INVESTIGATION OF THE VOLTAGE REGULATION CAPABILITY OF A CONSUMER-LEVEL PV-BESS SYSTEM

NGHIÊN CỨU KHẢ NĂNG ĐIỀU CHỈNH ĐIỆN ÁP CỦA HỆ THỐNG PV-BESS LẮP ĐẶT TẠI HỘ TIÊU THỤ

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Abstract - This paper investigates the voltage regulation capability at the point of common coupling (PCC) of a grid-connected photovoltaic (PV) system combined with a battery energy storage system (BESS) installed at the consumer level. Voltage regulation is achieved through the flexible control of the active and reactive power output of the BESS using a smart inverter control strategy. A simulation model is developed on the MATLAB/Simulink platform to evaluate the effectiveness of the proposed control algorithm under different solar irradiance conditions. Simulation results demonstrate that the BESS can effectively regulate voltage by supplying or absorbing reactive and active power, thereby maintaining the PCC voltage within acceptable limits. This study highlights the potential of PV-BESS systems to provide localized ancillary services and enhance voltage stability in low-voltage distribution networks.

Key words - Smart inverter; PV system; reactive power control; voltage control; Battery energy storage.

Tóm tắt - Bài báo này nghiên cứu khả năng điều chỉnh điện áp tại điểm đấu nối lưới của một hệ thống điện mặt trời (PV) kết hợp với hệ thống lưu trữ năng lượng bằng pin (BESS) lắp đặt tại hộ tiêu thụ. Việc điều chỉnh điện áp được thực hiện bằng cách điều khiển linh hoạt công suất tác dụng và công suất phản kháng đầu ra của hệ thống BESS thông qua điều khiển bộ nghịch lưu thông minh. Mô hình mô phỏng được xây dựng trên nền tảng MATLAB/Simulink nhằm đánh giá hiệu quả của thuật toán điều khiển đã đề xuất với các điều kiện bức xạ mặt trời khác nhau. Kết quả mô phỏng cho thấy hệ thống BESS có khả năng điều chỉnh điện áp hiệu quả bằng cách cung cấp hoặc tiêu thụ công suất phản kháng/công suất tác dụng, từ đó duy trì điện áp tại điểm đấu nối trong giới hạn cho phép. Nghiên cứu này cho thấy khả năng của hệ thống PV-BESS trong việc tham gia cung cấp các dịch vụ phụ trợ tại chỗ và nâng cao độ ổn định điện áp trên lưới điện phân phối hạ áp.

Từ khóa - Bộ nghịch lưu thông minh; điện mặt trời; điều khiển công suất phản kháng; điều khiển điện áp; pin lưu trữ.

1. Introduction

In conventional distribution networks, voltage regulation is mainly achieved through transformer tap-changing operations and capacitor bank switching. However, with the increasing penetration of renewable energy sources, such as photovoltaic (PV) systems and wind power, distribution networks are facing growing voltage-related challenges, including overvoltage, voltage sag, and voltage fluctuations, due to the intermittent and uncertain nature of these resources. Traditional voltage regulation solutions can no longer effectively meet operational requirements in modern power grid environments [1], [2]. Recent studies have shown that smart inverters, which interface distributed energy resources with the power grid, not only convert direct current into alternating current but also provide voltage regulation support for distribution networks in a flexible, rapid, and controlled manner [3].

IEEE Standard 1547-2018 [4] recommends the use of smart inverters with voltage and reactive power control functions to connect distributed energy resources to the power grid. In recent years, numerous studies on control methods and algorithms for PV inverters aimed at enhancing voltage regulation capability in distribution networks have been published. In particular, [5] proposes a two-stage Volt/Var control strategy based on the Affinely Adjustable Robust Counterpart method to mitigate overvoltage issues caused by the integration of photovoltaic systems into distribution networks. The paper in [6] develops a two-stage optimal Volt/Var control strategy that coordinates conventional power control devices with the operation of smart inverters in distribution networks with high PV penetration. To optimize the effectiveness of Volt/Var control for PV inverters, the study in [7] proposes a multi-objective hierarchical coordination method based on droop control, which enables simultaneous adjustment of the reactive power setpoints of centralized inverters and the droop control parameters of local controllers, thereby reducing the average nodal voltage deviation and power losses in the network. The study in [8] proposes a Volt/Var-based voltage control strategy for PV inverters to mitigate voltage drop issues in distribution grids with integrated PV systems under shading conditions. However, employing PV inverters for voltage regulation may reduce the active power delivered by the PV system.

Battery energy storage systems (BESSs) have become a feasible option for consumers equipped with PV systems for smoothing the fluctuating power output of PV systems, enhancing local self-consumption, and reducing the cost of electricity purchased from the grid [9]. In addition, PV-BESS systems can also participate in the provision of ancillary services, such as peak load shaving, line loading reduction, and especially voltage regulation services in distribution networks [10], [11]. The functionality of smart inverters and the interoperability of BESSs have been verified in [12]. Accordingly, the smart inverter of a BESS can provide grid-support functions similar to those of the smart inverter of a PV system. In [13], a control strategy combining centralized control and local control of PV and BESS inverters over different time scales is proposed to satisfy voltage limit requirements and reduce power losses in the network. An optimal control method for the smart inverters of both PV and BESS systems to improve the hosting capacity of PV sources connected to the grid is presented in [14].

This paper proposes a voltage control strategy at the point of common coupling (PCC) through the control of the reactive and active power of the BESS in a PV-BESS system configuration installed at the consumer level.

2. System model and control strategy

2.1. System model

Consider a rooftop photovoltaic (PV) system combined with a battery energy storage system (BESS) supplying power to a load. The system is connected to the low-voltage distribution grid at the point of common coupling, as illustrated in Figure 1.

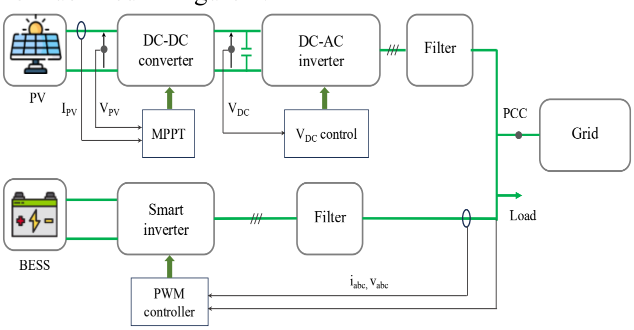

Figure 1. *PV-BESS system model*

The PV panels are connected to the PCC through two converters: a DC-DC converter operating in maximum power point tracking (MPPT) mode, and a subsequent DC-AC inverter that maintains a stable DC-link voltage between the output of the DC-DC converter and the input of the inverter. The BESS is connected to the grid through a smart inverter, allowing simultaneous control of active and reactive power, thereby supporting voltage regulation at the PCC and enhancing the voltage stability of the distribution network.

2.2. Control strategy

To maximize the power generated from the PV system, the PV inverter operates in maximum power point tracking (MPPT) mode. Voltage regulation at the PCC is performed through the control of the smart inverter of the BESS. The control strategy is designed to maintain the voltage at the PCC within the permissible range, satisfying voltage quality requirements according to the technical standards of low-voltage distribution networks. The principle diagram of the smart inverter control is illustrated in Figure 2.

The voltage control strategy for the BESS inverter is developed based on two independent components: reactive power control according to the Volt-Var characteristic and active power regulation. The measured current and voltage signals at the PCC are used to calculate the active power P_{meas} and reactive power Q_{meas}. These values are fed into the active power regulation block and the reactive power regulation block to perform the corresponding control functions.

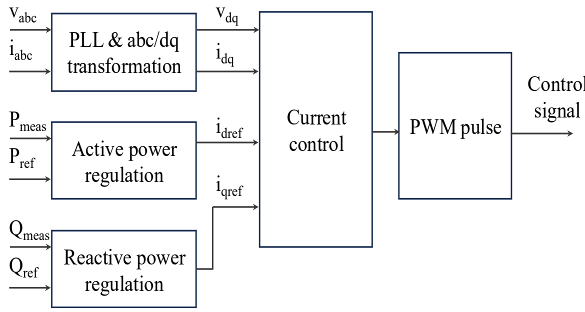

Figure 2. *Principle diagram of smart inverter control*

Voltage regulation is carried out through reactive power control by comparing the measured reactive power Q_{meas} with the reference reactive power Q_{ref}, where Q_{ref} is calculated according to Equation (1).

$$Q_{ref}(t) = \begin{cases} Q_{max}; & V_{pcc}(t) < V_{min} \\ \dfrac{V_1 - V_{pcc}(t)}{V_1 - V_{min}} \cdot Q_{max}; & V_{min} \le V_{pcc}(t) < V_1 \\ 0; & V_1 \le V_{pcc}(t) \le V_2 \\ -\dfrac{V_{pcc}(t) - V_2}{V_{max} - V_2} \cdot Q_{max}; & V_2 < V_{pcc}(t) \le V_{max} \\ -Q_{max}; & V_{pcc}(t) > V_{max} \end{cases} \quad (1)$$

where Q_{max} is the maximum reactive power capability that the inverter can generate or absorb; V_1 and V_2 are the limits of the inverter deadband; V_{min} and V_{max} are the minimum and maximum permissible voltages at the PCC, respectively; and $V_{pcc}(t)$ is the voltage at the PCC at time t.

The voltage control characteristic based on the reactive power of the BESS is described in Figure 3 [15]. According to this characteristic, when the voltage at the PCC is lower than the preset voltage threshold V_1, the BESS inverter generates reactive power to support voltage rise. Conversely, when the voltage at the PCC exceeds the preset value V_2, the BESS absorbs reactive power to limit the voltage increase, contributing to maintaining the grid voltage within the permissible range. When the voltage exceeds V_{max} or falls below V_{min}, the reactive power reaches the limit Q_{max} due to the power constraint of the inverter. Therefore, although the voltage continues to increase or decrease, the reactive power cannot increase further and remains in a saturated state.

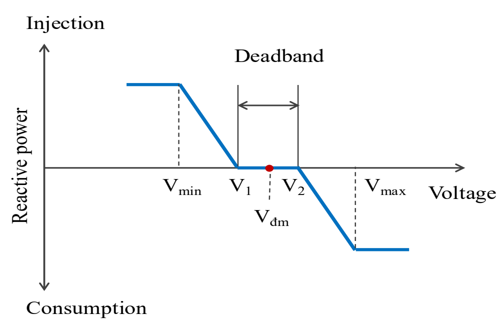

Figure 3. *Voltage control characteristic based on the reactive power of the smart inverter*

The reactive power error is expressed as:

$$e_Q = Q_{ref} - Q_{meas} \quad (2)$$

This power error is passed through a PI controller to generate the reference current i_{qref} for controlling the q-axis voltage in the dq reference frame, ensuring a fast and accurate response according to the requirements of the Volt-Var characteristic. It should be noted that reactive power does not change the stored energy in the battery system; therefore, ideally, it does not affect the state of charge (SoC) of the BESS. However, under practical conditions, reactive power exchange still causes a certain amount of loss in the inverter and auxiliary components, resulting in a very small decrease in SoC over time.

When the voltage at the PCC increases because the power generated by the PV system exceeds the load demand, the surplus power is prioritized for charging the BESS through the active power regulation block. This charging process helps reduce the amount of surplus power injected into the grid, thereby reducing the power flow on the line and limiting overvoltage at the point of common coupling. However, the BESS charging power is constrained by the state of charge (SoC) and the inverter power rating. Once the SoC reaches its upper limit or the inverter output reaches its rated capacity, the ability to absorb excess power becomes limited, and voltage regulation then mainly relies on reactive power control.

3. Simulation results and discussion

To evaluate the effectiveness of the proposed control method, a system model is developed and simulated on the MATLAB/Simulink platform. The system consists of a PV source with an installed capacity of 1000 kWp, a BESS with a capacity of 1000 kWh and a maximum charging/discharging capability of 300 kW. The smart inverter has a maximum reactive power regulation capability of ±300 kVAr. The load connected at the PCC has an active power of 750 kW and a reactive power of 200 kVAr. The grid is simulated with a rated voltage of 400 V. The initial state of charge of the BESS (SoC) is assumed to be 70%. The simulation is carried out with three solar irradiance levels representing different operating conditions: 650 W/m^2, 150 W/m^2, and 1000 W/m^2.

When the BESS does not participate in voltage regulation, the simulation results shown in Figures 4 and 5 indicate that the grid supplies the power deficit whenever the PV output is lower than the load demand. Consequently, the voltage at the PCC decreases and remains below the nominal grid voltage in most operating periods. This is due to the increase in power flow from the grid when the output power of the PV system decreases, combined with the equivalent impedance of the grid at the point of common coupling, resulting in a significant voltage drop, especially under weak-grid conditions. Conversely, when the PV output power exceeds the load demand, the surplus power is fed back into the grid, causing the voltage at the PCC to increase. Specifically, when solar irradiance decreases from 650 W/m^2 to 150 W/m^2, the PCC voltage drops from 0.998 pu to 0.957 pu. When solar irradiance increases to 1000 W/m^2, the voltage rises to 1.013 pu, as shown in Figure 5.

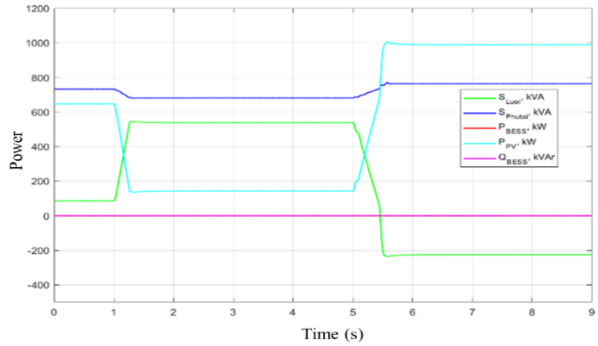

Figure 4. *System power when the BESS does not participate in voltage regulation*

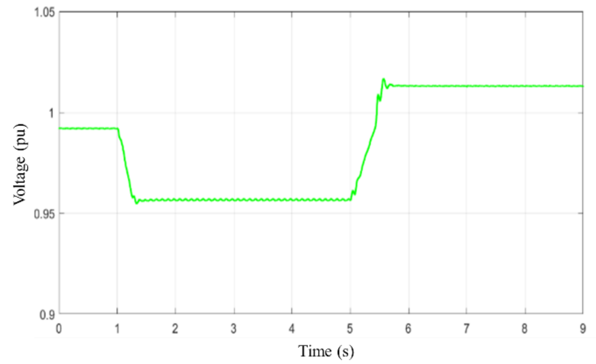

Figure 5. *Voltage at the PCC when the BESS does not participate in voltage regulation*

In the case where the BESS participates in voltage regulation, the simulation results clearly demonstrate a significant improvement in voltage quality, as shown in Figure 6 and Figure 7.

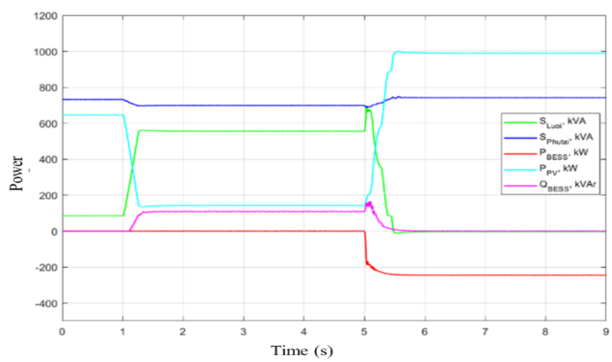

Figure 6. *System power at the PCC when the BESS participates in voltage regulation*

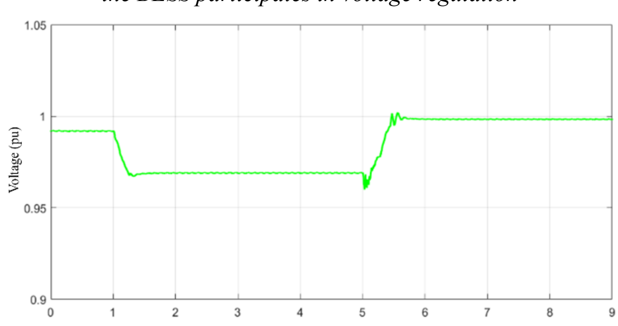

Figure 7. *Voltage at the PCC when the BESS participates in voltage regulation*

During the time interval from 0 to 1 s, since the PV power is lower than the load demand, the system continues to draw power from the grid, while the BESS is not activated because the voltage remains within the deadband range. From 1 to 5 s, due to a sharp decrease in solar irradiance, the PV output power decreases significantly, causing the voltage at the PCC to fall below the low-voltage threshold V_1. The BESS inverter is activated and generates approximately 108 kVAr of reactive power to raise the voltage to 0.968 pu and maintain it stably at this level.

At 5 s, the solar irradiance increases abruptly, causing the PV output power to exceed the load power, and the voltage at the PCC rises above the rated voltage value. At this point, the BESS stops generating reactive power and switches to active power charging mode to absorb the surplus power from the PV system. As a result, the reverse power flow to the grid becomes zero, and the voltage is regulated back to the rated value.

A comparison between the two cases, with and without BESS control participation, shows that the proposed control method significantly reduces the voltage fluctuation range at the PCC, from approximately 0.957–1.013 pu to 0.968–1.000 pu. This demonstrates the effectiveness of the coordinated active and reactive power control strategy of the BESS in maintaining grid voltage stability under variations in renewable energy sources or loads.

4. Conclusion

This paper has presented and verified a control strategy that combines the active and reactive power of a PV-BESS system to regulate the voltage at the PCC with the low-voltage grid. In this strategy, the PV system operates in MPPT mode to optimize generated energy, while the BESS is flexibly controlled through a smart inverter capable of charging/discharging active power and regulating reactive power according to actual operating conditions.

Simulation results obtained using MATLAB/Simulink under different solar irradiance conditions have demonstrated the effectiveness of the proposed control strategy. The BESS is capable of responding rapidly to variations in generated power and voltage at the PCC by generating reactive power when the voltage is low and charging active power when the voltage is high. As a result, it contributes to maintaining the grid voltage within permissible limits and enhancing the stability of the distribution system.

This control strategy demonstrates practical application potential in distributed power systems integrated with renewable energy sources and storage systems, particularly in the context of increasing PV penetration in low-voltage distribution systems.

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APPENDIX

***Table 1.** Threshold voltage values in the simulation*

Voltage	Values (pu)
V_{min}	0.95
V_1	0.98
V_2	1.02
V_{max}	105