Research on Photovoltaic Grid-connected System With Energy Storage Based on Improved Energy Management Strategy

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***Abstract*—This paper proposes an improved energy management strategy for simultaneous power management of the photovoltaic grid-connected system with energy storage. Based on the DC bus voltage and the working states of grid, the PV system is divided into six working modes by the proposed energy management strategy. This can avoid the effect of grid failure on PV system, and achieve the optimal utilization of light energy. Firstly, based on the management strategy, a photovoltaic grid-connected system with energy storage units is constructed in this paper, which is consisted of the photovoltaic units, energy storage units, an inverter and the local loads. Then, the working conditions of different modes and the switching process between modes are described in detail. Finally, the control method of the photovoltaic system is given, so that the system can be switched smoothly between different working modes. The simulation results show that, through the improved energy management strategy, the PV grid-connected system with energy storage units is capable of ensuring normal running of the local loads when the grid fails and achieving system stability when the local loads are changed.**

Keywords—photovoltaic grid-connected system; energy storage unit; energy management strategy; control strategy

I. INTRODUCTION

The negative impacts of traditional fossil fuels on the environment is becoming more and more obvious [1]. The clean energy is needed urgently to decrease the use of fossil fuels. Because of no noise and no pollution, there is a lot of development room for the photovoltaic energy [2]. With the improvement of technical level, MPPT, energy storage, bi-directional DC/DC converter and the grid-connected inverter has been researched widely [3]-[5]. The instability of photovoltaic cells can be remedied by energy storage [6], and the impact of grid failure can be avoided also. Due to the instability of PV power, it is important to coordinate the working between each part of the system.

An energy management strategy lied on the DC bus voltage was presented by the paper [7]. In the system, the DC bus voltage is varied with the working modes, which is disadvantageous for the normal work of the local loads. A controller based on the current signals was designed in the paper [8], which is used to control the grid-connected inverter and the power flow. A new DC converter was presented in the paper [9], which can be applied to the photovoltaic grid-connected system. And a photovoltaic grid-connected system with the energy storage was designed in that paper.

In this paper, an modified energy management method was proposed based on photovoltaic grid-connected system with energy storage [10]-[12]. Through the energy storage, grid-connected state and off-grid state can be achieved in the system, and the problem of grid failure was solved. Based on the DC bus voltage the system is switched between different working modes, which makes sure PV cells run efficiently. The problem of coordination between parts is solved in this system. In the end, the feasibility of the system is proved by the simulation.

II. THE STRUCTURE AND WORKING MODES OF THE PHOTOVOLTAIC SYSTEM

A. The Structure of the Photovoltaic System

The topology of the photovoltaic grid-connected system is shown in the Fig. 1, which is consisted of the photovoltaic units, energy storage units, an inverter and the local loads. In the figure, PV denote the photovoltaic battery pack. Due to the output instability of photovoltaic cells, the maximum output power is achieved by the maximum power point tracking. The MPPT is implemented through the Boost converter. The energy generated by the PV units is filtered by LC filter and fed into the DC bus [13], [14]. The single-phase full-bridge inverter is adopted to steady the DC bus voltage and inverts direct current to alternating current. The current harmonics generated by inverters can be filtered out by the filter inductance L_4. The energy storage units are consisted of rechargeable batteries and a bi-directional DC/DC converter. The storage and release of energy can be achieved through the converter. When the voltage of DC bus is higher than stabilized value, the converter stabilizes at Buck mode to charge for the battery. When the DC bus voltage is below the stable value, it works at the Boost mode, and the DC bus voltage is stabilized by the battery. The local loads are composed of R_1 and R_2.

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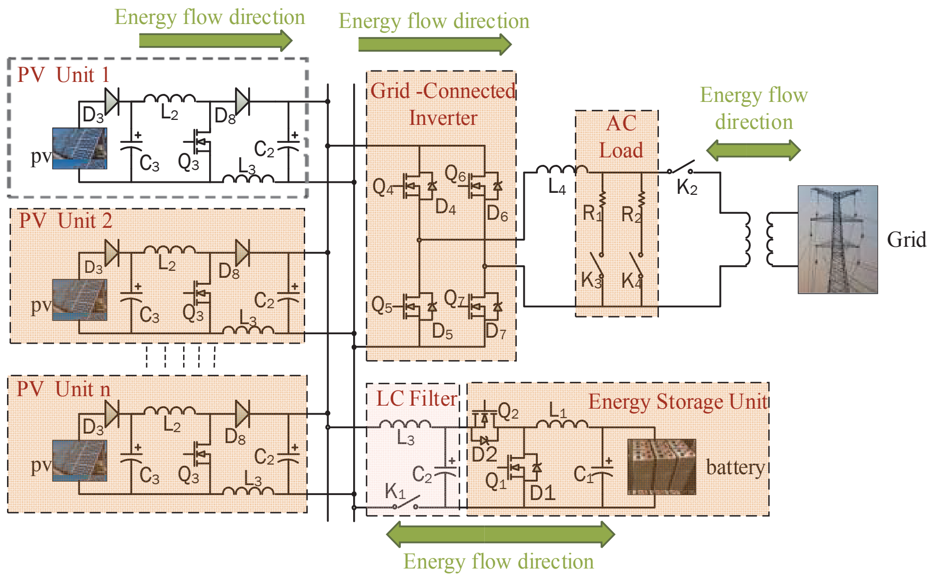

Fig. 1. The topology of the photovoltaic system

B. The Working Modes of the Photovoltaic System

To solve the problem of grid failure, the system is designed two kinds of working states, grid-connected state and off-grid state. As shown in Fig. 1, when the grid fails, K_1 is opened and K_2 is closed. The system runs at off-grid state. The energy storage unit is started. When the grid is back to normal, K_1 is closed and K_2 is opened. The grid-connected state is recovered, and the energy storage units be stopped. Based on the DC bus voltage and the grid state, the system is designed six different working modes. It is described as follows:

P_{load} and P_{pv} denote the power of local loads and photovoltaic cells, respectively.

1) The grid is normal:

a) Working mode 1: The system works at grid-connected state. P_{load}=0. The energy generated by PV cells is fed into the grid. The voltage of DC bus is stabilized by the inverter. The bi-directional DC/DC converter does not work.

b) Working mode 2: The system works at grid-connected state. $0<P_{load}<=P_{pv}$. The energy expended by loads is offered by PV cells and remaining energy is fed into the grid. The voltage of DC bus is stabilized by the inverter. The bi-directional DC/DC converter does not work.

c) Working mode 3: The system works at grid-connected state. $P_{load}>=P_{pv}$. The energy consumed by loads is provided by PV cells and the grid simultaneously. The voltage of DC bus is stabilized by the inverter. The bi-directional DC/DC converter does not work.

2) The grid fails:

a) Working mode 4: The system works at off-grid state. P_{load} =0. The energy generated by PV cells is fed into the rechargeable batteries. The DC bus voltage is stabilized by the bi-directional DC/DC converter which works at Buck mode to charge for the rechargeable batteries.

b) Working mode 5: The system works at off-grid state. $0<P_{load}<=P_{pv}$. The energy expended by loads is offered by PV cells and remaining energy is fed into the rechargeable batteries. The DC bus voltage is stabilized through the converter which works at Buck status to charge for the rechargeable batteries.

c) Working mode 6: The system works at off-grid state. $P_{load}>=P_{pv}$. The energy consumed by loads is provided by PV cells and rechargeable batteries simultaneously. The DC bus voltage is stabilized by the converter which works at Boost status. The rechargeable battery is discharged.

C. The Switching of Working Modes

In this system, both converter and inverter can sample the voltage of DC bus. The voltage of DC bus is varied with local loads power. Therefore, the monitoring of local loads can be achieved by sampling the DC bus voltage. Depending on the change of local loads, the switching between six working modes is shown in Fig. 2.

The switching of working modes is decided by the power of local load and photovoltaic cells. The three working modes of grid-connected state are corresponding to the three working modes of off-grid state. Generally, the grid is normal, and the system works at the first three working modes. With the increase or decrease of the local loads, the working state of the system is switched between the first three working modes. At any time, when the grid fails, the system can be switched from the first three working modes to the corresponding latter three working modes. When the grid is back to normal, the system can be switched to the first three working modes again.

The system can be switched smoothly between six working modes.

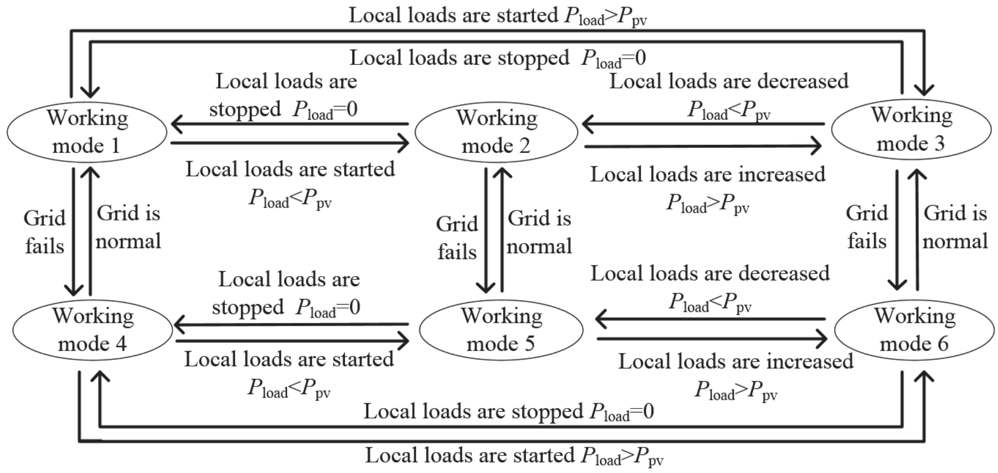

Fig. 2. The switching of working modes

III. Control Strategy Analysis

A. *The Control Strategy of Boost Converter*

MPPT is achieved through the Boost converter that is controlled by the dual closed-loop control strategy. The control block diagram of the converter is shown in the Fig. 3.

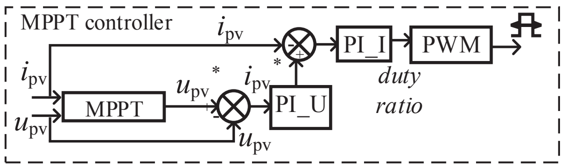

Fig. 3. The control block diagram of the Boost converter

In the Fig. 3, u_{pv} and i_{pv} denote output voltage and output current of the PV cells, respectively. The perturbation observation method is taken by MPPT. u_{pv}^* and i_{pv}^* denote the reference voltage and the reference current, respectively. The reference voltage u_{pv}^* can be obtained by the perturbation observation method. The reference current i_{pv}^* is determined by the regulator of voltage outer ring. PI_U and PI_I denote the regulators of voltage ring and current ring, respectively. The duty ratio of switching tube is determined by the current inner ring.

B. *The Control Strategy of Bi-directional DC/DC Converter*

When the grid fails, the converter can be started to realize the two-way flow of energy and stabilize the DC bus voltage. The control block diagram of the converter is shown in the Fig. 4.

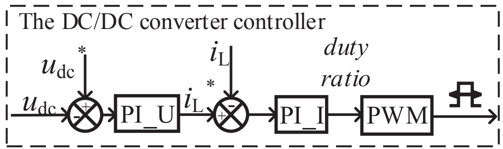

Fig. 4. The control schematic diagram of converter

In the Fig. 4, u_{dc} and i_L denote the DC bus voltage and the output current of rechargeable batteries, respectively. u_{dc}^* and i_L^* denote the reference voltage and the reference current, respectively. The reference current i_L^* is determined by the regulator of voltage outer ring.

C. *The Control Strategy of the Full-bridge Inverter*

When the grid is normal, energy storage unit is stopped. Through the full-bridge inverter, the voltage of DC bus is stabilized, and the direct current is turned into the alternating current which has same phase angle with the network voltage. The schematic diagram of the inverter is shown in the Fig. 5.

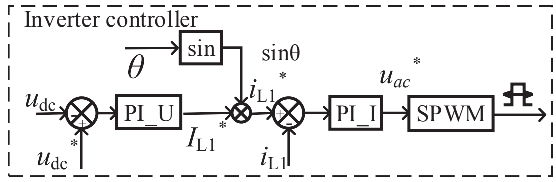

Fig. 5. The control block diagram of the Full-bridge inverter

i_{L1} and i_{L1}^* denote the current of filter and the reference current, respectively. I_{L1}^* denote the amplitude of i_{L1}^*, which is determined by the regulator of voltage outer ring. θ denote the phase angle of network voltage, which can be obtained by testing the network voltage. i_{L1}^* can be obtained by the product of I_{L1}^* and $\sin\theta$. u_{ac}^* denote the modulated wave of SPWM.

When the grid fails, the DC bus voltage is stabilized through bi-directional DC converter. Through full-bridge inverter, voltage of local loads is stabilized, and the direct current is turned into the alternating current which has same frequency with the network voltage. SPWM controller is taken by the full-bridge inverter. When the switch frequency is high enough, the amplification characteristic of the inverter can be approximated as a proportional gain. So the modulated wave of SPWM can be obtained as the equation (1). U and ω denote the peak value and the fundamental wave angular frequency of network voltage, respectively.

$$u_{ac}^* = \frac{U \sin \omega t}{u_{dc}} \quad (1)$$

IV. Simulation Results

Simulations are carried in MATLAB/Simulink to validate the proposed system and the controllers. Under standard illumination intensity and ambient temperature, the open-circuit voltage of PV cells is 280V, and the short-circuit current is 26.15A. At the maximum power point, the output voltage and current of photovoltaic cells are 200V and 25.68A, respectively. The rated voltage of the battery units is 200V. The stable DC bus voltage is stabilized at 370V. The effective value of network voltage is 220V, and the frequency is 50HZ. Both the rated power of local loads are 3KW.

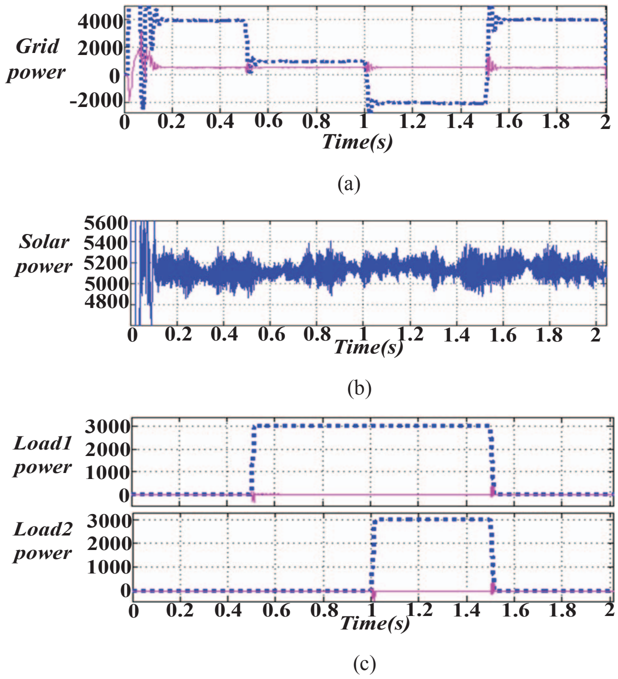

Fig. 6. The power of each part at the grid-connected state

A. At the Grid-Connected State

When the grid is normal, the photovoltaic grid-connected system works at the grid-connected state. The energy storage units stop working. The power of each part is shown in Fig. 6.

Based on the states of local loads, the three working modes of the grid-connected state are simulated.

1) $T\in[0s,\ 0.5s]$: The system works at mode 1. There is no local loads. The energy generated by photovoltaic cells is fed into the grid.

2) $T\in[0.5s,\ 1s]$: The system works at mode 2. The local load R_1 starts working. The power expended by loads is offered by the photovoltaic cells and remaining energy is fed into the grid.

3) $T\in[1s,\ 1.5s]$: The system works at mode 3. The energy consumed by loads is provided by photovoltaic cells and the grid simultaneously.

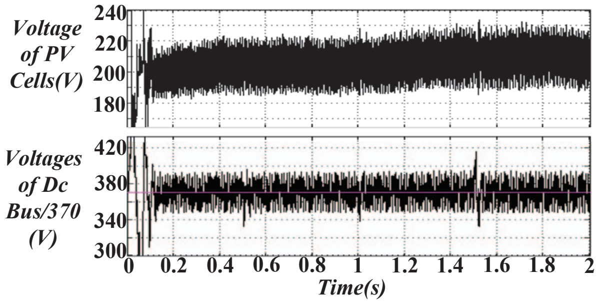

Fig. 7. The voltages of DC bus and PV cells at the grid-connected state

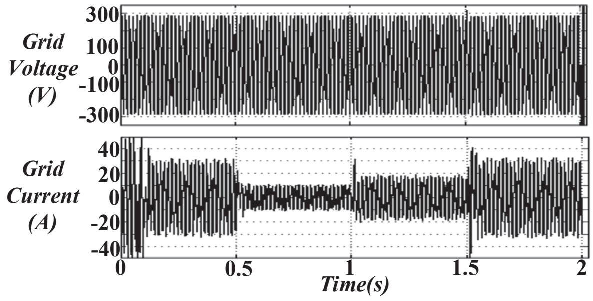

Fig. 8. The voltage and current of grid at the grid-connected state

At the grid-connected state, voltage and current of the system is shown in Fig. 7 and Fig. 8. From figures we can see that the output voltage of PV cells is stabilized at 200V. The DC bus voltage is stabilized at 370V. The effective value of network voltage is stabilized at 220V. The current tendency of grid side accords with power shown at Fig. 6.

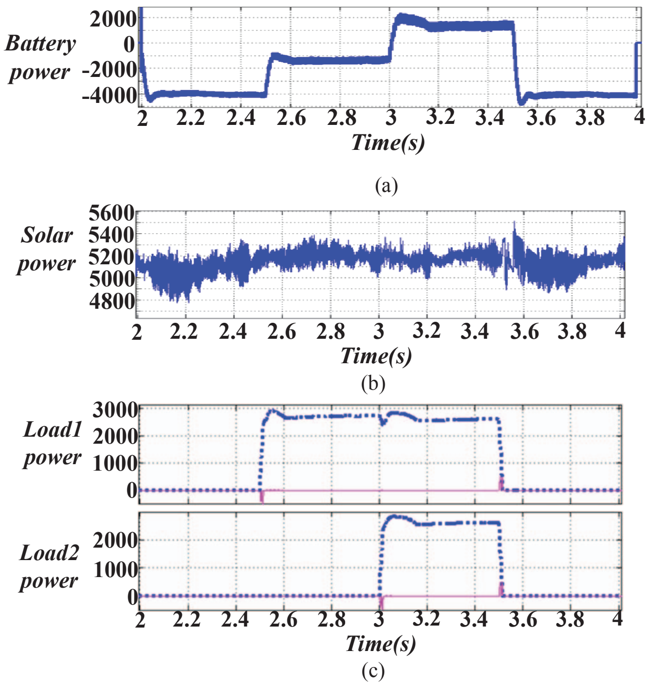

Fig. 9. The power of each part at the off-grid state

B. At the Off-Grid State

When the grid fails, the system works at the off-grid state. The energy storage units start working. The power of each part is shown at Fig. 9.

1) T∈[2s, 2.5s]: The system works at mode 4. There is no local loads. The energy generated by photovoltaic cells is fed into the rechargeable batteries.

2) T∈[2.5s, 3s]: The system works at mode 5. The local load R_1 starts working. The power expended by loads is offered by the photovoltaic cells and remaining energy is fed into the rechargeable batteries.

3) T∈[3s, 3.5s]: The system works at mode 6. The power consumed by loads is provided by photovoltaic cells and the rechargeable batteries simultaneously.

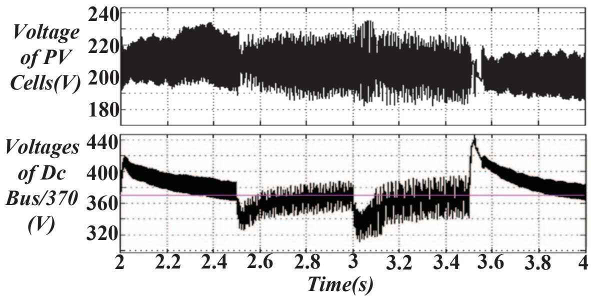

Fig. 10. The voltages of DC bus and PV cells at the off-grid state

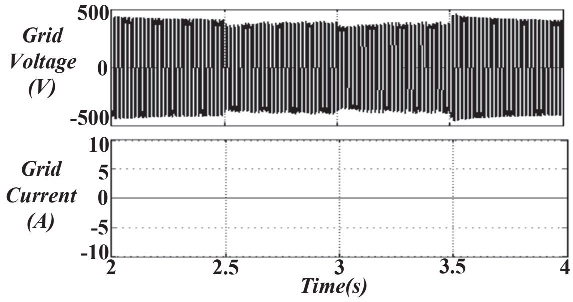

Fig. 11. The voltage and current of grid at the off-grid state

At the off-grid state, voltage and current of the system is shown in Fig. 10 and Fig. 11. From figures we can see that the output voltage of PV cells is stabilized at 200V. The DC bus voltage is stabilized at 370V. When the system is switched between different working modes, there will be slight fluctuations. But the system can be restored stability in a short time. The current of grid is zero, which accords with the off-grid state.

V. Conclusion

This paper proposes an improved energy management strategy and constructs a complete photovoltaic grid-connected system with energy storage. The photovoltaic grid-connected system is divided into six working modes. And the switching between modes is determined by the grid running state, local loads and photovoltaic cells power.

1) In the paper, the system can work stable at each working mode through the proposed control strategy.

2) The judgment of DC bus voltage can achieve the switching between different working modes, which can solve the variation of local loads, effectively.

3) When the grid fails, the PV grid-connected system can work normally.

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