonomous voltage balancing control strategy, each module has the same control loop as shown in Fig.2. And each module



(a) $k_{vo}=0$.



(b) Small k_{vo} .



(c) Large k_{vo} .

Fig. 4. Impact of k_{vo} on output voltage.

is controlled by its own controller with its own voltage samples. No information exchange among these modules and fully modular design implementation can be realized. Each module's output voltage is sampled and used to adjust module's input voltage reference, which can be obtained as

$$V_L = V_{Lroi} = V_{Lri} + k_{vo} V_{oi} \quad (i = 1, 2, \dots, N) \quad (1)$$

V_{Lri} is the given input voltage reference of module $i\#$, V_{oi} is the output voltage sample and V_{Lroi} is the actual input voltage reference. k_{vo} is the output voltage superposition coefficient.

Compared with traditional control methods, information of output voltage is introduced into input voltage reference in the presented control strategy. Both input and output voltages of each module can be controlled simultaneously by using only one input voltage control loop.

Fig.3 is the relation between input and output voltages of each modules. According to Fig.3, a higher output voltage will lead to a higher input voltage. Since inputs are all connected in parallel, an increase of input voltage will lead to a decrease of input power. Therefore, output voltage of this module will decrease. And the module with smaller output voltage will absorb more power from input and lead an increase of its output voltage. Hence, voltage unbalance rate decrease and distributed autonomous voltage balancing control is realized.

III. OUTPUT VOLTAGE BALANCING PERFORMANCE ANALYSIS

The balance of output voltage of each module reflects equalization of power stress in modular IPOS DC grid-connected system. Taking two-module IPOS system as an example to analyze characteristics of autonomous balancing control strategy studied in this paper. Supposed that due to the inconsistency of parameters, the relation of two modules' given input voltage references V_{Lr1} and V_{Lr2} is as follows

$$V_{Lr2} = V_{Lr1} + \Delta V \quad (2)$$

ΔV represents the influence of inconsistency of sampling, reference and circuit parameters.

The voltages of two modules of IPOS system in steady state satisfy that

$$V_L = V_{Lr1} + k_{vo}V_{o1} = V_{Lr2} + k_{vo}V_{o2} \quad (3)$$

According to (2) and (3), we have

$$V_{o1} - V_{o2} = \frac{\Delta V}{k_{vo}} \quad (4)$$

From (4), it can be found that module (module 1#) have a higher output voltage with a lower given input voltage reference. The difference of two modules' output voltage is directly proportional to ΔV , and inversely proportional to k_{vo} .

Fig.4 is the impact of k_{vo} on output voltage sharing. Obviously, as shown in Fig. 4 (a), when $k_{vo} = 0$, V_L is determined by V_{Lr1} . And module 1 will undertake total output power and output voltage. Module 2 output voltage and power are 0. With the increase of k_{vo} , output voltage balancing behavior of two modules is also become better. It can be seen that output voltages balancing accuracy improve as k_{vo} increases. However, With the increase of k_{vo} , the range of input voltage regulation also increases. Therefore, a large k_{vo} lead to a great regulation range of voltage V_L . As a result, a trade-off must be made between the range of input voltage regulation and the output voltage sharing performance when designing the control loop. The analysis above shows that the presented control strategy is more suitable for applications with flexible input voltage.

With regard to IPOS DC grid-connected system showed in Fig.1, obviously, LV-DC bus allows a certain range of voltage regulation. Moreover, in practical circuit, due to the difference of sampling and reference parameters between different modules are easy to control within 1%. There is no need to have a large k_{vo} to achieve good output voltage balancing performance.

Although the analysis above is illustrated by two-module IPOS system, the conclusion is also applicable to the system of generated by more modules. Because each module has complete independent control loop, single module cut in or cut out will not affect the current modules' own control loops, which can realize cut out of fault modules and cut in of new modules in the system. With realizing the hot-swap, system's reliability, expansibility and maintainability are effectively increased.

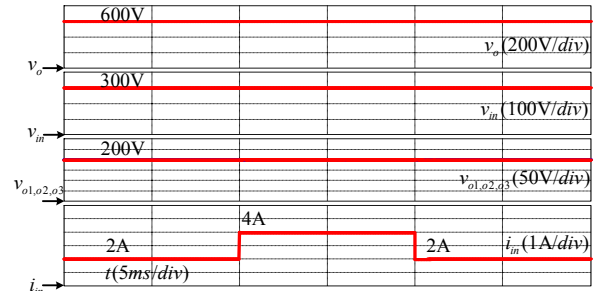


Fig. 5. Respond of simulation system with input power changes.

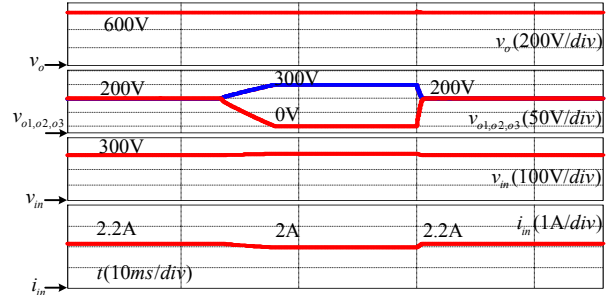


Fig. 6. Respond of simulation system with hot-swap of one module.

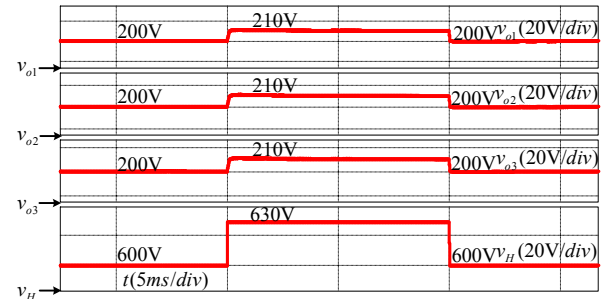


Fig. 7. Respond of simulation system with DC grid voltage variation.

IV. SIMULATION AND EXPERIMENT VERIFICATION

In order to verify the theoretical analysis in previous sections, we have constructed verification platforms including three modules both in simulation environment and lab. And fully modular implementation has been ensured. Only modules' own voltages have been sampled, and both power circuit and control circuit among these modules are same.

A. Simulation results of three-module IPOS system

A system simulation model consists of three module converters, has been built in the PSIM simulation environment to verify the effectiveness of the proposed system and its control strategy. The input voltage and output voltage of each module is set to 300V and 200V. And V_H is set to 600V. The simulation results of the presented system with its control strategy are shown in Fig. 5-Fig.7. It can be seen that good output voltage balancing performance and output power balancing by delivering the differential power through LV-DC bus can be realized under steady state. Meanwhile, system's output voltage v_o is equal to V_H , and verify the effectiveness of the presented control strategy.

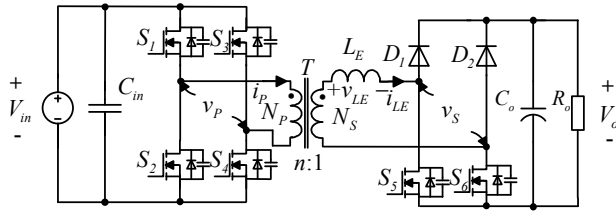
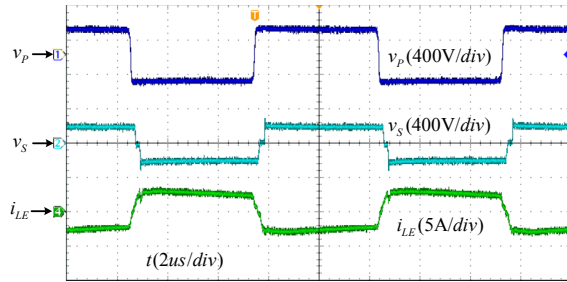


Fig. 8. Topology of semi-active full-bridge converter.

Table.1. Key parameters of single module

Components	Parameters
Input voltage (V_{in})	300V
Output voltage (V_o)	200V
Turns ratio ($n=N_p:N_s$)	3:2
Frequency (f_s)	100kHz
Energy transfer Inductor (L_E)	25 μ H



(a) v_p, v_s, i_{LE}

(b) $v_{GS1}, v_{GS2}, v_{GS3}, i_p$

Fig.9. Experimental operational waveforms of single module.

And the respond of system to input power changes is shown in Fig. 5. The output voltages of three modules v_{o1}, v_{o2}, v_{o3} and input voltage of system v_{in} remain constant with input power of system changes. And meantime the input current i_{in} is changing with the change of input power. The whole output voltage of system and good output voltage sharing performance can still be ensured during dynamic process.

Fig. 6 shows the system response when module 3# is cut out and cut in. After module 3# is cut out from system, output voltage v_{o3} of module 3# decrease to zero, and meanwhile output voltage of module 1# and 2# v_{o1}, v_{o2} increase to 300V in order to keep output voltage of system constant. The IPOS system's input voltage v_{in} increases slightly because input voltage references of remaining module 1# and 2# increase according to the presented control strategy. When module 3# is

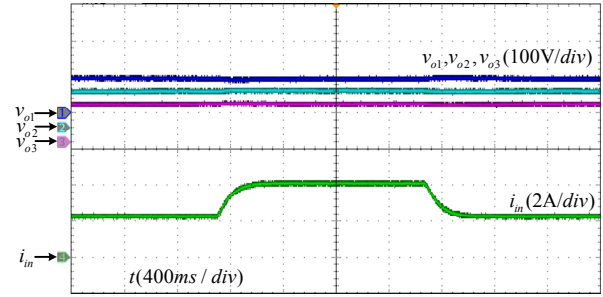
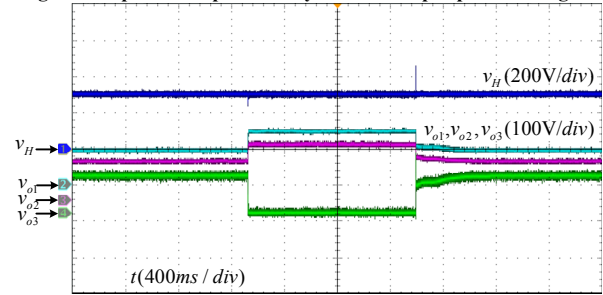
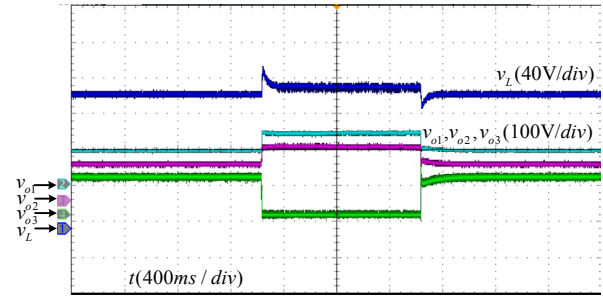


Fig. 10. Respond of experiment system with input power changes.



(a) $v_{o1}, v_{o2}, v_{o3}, v_H$.



(b) $v_{o1}, v_{o2}, v_{o3}, v_L$.

Fig. 11. Respond of experiment system with hot-swap of one module.

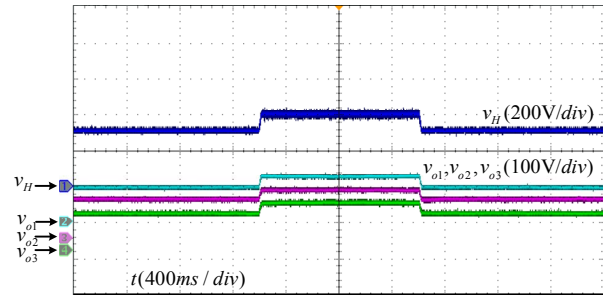


Fig. 12. Respond of experiment system with DC grid voltage variation.

cut in to system, output voltages of three modules v_{o1}, v_{o2}, v_{o3} are sharing system's output voltage in a short time. It can be concluded that good output voltage balancing performance can be ensured during hot-swap of one module .

Fig. 7 shows the system's response with the DC grid voltage variation (V_H changes from 600V to 630V and back to 600V). It can be seen that with variation (increase or decrease) of DC grid voltage, output voltage of each module can follow the variation and have a good output voltage sharing performance during dynamic process. The experimental results

show the effectiveness of presented distributed autonomous voltage balancing control strategy.

B. Experimental results of three-module IPOS system

The topology of single module [15] of the IPOS system is shown in Fig.8. The key parameters of each module is shown in Table.1. The experimental operational waveforms of single module under the condition of $V_{in}=300V$, $V_o=200V$ and $P_o=500W$ are shown in Fig. 9.

Due to the limit of time and test conditions in lab, only an experimental prototype with three small-scaled prototypes has been built and test. Still, it can be used for the effective verification of the presented system and its control strategy.

The experimental results are shown in Fig.10-Fig.12. Fig. 10 is the respond of system with input power changes, and i_{in} represents total input current of the IPOS system. It can be seen that output voltages of three modules remain stable at about 100V when input power changes. Hence, a good output voltage sharing performance can be ensured both in steady state and dynamic process.

Fig. 11 is the respond of system with hot-swap of one module (module 3#). It can be seen that system's output voltage is evenly shared by the remaining two modules when module 3# is cut out. System's input voltage increases slightly because output voltages change from about 100V to 150V of modules 1# and 2#, and input voltage references increase according to the presented control strategy. After module 3# is cut in, three modules share system's output voltage, and input voltage is restored to be stable. Hence, without any information exchange among these modules, redundancy in combination with hot-swap capability of modules can be easily achieved.

Fig.12 shows the system's response with the DC grid voltage variation. It can be seen that with variation (increase or decrease) of DC grid voltage, output voltage of each module can follow the variation and have a good output voltage sharing performance during dynamic process. The experimental results show the effectiveness of presented distributed autonomous voltage balancing control strategy.

V. CONCLUSION

A distributed autonomous voltage balancing control strategy for a modular IPOS DC grid-connected renewable power system has been analyzed in this paper. Autonomous sharing of output voltages and distributed voltage regulation of input voltage of these IPOS modules are achieved by introducing output voltage into input voltage reference of each module. Each module is self-contained and no extra supervisory controller is needed to achieve the output voltage sharing among these modules. Stable Operation of whole modular DC grid-connected system can be ensured, and fully distributed control and hot-swap can be realized with the presented control strategy. Hence, simple control, easy

realization and high reliability can be realized. Simulation and experimental results verified the validity and advantages of the analyzed IPOS system and its control strategy.

REFERENCES

- [1] J. Zeng, W. Qiao, L. Qu, Y. Jiao, "An Isolated Multiport DC-DC Converter For Simultaneous Power Management of Multiple Different Renewable Energy Sources," *IEEE J. Emerg. Sel. Topics Power Electron*, vol. 2, no. 1, pp. 70-78, Mar. 2014.
- [2] H W, R Chen, J Zhang, Y Xing, H Hu, "A Family of Three-Port Half-Bridge Converters for a Stand-Alone Renewable Power System," *IEEE Trans. Power Electron*, vol. 26, no. 9, pp. 2697-2706, Sep. 2011.
- [3] Roger Gules, Juliano De Pellegrin Pacheco, Hélio Leães Hey, and Johnson Imhoff, "A Maximum Power Point Tracking System With Parallel Connection for PV Stand-Alone Applications," *IEEE Trans. Ind. Electron*, vol. 55, no. 7, pp. 2674-2683, Jul. 2008.
- [4] H Wu, K Sun, R Chen, H Hu, Y Xing, "Full-Bridge Three-Port Converters With Wide Input Voltage Range for Renewable Power Systems," *IEEE Trans. Power Electron*, vol. 27, no. 9, pp. 3965-3974, Sep. 2012.
- [5] Z. Zhang, Y. Cai, Y. Zhang, D. Gu, Y. Liu, "A Distributed Architecture Based on Microbank Modules With Self-Reconfiguration Control to Improve the Energy Efficiency in the Battery Energy Storage System," *IEEE Trans. Power Electron*, vol. 31, no. 1, pp. 304-317, Jan. 2016.
- [6] C. Chen, Y. Chen, "Analysis of the series-connected distributed maximum power point tracking PV system," in *IEEE 2015 Applied Power Electronics Conference and Exposition*, 2015, pp. 3083-3088.
- [7] R. Pilawa-Podgurski and D. Perreault, "Submodule integrated distributed maximum power point tracking for solar photovoltaic applications," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2957-2967, Jun. 2013.
- [8] A. I. Bratecu, I. Munteanu, S. Bacha, D. Picault, and B. Raison, "Cascaded DC-DC converter photovoltaic systems: Power optimization issues," *IEEE Trans. Ind Electron.*, vol. 58, no. 2, pp. 403-411, Feb. 2011.
- [9] K. Sun, X. Wang, Z. Qiu, H. Wu, Y. Xing, "A PV generation system based on centralized-distributed structure and cascaded power balancing mechanism for DC microgrids," in *IEEE 2015 International Future Energy Electronics Conference*, 2015, pp.1-6.
- [10] Y Lu, H Wu, X Dong, Y Xing, K Sun, "A three-port converter based DC grid-connected PV system with autonomous output voltage sharing control," *Applied Power Electronics Conference and Exposition*, 2017, pp. 2057-2061.
- [11] Chen W, Wang G, Ruan X, Jiang W, Gu W, "Wireless input-voltage-sharing control strategy for input-series output-parallel (ISOP) system based on positive output-voltage gradient method," *IEEE Trans. Ind Electron*, vol. 61, no. 11, pp. 6022-6030, Nov. 2014.
- [12] Hu X, Gong C, "A high gain input-parallel output-series DC/DC converter with dual coupled inductors," *IEEE Trans. Power Electron*, vol. 30, no. 3, pp. 1306-1317, Mar. 2015.
- [13] Xu G, Sha D, Liao X, "Decentralized inverse-droop control for input-series output-parallel DC-DC converters," *IEEE Trans. Power Electron*, vol. 30, no. 9, pp. 4621-4625, Sep. 2015.
- [14] Y. Levron, D. R. Clement, B. Choi, C. Olalla, and D. Maksimovic, "Control of submodule integrated converters in the isolated-port differential power-processing photovoltaic architecture," *IEEE J. Emerg. Sel. Top. Power Electron*, vol. 2, no. 4, pp. 821-832, Dec. 2014.
- [15] Hongfei Wu, Yangjun Lu, Tiantian Mu, Yan Xing. "A Family of Soft-Switching DC-DC Converters Based on a Phase-Shift-Controlled Active Boost Rectifier," *IEEE Trans. Power Electron*, vol. 30, no. 2, pp. 657-667, Feb. 2015.