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Research on the Stability of Energy Storage Systems for Distributed Photovoltaic Systems Under Smart Grids

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Abstract:
This paper investigates the impact of energy storage systems on the stability of distributed photovoltaic systems in the context of smart grids. Firstly, the paper delineates the fundamental components and functions of distributed photovoltaic systems. Consequently, the intermittent and fluctuating nature of these phenomena gives rise to questions regarding its effect on the stability of the power grid. In order to address the aforementioned issues, the paper employs the MATLAB/Simulink platform to create a simulation model of a photovoltaic system in collaboration with a lithium battery energy storage system, analysing the influence of the energy storage system on voltage, current, power generation efficiency, and power. The results of the simulation demonstrate that the combination of energy storage systems has the potential to enhance grid stability. The introduction and utilisation of energy storage systems has engendered economic and low-carbon benefits for the power grid. In conclusion, the study explores the prospective evolution of optical storage systems, with a focus on intelligent control methodologies and novel energy management algorithms.

Keywords: Smart grid; distributed photovoltaic systems; energy storage systems; stability.

1. Introduction

The current global energy structure is gradually beginning to transform towards low-carbonization. The combined use of smart grids and distributed photovoltaic systems is the key to improving the energy utilization efficiency of the power grid [1]. Distributed photovoltaic systems, with their advantages such as flexible installation locations without limitations, clean power generation, and green products, occupy a major part of the power generation of the whole power system. However, photovoltaic power generation also has intermittency and volatility under the influence of issues such as the real-time changes in light intensity, temperature changes, and weather changes, which leads to the power grid not having good stability [2]. In the event of extreme weather or sudden changes in load, problems such as voltage and current fluctuations, reduced power and maximum point efficiency may occur. Therefore, energy storage systems are introduced as a buffer medium to explore whether the application of energy storage systems will affect the stability of photovoltaic systems [3]. At present, most studies focus on the static performance analysis about the single technology for storing energy, while there is lack of research on the impact of whether to introduce an energy storage system. The present paper will conduct a stability analysis on individual photovoltaic systems and photovoltaic energy storage systems following the introduction of energy storage systems.

In consideration of the aforementioned issues, this study aims to construct the basic framework of the photovoltaic energy storage systems under smart grid. The power generation model of the distributed photovoltaic system was established through MATLAB/Simulink software, and the model of the lithium battery energy storage system was introduced to analyze the influence of the energy storage system on voltage/current stability, power generation efficiency and power [4]. Meanwhile, through the analysis of the economic and environmental benefits of the photovoltaic energy storage system, the intelligent control strategies and future development directions of the smart grid are proposed [5].

2. The Basic Principle of Photovoltaic Storage Systems

2.1 The Composition of Distributed Photovoltaic Systems

The following figure shows the important basic components of a simple photovoltaic system:

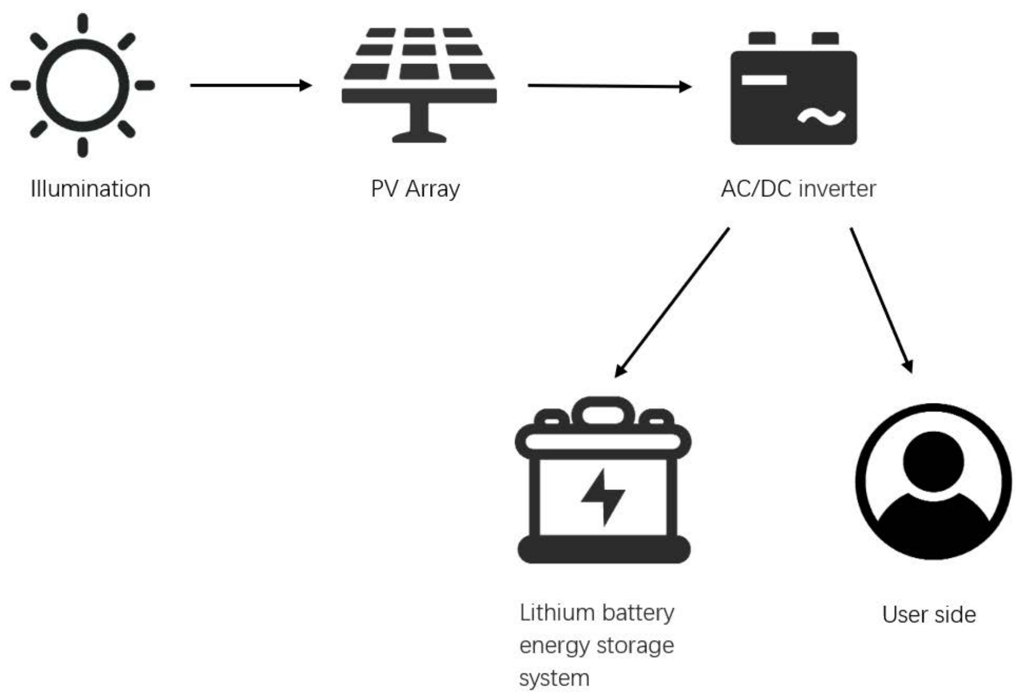

Fig. 1 The basic components of photovoltaic systems

As shown in Fig. 1, the specific components of a photovoltaic system and their functions are as follows:

(1) Power generation unit (PV array)

The power generation unit is composed of photovoltaic arrays. Currently, photovoltaic systems adopt polycrystalline silicon or thin-film solar panels with a series-parallel structure. Solar panels convert solar radiation energy into direct current electrical energy through the photoelectric effect. Its output power is jointly affected by the light intensity (G, W/m²), ambient temperature (T, ℃) and the temperature coefficient of the solar panel (β), the power model can be expressed as [6]:

$$P_{pv} = G \bullet A \bullet \eta_{pv}[1-\beta\left(T-T_{ref}\right)] \quad (1)$$

Ais the area of the photovoltaic panel, η_{pv} is the photoelectric conversion efficiency, and T_{ref} is the reference temperature, which is usually 25℃.

(2) Electrical energy conversion unit (inverter)

DC/AC inverter: The electrical energy collected by solar panels is of a direct current nature, which means that it cannot be directly supplied to the smart grid. In this con-

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figuration, a DC/AC inverter is employed to facilitate the conversion of direct current output from the photovoltaic array into alternating current, thereby ensuring compatibility with and utilisation for the power grid. The inverter integrates an maximum power point tracking (MPPT) algorithm, enabling the real-time determination of the maximum power point of the power grid. The MPPT control adopts the perturbation observation method or the incremental conductance method, dynamically adjusting the working voltage to achieve tracking maximum power and grid connection control, which satisfies the following conditions:

$$\frac{dP}{dV} = 0\left(\textit{The derivative of power with respect to voltage is zero}\right) \quad (2)$$

(3) Energy buffer unit (the system for energy storage)

Devices to store energy: The energy storage device, which is composed primarily of lithium batteries, is connected to the DC bus through a bidirectional DC/DC converter. The charge and discharge characteristics of the device are described by the equivalent circuit model, which includes ohmic internal resistance(R_0), polarization resistance(R_p) and capacitance(C_p). The dynamic response equation is as follows [7]:

$$V_{bat} = V_{oc} - I_{bat}\left[R_0 + R_p\left(1 - e^{-t/R_pC_p}\right)\right] \quad (3)$$

V_{oc} is voltage of open-circuit, I_{bat} is current during charging and discharging.

(4) Grid interaction Unit (Grid Connection and Protection Organization)

Grid-connected circuit breakers and islanding protection are responsible for automatically and safely disconnecting the entire system when a grid failure occurs. The power quality detection module is responsible for real-time monitoring of parameters such as harmonic distortion rate and voltage sudden change to ensure compliance with the operation standards of the power grid.

(5) Intelligent control Unit (Monitoring and Capability Management System)

Real-time data such as photovoltaic output, energy storage SOC, and load demand are obtained through sensors and smart meters. Based on artificial intelligence algorithms such as model predictive control, the system under discussion has been demonstrated to coordinate photovoltaic power generation, energy storage, charging and discharging, and load management in a dynamic manner. Relying on 5G or optical fiber networks, it realizes information interaction with the power grid dispatching center and supports communication between demand response and virtual power plant [8].

(6) Terminal power consumption unit (user-side load)

This includes the power supply for household electricity, factory power loads, enterprise electricity, civilian electric vehicle charging piles and all public facilities. The smart grid has the capacity to adjust electricity consumption periods according to time-of-use electricity prices or grid instructions. In instances where the smart grid‘s stored energy proves inadequate, users have the option to sell electricity to the grid via the energy storage system.

2.2 The Photovoltaic Storage System Basic Structure

The basic structure of the photovoltaic storage system is shown in the following figure:

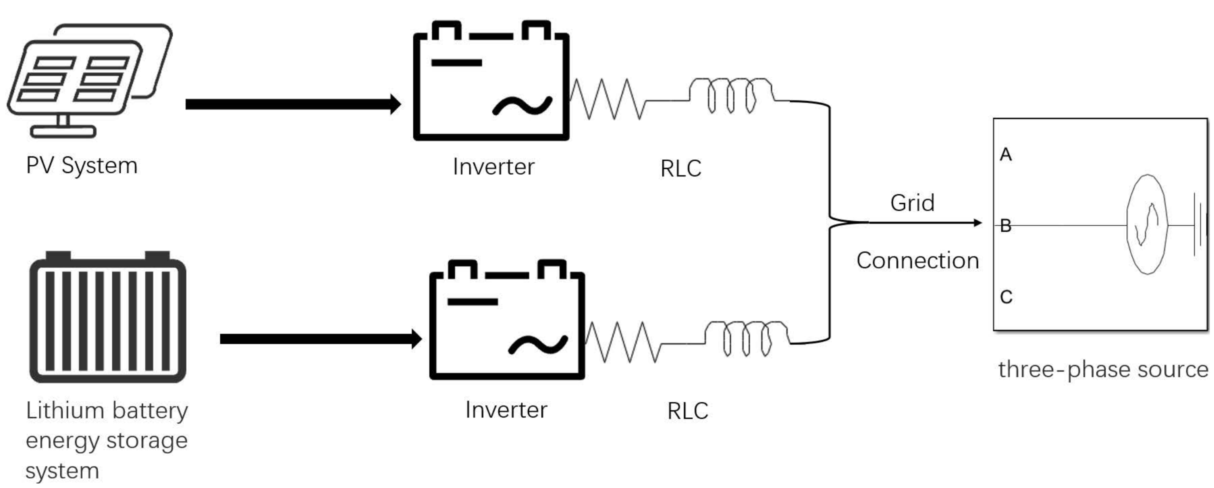

Fig. 2 The photovoltaic storage systems structure

As illustrated in Fig. 2, the photovoltaic (PV) system and the energy storage system, which is predominantly composed of lithium batteries, are interconnected with the grid via inverters and RLC modules. The photovoltaic grid-connected inverter represents a pivotal component within the broader framework of photovoltaic grid-connected power generation systems. The primary function of the inverter is to convert the direct current output of photovoltaic cells into alternating current that meets the requirements of the power grid. Concurrently, it achieves the tracking of the maximum power point and grid connection control. In this instance, the system selects a voltage source inverter and subsequently connects the entire system to a three-phase power supply. The on and off switch tube is controlled to ensure the stable conversion of direct current (DC) voltage into three-phase alternating current (AC) voltage. This enables the analysis of the steady state of the power grid.

3. Distributed Solar Stability Analysis Based on Simulink

3.1 The Methods about Photovoltaic System Modeling (PV Array)

For photovoltaic system selection, the conventional single-diode model of the photovoltaic unit was selected. An input signal with an irradiation intensity of 1000 was applied to the system, and the system temperature was maintained at a constant 25°C. The maximum power point (MPPT) of the photovoltaic system was tracked through the conductance increment method. With regard to maximum power tracking control, the aforementioned MPPT algorithm is generally adopted. It is possible to ensure that the photovoltaic cells are always operating at the maximum power point by manually adjusting the input voltage or current of the inverter.

Photovoltaic cells are devices that facilitate the conversion of light energy into electrical energy, a process known as the photovoltaic effect. Its basic equation is:

$$I = I_{Ph} - I_0[exp\left(\frac{q\left(V + IR_s\right)}{nkT} - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (4)$$

I is photovoltaic cell output current, I_{Ph} is photogenerated current, I_0 is reverse saturation current, q is electron charge(1.6×10^{-19}C), V is output voltage of photovoltaic cell, R_s is series resistance, R_{sh} is parallel resistance, n is ideal factor of the diode, k is Boltzmann constant(1.38×10^{-23}J/K) , T is the absolute temperature of photovoltaic cell.

The photogenerated current I_{Ph} is directly proportional to the light intensity G and area A of the photovoltaic cell, and can be expressed as:

$$I_{Ph} = K_i GA \quad (5)$$

K_i is the proportionality coefficient.

I_0 represents reverse saturation current and it is related to the temperature T. The relationship between them can be approximately expressed as:

$$I_0 = I_{0r}\left(\frac{T}{T_r}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (6)$$

I_{0r} is the reverse saturation current at the reference temperature T, and E_g is the bandgap width of photovoltaic cell material.

Based on the above content, the photovoltaic system model shown in Fig. 3 can be constructed:

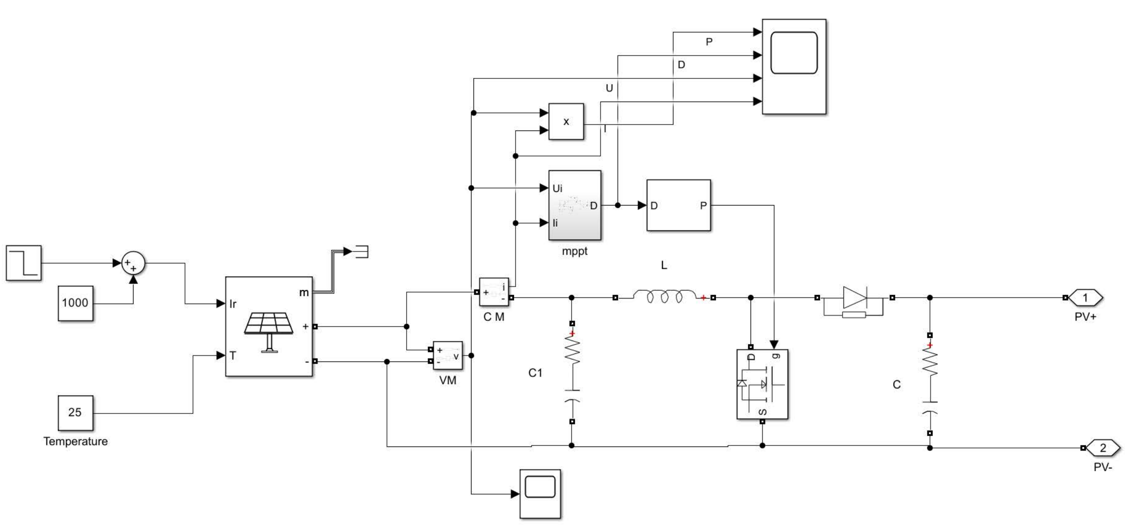

Fig. 3 Photovoltaic system

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3.2 Photovoltaic Systems without Energy Storage are Connected to the Grid

In the context of grid-connected current control, a current closed-loop control strategy is employed to ensure that the current output by the inverter is synchronised with the voltage of the power grid and meets the power quality requirements of the grid. In addition to the current closed-loop control strategy, commonly used current control methods for grid connection also include hysteresis current control and space vector pulse width modulation (SVPWM) control, amongst others. The SVPWM control paradigm is a pertinent case study. The fundamental principle underlying this process entails the conversion of the three-phase current to the coordinate system through coordinate transformation, which is based on the error between the reference current and the actual current. Subsequently, the conduction time of the inverter power switch tube is calculated by employing space vector modulation technology, thereby achieving precise control of the grid-connected current.

The coordination of the overall control strategy of the photovoltaic grid-connected power generation system with the MPPT algorithm system for control and the control of the inverter is imperative to achieve efficient and stable power generation and photovoltaic grid-connected operation. During the operation of the system, the real-time data of the operating parameters, such as the output voltage, current, light intensity and temperature of the photovoltaic cells, are monitored in real time through sensors. Subsequently, the MPPT algorithm calculates the maximum power point of the photovoltaic cell based on these parameters and sends control signals to the inverter to adjust the input voltage and current of the inverter. This ensures that the photovoltaic cell always operates at the maximum power point. Concurrently, the inverter employs an appropriate grid connection control strategy, informed by the phase and frequency information of the grid voltage, to inject the converted alternating current into the grid. In the course of the process of grid connection, it is also imperative to undertake the monitoring of grid voltage and current in order to ensure that the system meets the requisite grid connection standards. Such standards may include, but are not limited to, harmonic content and power factor, in addition to other pertinent indicators.

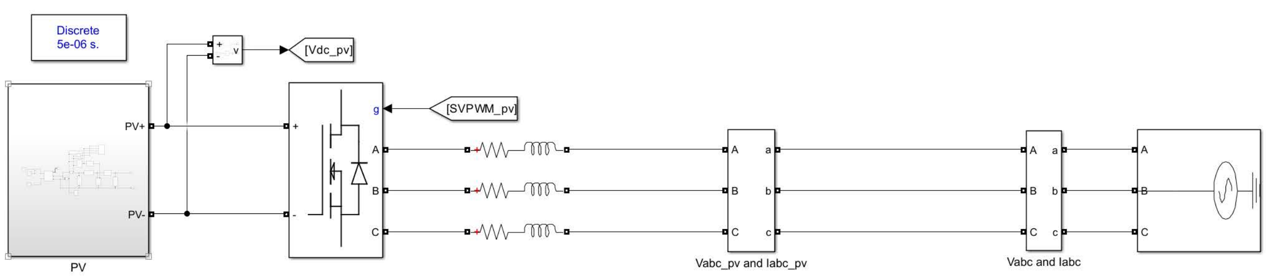

Fig. 4 Grid-connected photovoltaic systems without energy storage

In the context of photovoltaic systems that do not incorporate energy storage, the selection of grid-connected inverter topologies can be categorised into two primary types: voltage source inverters (VSI) and current source inverters (CSI). Of these, voltage source inverters are the most prevalent. In the context of voltage source inverters, the main circuit of a three-phase voltage source inverter typically comprises six power switch tubes (e.g., IGBTs). As illustrated in Fig. 4, the series RLC module and the three-phase V-I measurement module are connected, thus facilitating the monitoring of the three phases of power, voltage and current connected to the grid. Finally, the three-phase power supply is connected in order to convert the DC voltage into three-phase AC voltage, thus ensuring that the entire power grid system is within the normal range.

The data pertaining to the grid connection of the photovoltaic system was collected using an oscilloscope, thus yielding the voltage, current, and power results of the photovoltaic system as follows:

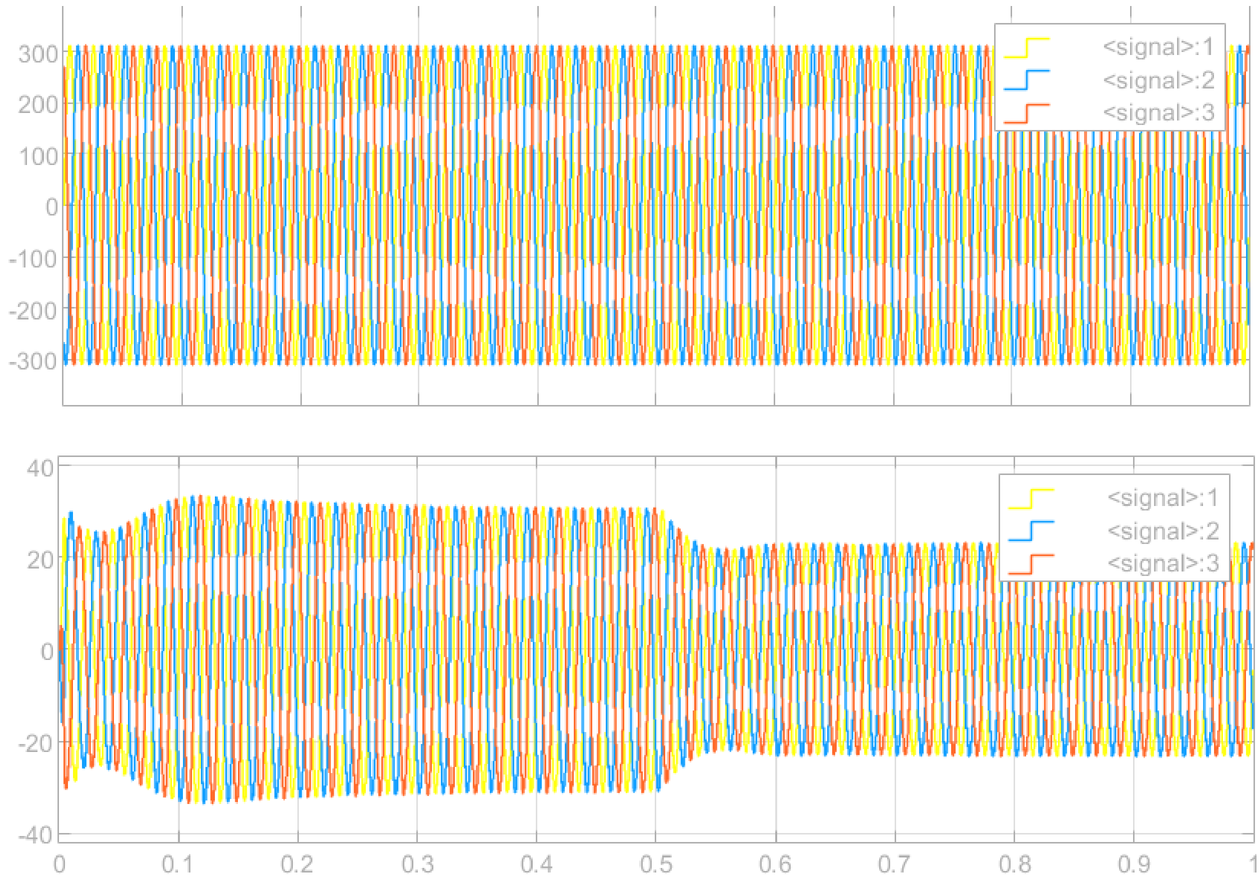

Fig. 5 Voltage, current and frequency images

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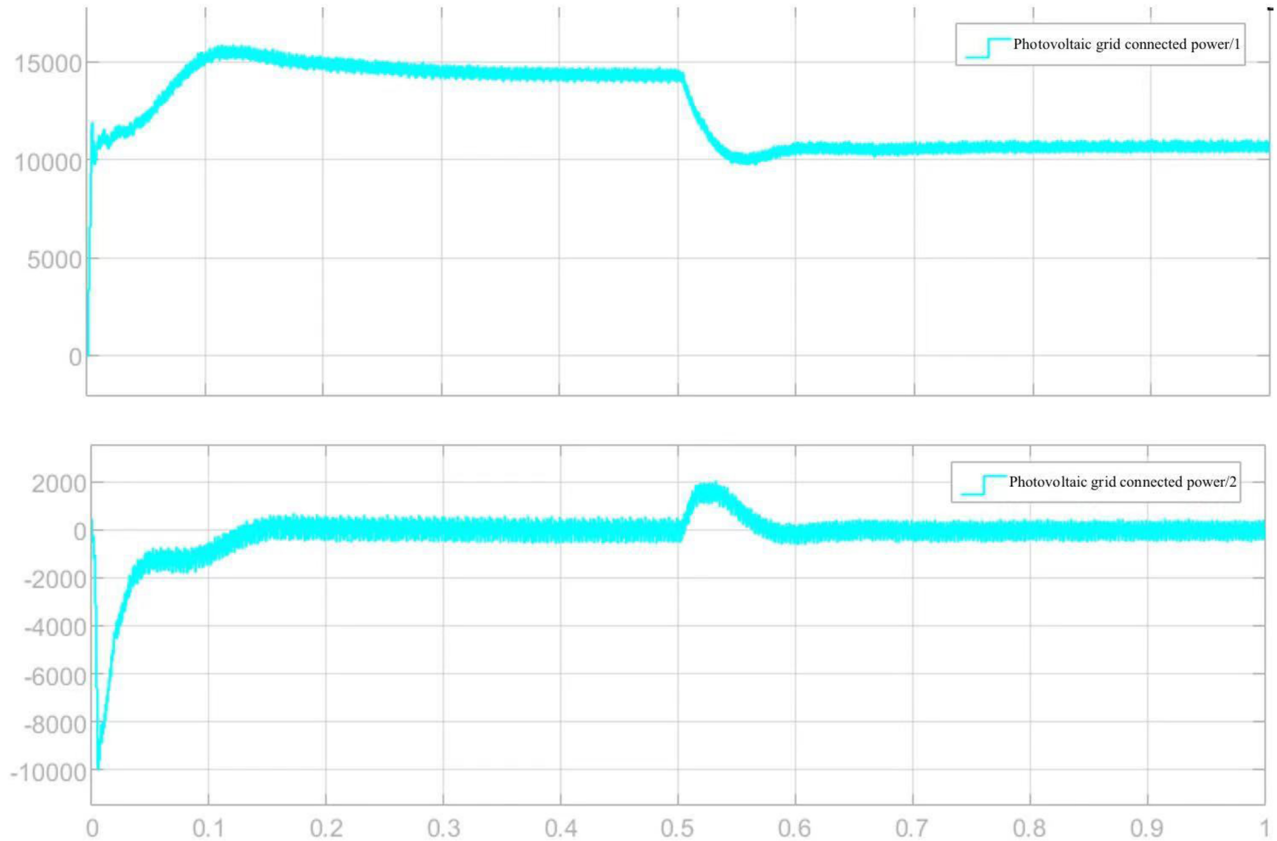

Fig. 6 Output power image

As demonstrated in Fig. 5 and 6, the voltage and current of the power grid fluctuate significantly. The current of the power grid demonstrates significant fluctuations in value, with voltage fluctuations ranging from $^{+}_{-}300V$. In the grid connection power image, there are clear peaks and troughs, indicating that the system is unstable in the absence of an energy storage system [9].

3.3 PID Control of Energy Storage Systems

In instances where the photovoltaic power generation exceeds the demand at the end of the road, the excess electricity is directed towards the lithium battery for the purpose of charging. During the charging process, it is imperative to meticulously monitor the voltage and current of the lithium battery in real time to ensure the safe charging of the energy storage system. In instances where photovoltaic power generation falls short of meeting demand at the load end, the system will resort to extracting electrical energy from lithium batteries to meet the load. It is imperative that the discharge current is regulated in order to prevent the battery from being over-discharged.

Energy storage systems invariably possess upper limits; therefore, a PID control strategy is adopted in this instance in order to adjust the lithium battery energy storage. This is used to regulate the charging and discharging current or power of the energy storage system, as well as to adjust the duty cycle of the bidirectional DC/DC converter [10]. It is imperative to regulate the charging and discharging processes of the battery in order to ensure the stability and responsiveness of the system. The PID control formula for lithium batteries is as follows:

$$u(t)=K_P e(t)+K_i\int_0^t e(\tau)d\tau+K_d\frac{de(t)}{dt} \tag{7}$$

In this context, $u(t)$ denotes the control signal, $e(t)$ signifies the error, which is the discrepancy between the set value and the actual value, and K_P, K_i and K_d represent the proportional, integral and differential gains, respectively.

Errors can be categorised as either charging or discharging errors. Errors in charging can be defined as the discrepancy between the set voltage and the battery voltage, expressed as follows:

$$e_{charge}(t)=V_{set}-V_{battery} \tag{8}$$

The error during discharge can be expressed as the difference between the power at the load end and the battery power, that is:

$$e_{discharge}(t) = P_{load} - P_{battery} \quad (9)$$

The above conditions are simulated in Simulink to obtain:

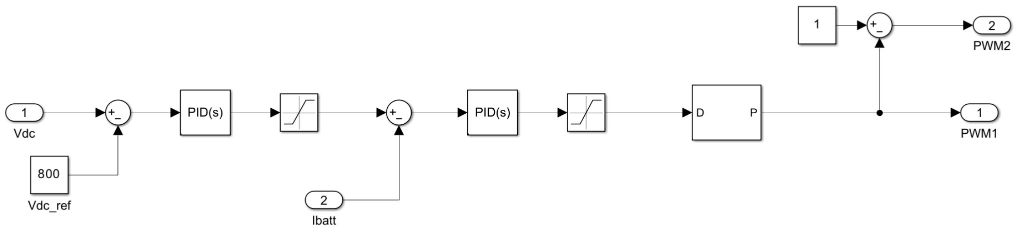

Fig. 7 PID control of lithium battery energy storage

As demonstrated in Fig. 7, the utilisation of a Simulink simulation setup facilitates the regulation of the charging and discharging of a lithium battery energy storage system, in conjunction with the balance of electrical energy, through the implementation of a PID control strategy.

3.4 The Construction of Energy Storage Systems

It is widely acknowledged that the various storage forms of energy can be categorised into three primary classifications: electromagnetic, mechanical and electrochemical. The field of electromagnetic energy storage encompasses a range of technologies, including capacitors and superconductor-based energy storage systems. The field of mechanical energy storage encompasses a range of technologies, including compressed air, pumped storage, and flywheel energy storage, among others. The field of electrochemical energy storage encompasses a wide range of technologies, including lithium-ion batteries and lead-acid batteries, among others. Lithium battery energy storage has become one of the most widely used energy storage devices in contemporary society. This is due to the following advantages: high energy density, good cycle characteristics and low operation and maintenance costs. Consequently, lithium batteries are utilised as the energy storage components in the simulation employed in this study. The positive electrode of a lithium-ion battery is composed of a metal oxide, while the negative electrode consists of graphite. The electrolyte is an organic liquid that contains lithium. The charging and discharging of lithium particle batteries are related to the movement direction of lithium ions inside the battery. In the event of lithium ions flowing from the positive electrode to the negative electrode of the battery, the lithium-ion battery is in a charged state. Conversely, lithium-ion batteries are in a discharged state. In the context of lithium-ion batteries, the utilisation of lithium cobalt oxide ($LiCoO_2$) as the positive electrode material, in conjunction with graphite as the negative electrode material, gives rise to the following chemical reaction equations:

$$Overallreaction: LiCoO_2 + 6C = Li_{(1-x)}CoO_2 + Li_xC_6 \quad (10)$$

$$Charging: LiCoO_2 + 6C = Li_{(1-x)}CoO_2 + Li_xC_6 \quad (11)$$

$$Discharging: 6C + xLi^+ + xe^- = Li_xC_6 \quad (12)$$

The charging and discharging of lithium-ion batteries are reversible electrochemical reactions. The following equivalent circuit models are included: the Thevenin circuit model, the internal resistance model and the Sheffield model, amongst others. In comparison with the Thevenin circuit model and the internal resistance model, the Sheffield model has the capacity to provide a more detailed description of the battery charging and discharging process. Therefore, the present study opts for the Sheffield model shown in Fig. 8, the circuit diagram of which is presented in the accompanying figure:

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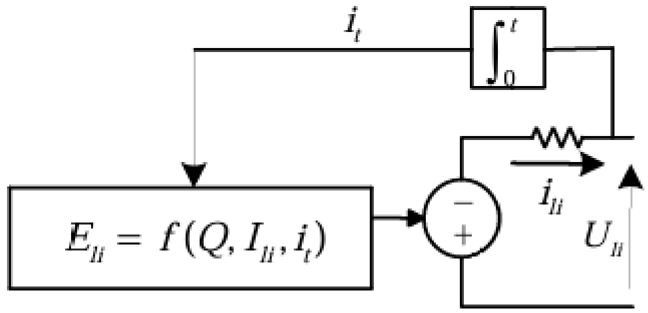

Fig. 8 Sheffield model circuit diagram

The circuit model under consideration comprises a controllable voltage source and a resistor connected in series. The mathematical model employed is as follows:

When discharging $(i_{li} > 0)$:

$$E_{li} = E_0 - \gamma \frac{Q}{Q - \int i_{li} dt} i_{li} - \gamma \frac{Q}{Q - \int i_{li} dt} \int i_{li} dt + \chi exp(-\eta \int i_{li} dt) \quad (13)$$

When charging $(i_{li} < 0)$:

$$E_{li} = E_0 - \gamma \frac{Q}{0.1Q - \int i_{li} dt} i_{li} - \gamma \frac{Q}{Q - \int i_{li} dt} \int i_{li} dt + \chi exp\left(-\eta \int i_{li} dt\right) \quad (14)$$

Terminal voltage of lithium-ion batteries:

$$U_{li} = E_{li} - R_b i_{li} \quad (15)$$

State of charge:

$$SOC = 100(1 - \frac{1}{Q} \int_0^t i_{li} dt) \quad (16)$$

E_{li} is used to denote the no-load voltage of the lithium-ion battery, E_0 is used to denote the constant electromotive force inside the lithium-ion battery, γ is used to denote the polarization constant, Q is used to denote the capacity of the lithium-ion battery, i_{li} is used to denote the current of the lithium-ion battery, χ is used to denote the amplitude of the exponential area, η is the reciprocal of the time constant in the exponential region, U_{li} is used to denote the terminal voltage of the lithium-ion battery, R_b is used to denote the internal resistance of lithium-ion batteries.

Based on the above principle, it is obtained through simulation in Simulink:

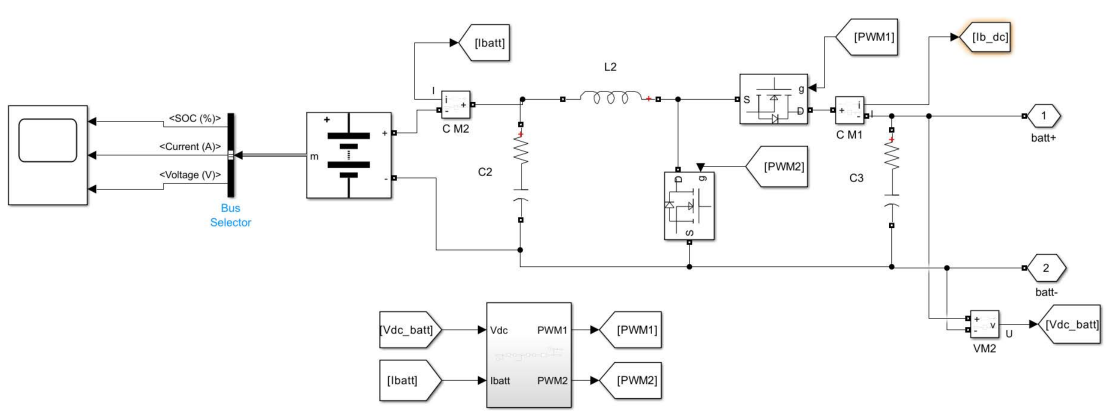

Fig. 9 Energy storage system

As demonstrated in Fig. 9, the substantial energy output of distributed photovoltaic systems necessitates careful consideration of storage solutions. It is imperative that an energy storage system with both excellent storage capacity and stable performance is developed. The defining characteristic of lithium battery energy storage is its high energy density. In this section, the lithium battery model is introduced as the energy storage system of the power grid, and an oscilloscope is incorporated for the purpose of monitoring the state of charge (SOC), voltage, and current conditions of the lithium battery.

3.5 Power Grid Modeling of Photovoltaic Storage Systems

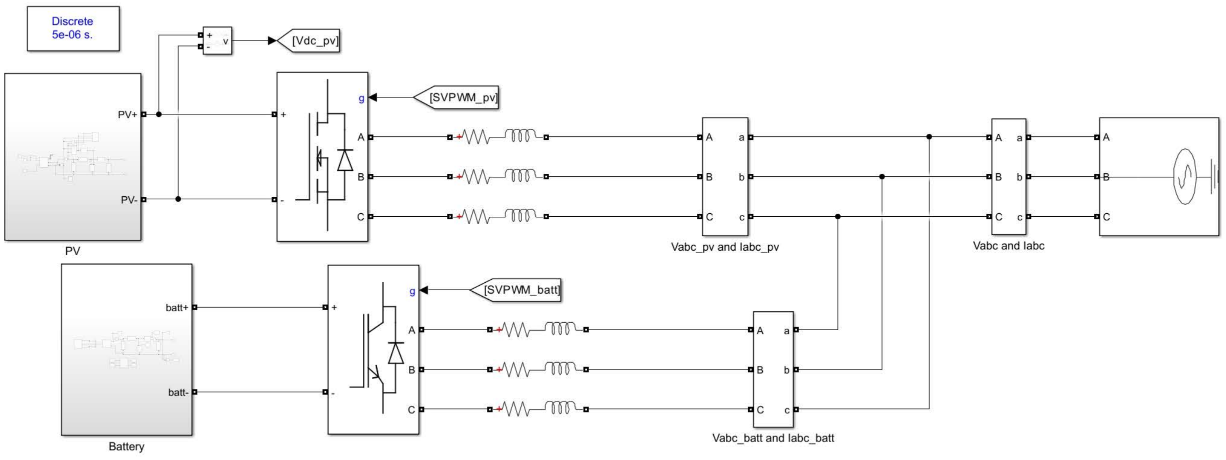

Fig. 10 Photovoltaic storage system

As demonstrated in Fig. 10, the photovoltaic system is integrated with the energy storage system, and subsequently, the data of the entire photovoltaic energy storage system is collected through the utilisation of an oscilloscope. The voltage, current and power results when the photovoltaic system is introduced into the lithium battery energy storage system for joint use are as follows:

Fig. 11 Voltage, current and frequency images

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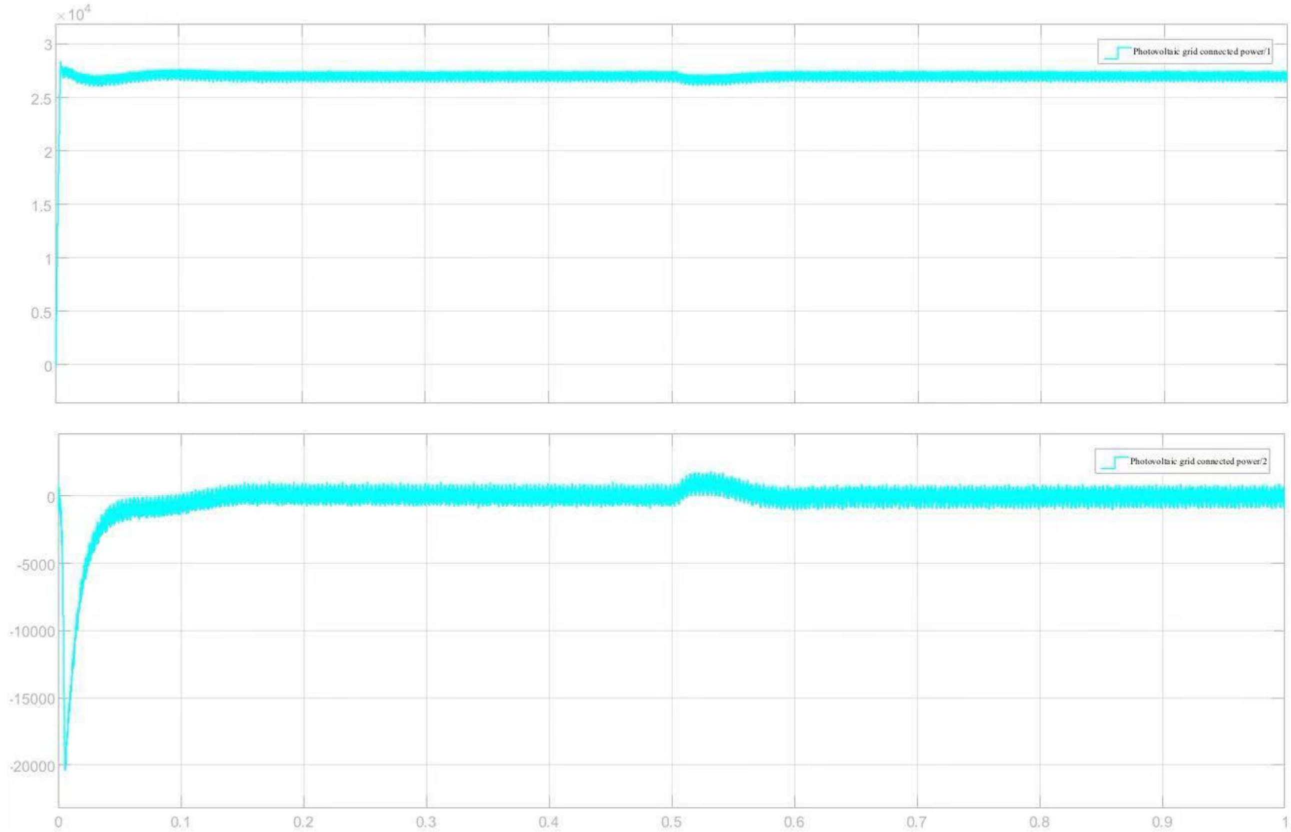

Fig. 12 Output power image

As demonstrated in Fig. 11 and Fig. 12, the simulation results indicate that the incorporation of a lithium battery energy storage system leads to stable voltage and current changes, with no alteration in the amplitudes of current and voltage. It has been demonstrated that the incorporation of an energy storage system enhances the system's responsiveness to grid fluctuations, thereby effectively mitigating the abnormal voltage and current caused by photovoltaic fluctuations through the regulation of charging and discharging [11].

The system power image demonstrates that the power generation efficiency of the system has been enhanced, the power is more stable, and the output is smoother, achieving peak shaving and valley filling. The energy storage system is able to store energy when the photovoltaic capacity is high and discharge when the photovoltaic system capacity is low or the load is large. This achieves effective energy allocation, improves the overall power generation efficiency, and smooths the output curve [12].

4. Analysis of the Economic and Environmental Benefits of Photovoltaic Storage Systems

In the context of the extensive implementation of smart grids and distributed photovoltaic systems, the economic and environmental benefits offered by photovoltaic storage systems are pivotal in determining their potential for widespread adoption. In comparison with conventional single photovoltaic systems, the photovoltaic storage synergy exhibits two key advantages. Firstly, it enhances energy utilisation efficiency, and secondly, it delivers economic returns and carbon reduction benefits.

Firstly, energy storage systems have been demonstrated to enhance the utilisation rate of solar energy resources. The intermittent and fluctuating nature of photovoltaic power generation, attributable to the significant influence of weather, climate and day-night conditions, poses a challenge in maintaining synchrony with user load demands. However, following the integration of an energy storage system, the capacity for peak shaving and valley filling is realised through the strategic storage of excess electricity during peak hours of photovoltaic power generation, with subsequent release during periods of grid insufficiency or peak user demand. This approach serves to mitigate the phenomenon of abandoned light, enhance the utilisation of photovoltaic energy, and fortify the system's resilience [4]. Concurrently, relevant enterprises and users can flexibly determine their electricity usage based on real-time electricity prices, adjust the load, reduce energy costs, and maximize economic benefits.

Secondly, the introduction of energy storage systems has enhanced the resilience and security of the power grid. The photovoltaic storage system has the capacity to function as a critical backup power source, thereby ensuring the provision of a continuous power supply to the power grid in circumstances such as extreme weather, power grid failures or sudden load fluctuations [5]. This capacity to function as a backup power source enhances the system's risk resistance capacity. Furthermore, the implementation of intelligent control algorithms has the potential to enhance the efficiency of energy storage systems by optimising the charging and discharging logic. This, in turn, can contribute to extending the lifespan of energy storage equipment and reducing both the operational and replacement costs of these systems throughout their entire life cycle [8].

In terms of environmental benefits, photovoltaic storage systems have promoted the realization of green, low-carbon and sustainable development goals. Energy storage systems have been demonstrated to promote the utilisation of renewable energy sources, reduce reliance on fossil fuels, and effectively mitigate greenhouse gas emissions, thereby contributing to the mitigation of the greenhouse effect [6]. It is evident that the configuration of the photovoltaic storage system, when optimised in accordance with real-time operation data detection records of the electricity meter, has the capacity to reduce carbon emissions per unit of power generation. This, in turn, can contribute effectively to the achievement of the carbon peaking and carbon neutrality goals. Moreover, the extensive utilisation of photovoltaic energy storage systems has catalysed the evolution of associated domains, including distributed energy, energy storage, and intelligent control, engendering advantageous social and economic ramifications [12].

5. Conclusion

The results of the analysis of distributed photovoltaic systems with and without energy storage systems, as based on simulation results, demonstrate that: The integration of lithium battery energy storage systems in conjunction with photovoltaic systems has been demonstrated to enhance the stability of voltage, current, frequency, and power across the entire power grid. This enhancement in system resilience is a key benefit of this approach. Secondly, the intelligent control of the energy storage system through the PID algorithm has been demonstrated to regulate power output with great efficacy, thereby improving power generation efficiency and extending the life of energy storage. Thirdly, the integration of energy storage systems has been demonstrated to enhance the sustainability, low-carbon profile and efficiency of the entire power grid system. This development is associated with notable economic and environmental advantages.

In the future, as smart grid technology continues to develop and mature, photovoltaic energy storage systems are expected to adopt more intelligent energy management algorithms, such as machine learning and deep reinforcement learning. These systems are also expected to achieve new operation modes, such as multi-energy complementarity and virtual power plants. Concurrently, advancements in energy storage technology and the decline in energy storage costs have prompted the promotion of distributed photovoltaic and energy storage systems for wider application. These systems are poised to contribute to the transformation of the energy structure and the realisation of the carbon neutrality goal.

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