Energy Proceedings
Vol 31, 2023
ISSN 2004-2965

Coordinated Control Strategy of Hybrid AC/DC Microgrid with Photovoltaic and Energy Storage System

HU Yiwen [1], LIU Chuang [1*], WANG Jingyue [1], PEI Zhongchen [1]

1 School of Electrical Engineering, Northeast Electrical Power University, Jilin 132000(*Corresponding Author)

ABSTRACT

Around microgrid with PV and energy storage system, this paper adopts a module-level configuration scheme and proposes coordinated control strategy to further release the potential of PV power generation and promote the efficient operation of energy storage unit. Firstly, aiming at the 'barrel effect' caused by PV module mismatch and low efficiency of energy storage converter, the module-level PV power optimizer and the energy storage partial power converter are configured respectively to maximize the utilization of solar energy and electrical energy. Secondly, the multi-mode switching of PV array and energy storage unit under on/off-grid conditions is discussed, and a coordinated control strategy of microgrid with PV and energy storage system is proposed to realize the smooth switching and power automatic distribution of each unit in different control modes. Finally, a 30kW microgrid with PV and energy storage system simulation platform is built by using Matlab/Simulink to verify the feasibility and effectiveness of the proposed coordinated control strategy.

Keywords: PV power optimizer, energy storage partial power converter, power balance, coordinated control strategy

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
MPPT	Maximum power point tracking
MPP	Maximum power point
PCC	Point of common coupling
SOC	State of charge

1. INTRODUCTION

Driven by the national goal of "double carbon", renewable energy, represented by PV power generation, will become the backbone of energy consumption structure[1].However, the mismatch of power output caused by PV modules in the actual operation of PV systems will lead to the "barrel effect" of PV strings, which will result in a significant reduction of the output power of the whole PV array and reduce the efficiency of PV power generation[2]. Meanwhile, along with the large-scale grid connection of massive PV, its randomness and intermittent characteristics will directly affect the safe and stable operation of microgrid. Therefore, there is an urgent need to utilize the power complementary characteristics of energy storage[3] to smooth out the power fluctuation of PV power generation, promote the deep integration of PV, energy storage, load and grid, and realize the full consumption and efficient utilization of renewable energy.

PV power optimization systems are important for the power optimization, condition monitoring and protection of PV modules. The literature [4] classifies the current circuit topologies applicable to module-level PV power optimizers and analyzes the operating principles and applicable scenarios of several commonly used topologies, and analyzes and summarizes several topologies in terms of efficiency, cost and complexity.

Traditional energy storage units are more often grid-connected using full power bi-directional DC/DC converters for voltage regulation, which has the problems of low operation efficiency, large footprint and high pre-investment cost. In order to solve the above problems, literature [5] analyzed and compared the topologies available for bidirectional DC-DC partial power converters with high voltage gain and high efficiency, concluding that isolated full-bridge converters can achieve significant reductions in converter size, weight and price.

To ensure the real-time power dynamic balance between PV, load and grid, the literature [6] introduces energy storage unit in the grid-connected PV system to achieve peak shaving, valley filling of PV power generation and smooth out power fluctuations by real-time detection of PV and grid power information. But the control accuracy of PV system in this paper is low, which is easy to cause MPP "misjudgment phenomenon", and the energy storage unit adopts full power converter, which reduces the operating efficiency of the microgrid with PV and energy storage system.

Based on reference [4-6], this paper proposes a network configuration of microgrid with PV and energy storage system based on partial power conversion, which realizes the power optimization and improvement of microgrid with PV and energy storage system by using a module-level power optimizer of PV system and a partial power converter of energy storage. At the same time, this paper proposes a coordinated control strategy of microgrid with PV and energy storage system considering PV output fluctuation, energy storage charge state and DC bus voltage. So as to ensure the maximization of renewable energy consumption while smoothing the power fluctuation and realize the efficient, safe and economic operation of microgrid with PV and energy storage system.

2. MICROGRID WITH PV AND ENERGY STORAGE SYSTEM

2.1 Network configuration

The microgrid with PV and energy storage system structure constructed in this paper is shown in Fig. 1, where the PV modules are connected to the DC bus through the PV power optimizer in series, and the two energy storage battery packs are connected to the DC bus through their respective partial power bi-directional DC/DC converters in parallel[7]. The two energy storage battery packs realize the switching between charge/discharge and idle modes according to the power demand of the microgrid to suppress the power fluctuation of the grid-connected PV and achieve the full consumption of PV[8].

If the real-time power of each unit in the microgrid with PV and energy storage system can maintain dynamic balance and ignore power loss, the power balance relationship in the system is

$$P_{\mathrm{PV}} + P_{\mathrm{ESS}} + P_{\mathrm{G}} - P_{\mathrm{L}} = 0 \quad (1)$$

Where, P_{ESS} is the power released or absorbed by the energy storage unit; P_{PV} is the output power from the PV array; P_L is the total load power of the system; P_G is the power supplied or absorbed by the grid.

In order to further improve the reliability and efficiency of microgrid with PV and energy storage system, this paper will will conduct the research of PV power optimizer and energy storage bi-directional DC/DC converter.

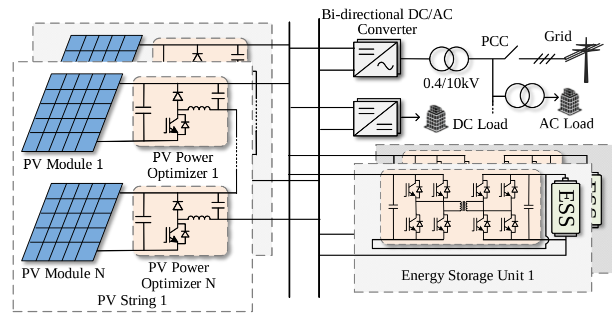


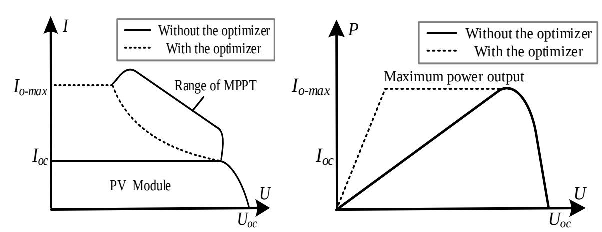
Fig. 1. Network configuration of microgrid with PV and energy storage system with common DC bus

2.2 PV power optimizer

In order to overcome the 'barrel effect' of PV power generation system in microgrid with PV and energy storage system due to module mismatch, a module-level Buck-type PV power optimizer is proposed in this paper to make each module in the string work at the MPP of its characteristic curve, so as to avoid the potential waste of PV power generation system caused by local shading, aging and other factors of PV modules[9].

This paper adopts the Buck-type power optimizer structure shown in Fig. 1 to improve the installation capacity of the PV string, and ensure that the other unshaded modules in the string are at the MPP operating point by increasing the output current of the shaded modules[10].

The I-U and P-U characteristic curves of PV modules connected to Buck power optimizer are shown in Fig. 2.



(a) I-U curve (b) P-U curve

Fig. 2. Characteristic curve of PV module before and after adding Buck Power optimizer

Where I_{o_max} is the maximum output current of the optimizer and the middle section of the curve is the maximum power output stage. The PV module expands the original MPPT control range of PV module through the Buck power optimizer's step-down and current rise function.

2.3 Energy storage bi-directional DC/DC converter

The topology of energy storage bi-directional DC/DC converter mainly includes isolated and non-isolated structures[11]. To solve the problems of low operating efficiency, large footprint, and high pre-investment cost of traditional full power energy storage converter for microgrid with PV and energy storage system, this paper proposes a partial power energy storage converter, which not only has the advantages of easy soft switching and high reliability of the full power energy storage converter, but also the converter only flows through part of the power of the energy storage unit(the power flow diagram is shown in Fig. 3). Therefore, it is possible to select a converter structure with a much smaller rated power level than the energy storage unit and a more compact structure, which can significantly improve the conversion efficiency of the energy storage unit.

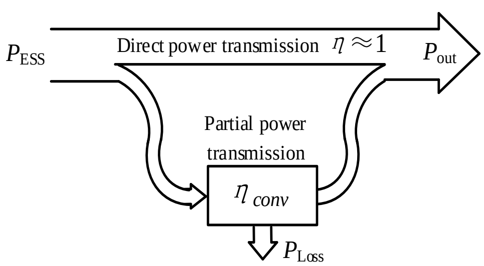


Fig. 3. Power flow diagram

The connection between the energy storage battery pack and the isolated energy storage bi-directional DC/DC converter is shown in Fig. 1. When the energy storage battery pack discharges to the DC bus, it is assumed that η_{Conv} is the efficiency of isolated bi-directional DC/DC converter; G is the gain of converter. The overall efficiency η_{ESS} of the energy storage unit can be derived as

$$\eta_{ESS} = \frac{P_{out}}{P_{in}} = \frac{I_{out} \cdot U_{bus}}{I_{ESS} \cdot U_{ESS}} = \frac{I_{out}}{I_{ESS}} \cdot (1+G) = \frac{\eta_{conv} \cdot (1+G)}{\eta_{conv} + G} \quad (2)$$

The losses of energy storage converter during operation mainly include filter loss(filter inductance/capacitance), switching tube loss and high-frequency transformer loss. The power flowing into the energy storage unit is simulated to be 20kW. The comparison of the loss power of the two converters is shown in Fig. 4.

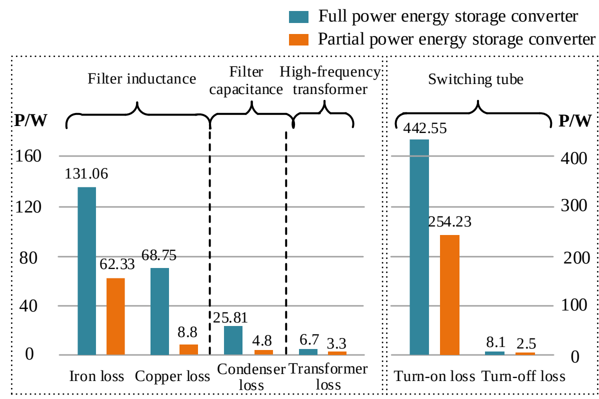


Fig.4. Power loss of full power and partial power converters

3. MICROGRID WITH PV AND ENERGY STORAGE SYSTEM CONTROL

3.1 *Coordination control strategy*

Considering the impact of intermittent power output of PV power generation system during the actual operation of microgrid with PV and energy storage system and the impact of power mutation of load in on/off-grid mode on the power dynamic balance in microgrid, a coordinated control strategy of microgrid with PV and energy storage system is shown in Fig. 5.

According to the opening and closing of the PCC between the microgrid with PV and energy storage system and the grid, the microgrid with PV and energy storage system can work in two operation modes: grid-connected and islanded.

(1) When the system is connected to the grid, the bi-directional DC/AC converter takes the DC bus voltage and three-phase current at the grid side as the control objectives to realize the power flow between the microgrid with PV and energy storage system and the grid. The energy storage unit is used to smooth out the power fluctuation when the PV array is connected to the grid, and allocates the power to be released or absorbed according to the SOC state, which can work in constant voltage or constant current mode. In order to realize the full consumption of renewable energy, the PV power optimizer always works in the MPPT mode.

(2) When the system is islanded, the energy storage unit works in constant voltage mode to maintain the DC bus voltage, and the bi-directional DC/AC converter works in V/f mode to provide stable voltage and frequency support for the AC side By monitoring the SOC state of the energy storage battery pack and the power matching between PV/storage/load in the system, the energy storage unit can realize the switching of charging/discharging working mode. At this

time, the PV power optimizer can work in MPPT mode or power-limited mode.

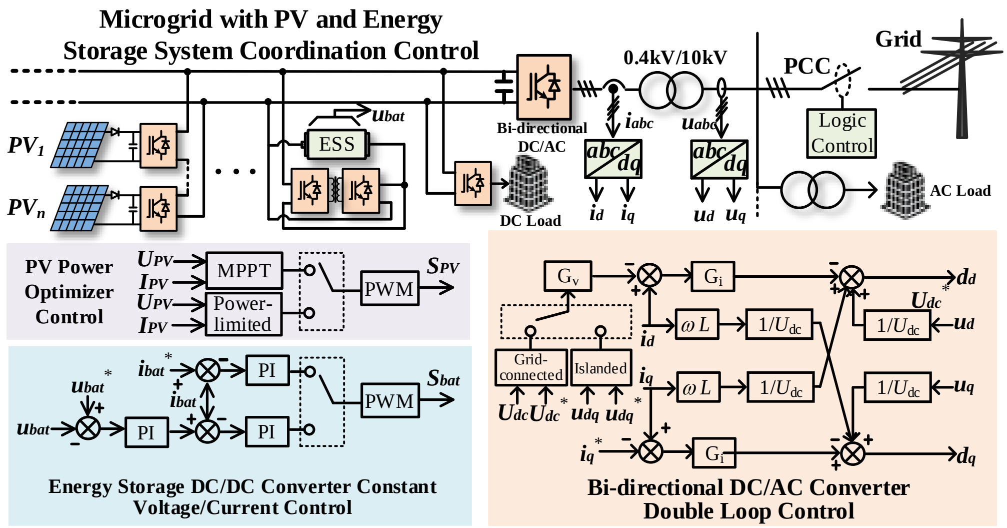


Fig. 5. Block diagram of coordinated control strategy of microgrid with PV and energy storage system

3.2 PV array control strategy

The Buck PV power optimizer has two functions: MPPT control mode and power-limited control mode. MPPT control ensures that the PV array always works at the maximum power output point to improve the efficiency of PV power generation. When the output power of the PV array is excessive, the PV power optimizer works in the power-limited control mode, which makes the PV array drop the power output to ensure the power balance of the system and prevent the fluctuation of the DC bus. As shown in Fig. 8, u_{PV} and i_{PV} are the PV module output voltage and current, respectively, and the duty cycle D can be obtained by MPPT control or power-limited control.

3.3 Control strategy of energy storage unit

The control block diagram of the energy storage unit is shown in Fig. 6. In order to ensure that the charging/discharging of energy storage can stabilize the instability of the system within its SOC state (20%~80%), the working mode of energy storage converter needs to be selected based on the relationship between the output power of the PV array, the rated power of the load, the capacity of the grid-side transformer, and the SOC of the energy storage. In this paper, two energy storage units are configured in the microgrid with PV and energy storage system, and its control flow chart is shown in Fig. 6. Assume that SOC_1 and SOC_2 are the SOC states of the two storage batteries in the storage unit, where mode 1 is to cut out the storage unit, mode 2 is to discharge the storage unit, mode 3 is to discharge the storage battery pack with SOC state greater than 50%, mode 4 is to charge the storage battery pack with SOC state less than 50%, and mode 5 is to charge the storage unit.

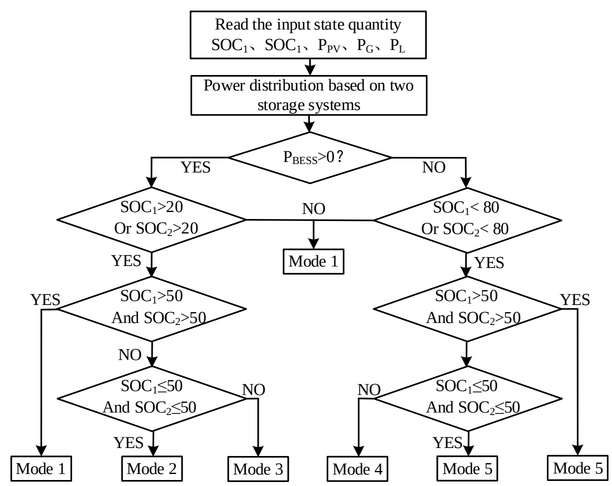


Fig. 6. Flow chart of dual energy storage control mode

4. SIMULATION VERIFICATION

In order to verify the feasibility and effectiveness of the microgrid with PV and energy storage system power optimization method and coordinated control strategy proposed in this paper, an microgrid with PV and energy storage system simulation model as shown in Fig. 1 is built in the MATLAB/Simulink environment, in which the PV array is composed of two PV strings, each string includes 20 PV modules, and the maximum transmission power of the connected bi-directional DC/AC converter is 10kW. Simulation analysis is carried out for different operating conditions. The simulation parameters are shown in Table 1.

Table 1 Simulation parameters

Parameter	Value
Reference value of DC bus voltage U_{dc_ref}/V	600
Ac bus voltage at low voltage side U_G/V	220
PV module short-circuit current I_{sc}/A	5.96
PV module open circuit voltage U_{oc}/V	64.2
MPP current of PV module I_m/A	5.58
MPP voltage of PV module U_m/V	54.7
Energy storage battery voltage U_{ESS}/V	500
Energy Storage battery pack capacity /(A • h)	20
Energy storage battery pack limiting value [SOC_L, SOC_H](%)	[20, 80]

4.1 Simulation analysis of photovoltaic power optimizer

By comparing the power difference between the two PV strings under the same working conditions with a module-level/string-level power optimizer, respectively, the optimization effect of the module-level Buck Power optimizer is verified. The comparison of the maximum output power value before and after optimization is shown in Fig. 7. It is assumed that the PV string includes 10 PV modules, which initially work under the standard condition(T=25℃, S=1000W/m^2), and there is no partial occlusion in both strings before 1.1s; after partial occlusion at 1.1s($S_{1\text{-}5}$=1000W/m^2, $S_{5\text{-}10}$=500W/m^2), the string with the module-level power optimizer can ensure that all modules work at the maximum power point, and the output power of the string is increased by 750W compared with that with string-level power optimizer.

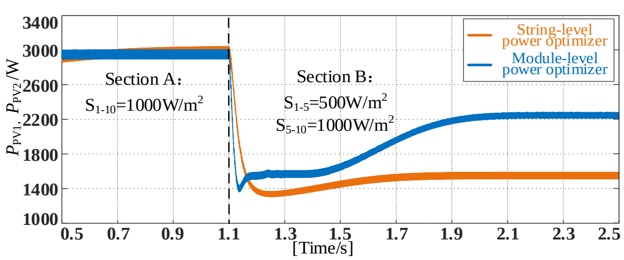


Fig. 7. Comparison of string output power

4.2 Simulation analysis of partial power converter

As shown in Fig. 8, in order to verify the effectiveness of the partial power energy storage converter, the power of the energy storage battery pack and the power flowing from the partial power storage converter and the full power storage converter are compared. Before 1.5s, the discharge power of the energy storage battery pack in the microgrid with PV and energy storage system is 3.2kW, and the power required by the load in the system is reduced by 500W at 1.5s. During the simulation process, the power loss of the full power energy storage converter is 60W and the power loss of partial power energy storage converter is 10W. The use of partial power converter reduces the power loss of the energy storage unit and improves the overall operating efficiency of the energy storage unit .

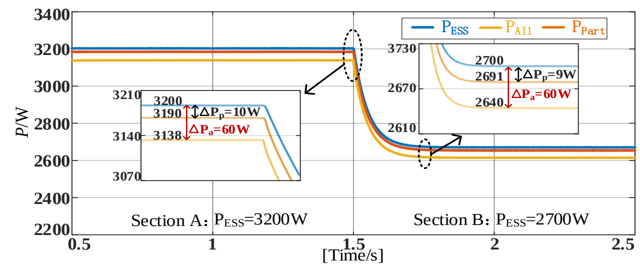


Fig. 8. Comparison waveform of power loss

4.3 Simulation analysis of microgrid with PV and energy storage system

Condition 1: The microgrid with PV and energy storage system works in grid-connected mode, where a bi-directional DC/AC converter is used to control the DC bus voltage and the grid-side three-phase current. The PV array is MPPT controlled by the module-level power optimizer. During the simulation, the irradiance is continuously changed, but the power required by the load is not changed. As shown in Fig. 9, under this working condition, the total power emitted by the PV array and energy storage unit is 6kW. When the irradiance of the PV array changes, the energy storage unit works in the charging or discharging mode to stabilize the power fluctuation emitted by the PV array, cut the peak and fill the valley, and meet the system balance conditions.

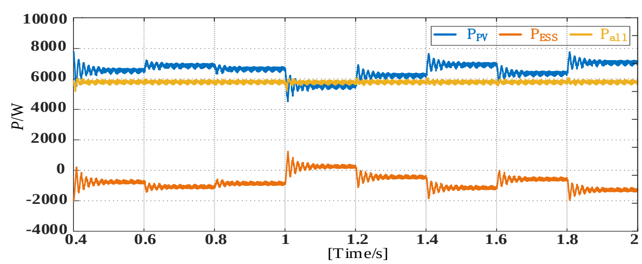


Fig.9. Output power of each unit of microgrid when stabilizing the fluctuation of PV grid connection

Condition 2: The microgrid with PV and energy storage system works in islanded mode. As shown in Fig. 10, the irradiance of the PV array in the system remains unchanged. At the beginning of the simulation, assuming that the SOC state of the energy storage battery pack is 60%, the PV array sends about 7.2kW power to supply the load and charge the energy storage unit at the same time, so as to maximize the consumption of renewable energy. Some of the load is cut out at 0.1s, at which time the charging power of the energy storage unit rises in order to maintain the power balance of the system. Adjust the SOC state of the energy storage battery pack to 80% at 0.2S, at this time, in order to prevent overcharge, the energy storage unit is cut out. However, since the output power of the PV array is much greater than the total load power, the PV power optimizer switches from the MPPT control mode to the power-limited control mode to ensure the balance, safe and stable operation of the system.

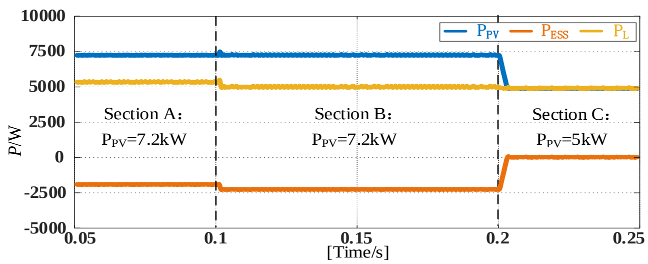


Fig. 10. Output power of each unit of microgrid under islanded condition

5. CONCLUSION

Through the comparison with string-level PV power optimizer and full power energy storage converter and the simulation results of various working conditions, it can be seen that the used module-level configuration scheme can eliminate the 'barrel effect' and improve the efficiency of energy storage units under on/off-grid conditions . Meanwhile, combined with the SOC state of energy storage battery pack, the proposed coordinated control strategy of microgrid with PV and energy storage system can manage and control the working mode of each converter, realize the independent power distribution of each unit, quickly eliminate the power fluctuation caused by PV and load, and ensure the safe and stable operation of the system while maximizing the consumption of renewable energy.

ACKNOWLEDGEMENT

This work was fully supported by the Changchun Jidian Energy Technology Co., Ltd.(PV power optimizer development and technical application project based on barrel effect, 2021-31-JLD-KY-C).

REFERENCE

[1] ZHANG Huaiyu, XU Chaoran, HUANG Zhilong, et al. Coordinated dispatch method of generation-grid-load-storage considering uncertainty of PV generation. Electrical & Energy Management Technology 2021; 5:86-92.

[2] LUO Yawen, TAN Heng, ZHOU Jianjun, et al. Comparative analysis of MPPT intelligent optimizer and parallel optimizer under local shadow. Tibet Science And Technology 2020; (12):21-23.

[3] LIU Chang, ZHUO Jiankun, ZHAO Dongming, et al. A review on the utilization of energy storage system for the flexible and safe operation of renewable energy microgrids. Proceedings of the CSEE 2020; 40(01):1-18+369.

[4] Kasper M, Bortis D, Kolar J W. Classification and comparative evaluation of PV panel-integrated DC–DC converter concepts. IEEE Transactions on Power Electronics 2013; 29(5):2511-2526.

[5] Bianchi M A, Zurbriggen I G, Paz F. Improving DC Microgrid Dynamic Performance Using a Fast State-Plane-Based Source-End Controller. IEEE Transactions on Power Electronics 2019; 34(8):8062-8078.

[6] QIU Peichun, GE Baoming, BI Daqiang. Battery energy storage-based power stabilizing control for grid-connected photovoltaic power generation system. Power System Protection and Control 2011; 39(3):29-33.

[7] WANG Zipeng, ZHENG Lijun, LÜ Shixuan. Coordinated control for islanded DC microgrid considering power sharing of multiple energy storages[J]. Electric Power Construction 2021; 42(4):89-96.

[8] LU Jinling, ZHANG Wei, ZHANG Xiangguo, et al. Coordinated control strategy for photovoltaic micro-grid system with hybrid energy-storage. Proceedings of the CSU-EPSA 2021; 33(8):102-108.

[9] CAI Xiaoyu, SHI Wangwang. Operation voltage optimization of series integrated photovoltaic module photovoltaic system. Renewable Energy Resources 2016; 34(4):494-499.

[10] QI Jizhi. Research on no-communication control strategy and analog control for series-connected photovoltaic power optimizer. Hangzhou: Zhejiang University; 2021.

[11] YANG Hui. Research on control strategy of the bidirectional DC-DC converter for the photovoltaic power generation and energy storage system. Xi'an: Xi'an University of Technology; 2018.