Simulation Research on Energy Management and Control of Small Hybrid Wind-PV-Diesel Power Supply System

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Abstract

For small hybrid wind-PV-diesel power supply system, a coordinated control of all parts of the distributed power supply is necessary, to ensure that the system can maintain a desired independent running time. The control strategy proposed in this paper can realize the coordinated control of distributed generation components, reasonably and efficiently dispatch the flow of energy, and distribute the active power output. At the same time, the charge and discharge of the battery is controlled, and the reasonable charging curve of the battery can be realized. Finally, based on the Matlab/Simulink simulation platform, a model of small microgrid with wind-PV-diesel-storage system is built, and the control strategy proposed in this paper is simulated and verified, and the result is in line with the expectation.

Keywords

DC microgrid, control strategy, charging curve.

1. Introduction

With the increasing energy crisis and the increasingly serious environmental pollution problems, renewable energy plays an increasingly important role in people's daily life. People have invested more in the research and development of renewable energy such as wind energy and solar energy [1, 2]. Due to the intermittent and random nature of wind energy and solar energy resources, it is necessary to achieve reliable, safe and efficient utilization of this part of renewable energy through corresponding control strategies [3, 4, 5]. The DC microgrid is a controllable system that uses DC power distribution to connect distributed power through a common DC bus. Compared with the AC microgrid, the DC microgrid does not need to control the phase and frequency, which reduces the energy conversion link, and the control is simple and reliable. However, an important technical indicator of the DC microgrid is to maintain the stability of the bus voltage within a certain range. Therefore, it is necessary to realize the stability of the micro-network DC bus voltage through coordinated operation of various distributed power sources. For the wind-PV-diesel DC microgrid system, the battery is usually connected to the bus through a bidirectional converter, thereby realizing its charge and discharge control. During the operation of the system, it needs to dynamically adjust the main power supply to control the energy distribution, and the power controller should switch the control mode correspondingly. This undoubtedly increases the complexity of the system and affects its reliability.

In this paper, a simple and efficient energy management control strategy is proposed for small off-grid hybrid wind-PV-diesel DC microgrid system, which realizes the coordinated operation of distributed power sources and maintains the stable operation of the system under off-grid conditions. At the same time, the charge and discharge part of the battery is controlled, and a reasonable charging curve of the battery is realized. Based on the Matlab/Simulink platform, the operation control strategy of the hybrid wind-PV-diesel DC microgrid system is simulated, which obtained the expected results and verified its feasibility.

2. System Structure

The structure of the wind-PV-diesel DC microgrid system is shown in Fig. 1, where diesel generators, lead-acid batteries, photovoltaic cells, direct-drive wind generator are the energy equipment of the system, which can coordinate the operation through the corresponding converter and controller to maintain the stability of the bus voltage within a certain range. It can directly supply the power for the local DC load. In addition, it can supply power for AC load through UPS inverter module. The system is also equipped with unloading part, when the system generates excess energy, it can be consumed by controlling the unloading load to maintain the energy balance of the system.

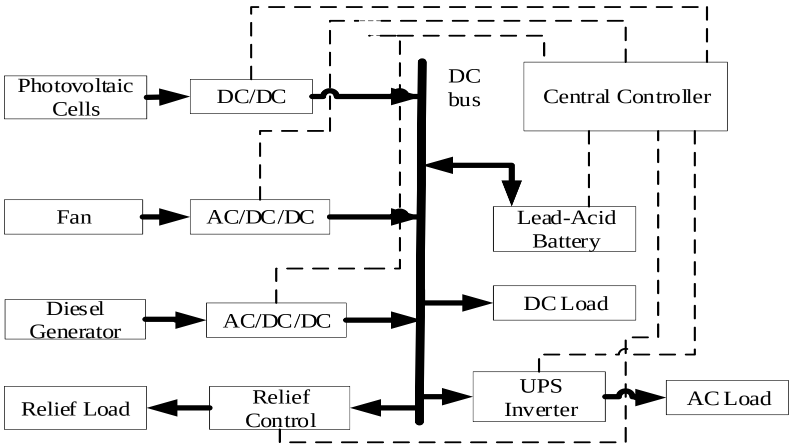

Fig 1. Structure of the wind-PV-diesel DC microgrid system

In this paper, it is based on a 48v DC bus voltage to supply a 2.7kW target load. The 48v battery is connected directly to the DC bus, eliminating the bidirectional converter that is typically added between the battery and the DC bus. At the same time, it controls the output of renewable energy (such as wind and light) and maintains the power of the system stable.

By controlling the output controller of the diesel generator terminal, the battery charging control is realized. The detailed control strategy will be described below.

2.1 Modeling and Control of Photovoltaic Cells

Photovoltaic cells convert solar radiation energy into electrical energy through photovoltaic effect. Its equivalent circuit is shown in Fig. 2.

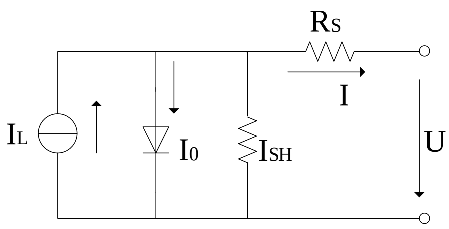

Fig 2. Equivalent circuit diagram of photovoltaic cells

According to the photovoltaic equivalent circuit diagram, the output characteristic expression of the photovoltaic cells can be obtained:

$$I = I_L - I_0\left[\exp\frac{q(U+IR_S)}{AKT} - 1\right] - \frac{U+IR_S}{R_{SH}}. \tag{1}$$

Where, I represents the photovoltaic cell output current, I_L represents photoinduced current, I_0 represents the reverse saturable current of the diode, q represents the electronic charge, K represents the Boltzmann constant, T represents the absolute temperature, A represents the photovoltaic cell diode factor, U represents the photovoltaic cell output voltage, R_S indicates the internal resistance of the battery; R_{SH} indicates the reverse saturation leakage resistance of the diode. According to the simplified physical model with characteristic parameters, the engineering mathematical model is as follows.

$$I = I_{SC}\left[1 - C_1\left(e^{U/C_2U_{OC}}\right) - 1\right]. \tag{2}$$

$$C_1 = (1 - I_m / I_{SC})e^{-U_m/C_2U_{OC}}. \tag{3}$$

$$C_2 = (U_m / U_{OC} - 1)\ln^{-1}(1 - I_m / I_{SC}). \tag{4}$$

In the equation, U_{OC} is the open circuit voltage of photovoltaic cell, I_{SC} is the short circuit current under standard test conditions, U_m is the voltage at maximum power point, I_m is the current at maximum power point. The simulation encapsulation model can be established based on this mathematical model.

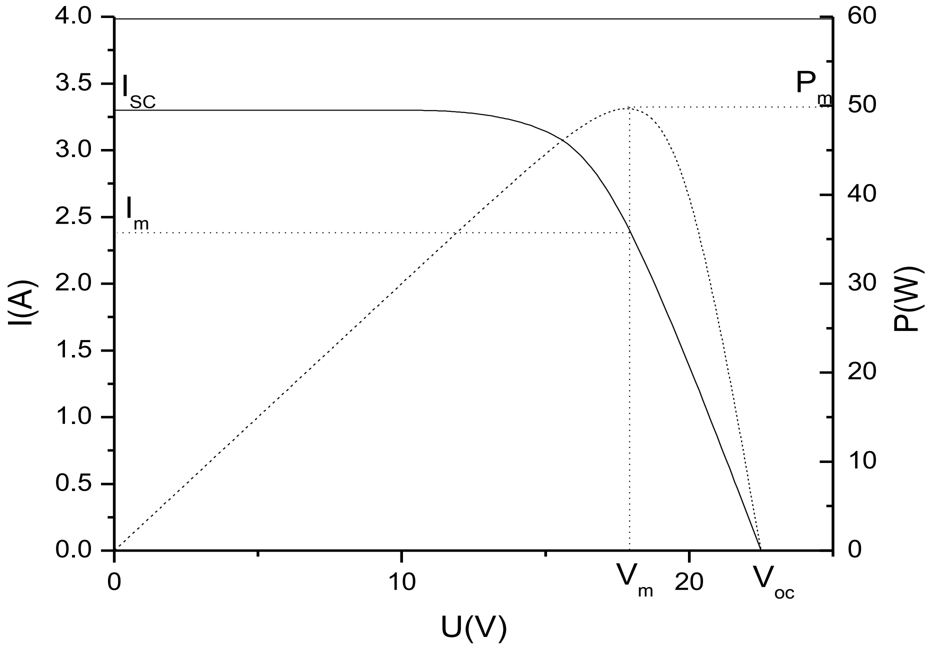

Fig 3. I-V and P-V characteristics of photovoltaic cells

According to Eq. 2, the I-V and P-V characteristic curves of the photovoltaic cell are shown in Fig. 3. From the figure, we can find the relationship between the output voltage and the output current of the photovoltaic cell under a certain intensity and temperature. From the curve we can know that the photovoltaic cell is a nonlinear DC power supply, and the output current is kept constant in most of the working voltage range, and the current will drop to zero as the voltage continues to rise. Therefore, we need to control the output voltage of the photovoltaic cell to achieve maximum power point tracking (MPPT) to maintain the maximum power output of renewable energy.

In the simulation study, the capacitance of the photovoltaic cell is 1 kW, and the output is connected to the DC bus by DC/DC converter circuit. The control structure diagram is as follows.

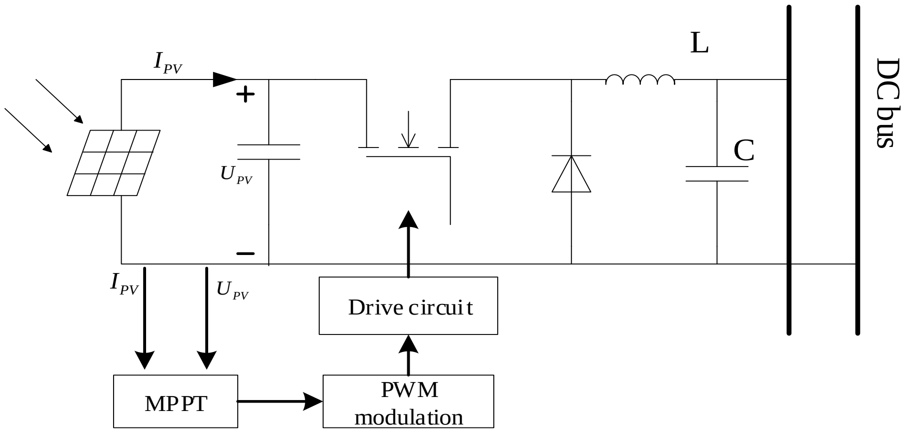

Fig 4. Photovoltaic power generation energy conversion control structure diagram

Maximum power point tracking (MPPT) is to monitor the voltage and current of photovoltaic cells in real time and achieve maximum power output through corresponding control strategies. We can achieve maximum power output by changing the duty ratio of DC/DC converter in real time, that is, to change the output impedance of the photovoltaic cell to achieve the best matching of impedance to achieve the maximum power output. In this way, the maximum utilization rate of renewable energy can be guaranteed when the external environment changes such as temperature and illumination. At present, the common photovoltaic MPPT methods include constant pressure control, disturbance observation and admittance increment. The disturbance observation method is widely applied because of its simple control, high accuracy and fast response. The principle is to apply a positive direction of disturbance step under a given duty ratio. If the system output and the direction of the disturbance increase synchronously, the disturbance in the direction is continued. If the system output is opposite to the disturbance direction, the reverse direction disturbance is applied, so that the system will work near the maximum power point. On this basis, the fast response and steady state balance of the system can be realized by changing the disturbance step length (Its principle is similar to the following fan maximum power tracking, in Section 2.2).

2.2 Fan Modeling and Control

At present, wind turbines commonly used at home and abroad mainly include ordinary three-phase synchronous power generation systems, doubly-fed wind power generation systems, and permanent magnet direct-drive wind power generation systems. Among them, the permanent magnet direct drive fan has higher efficiency at low wind speed, less energy consumption, and lower maintenance cost. Therefore, a permanent magnet direct drive fan is used as the wind power generation part in the wind-PV-diesel DC microgrid system in this paper.

The fan transforms wind energy into mechanical energy, and then converted mechanical energy to electrical energy by driving the permanent magnet synchronous motor. According to the Bates principle of wind energy utilization, the wind energy captured by the fan is:

$$P_M = 0.5\rho R^2 C_p V^3. \tag{5}$$

The mechanical torque of the fan output is as follows:

$$T_M = 0.5\rho\pi R^3 C_p V^2/\lambda. \tag{6}$$

$$\lambda = \omega R/V.$$

In the equation, ρ is air density, R is the fan radius, C_p is wind capacity utilization coefficient, V is wind speed, λ is tip speed ratio, ω is wind wheel rotation angular velocity.

$$C_p(\lambda, \beta) = 0.5176(116/A - 0.4\beta - 5)e^{-21/A} + 0.0068\lambda. \tag{7}$$

$$A = 1/\left(\frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{\beta^3 + 1}\right). \tag{8}$$

In the fomula, β is the pitch angle. According to this, the mathematical model of the fan can be established, and the permanent magnet synchronous motor module already packaged in Similink can be selected for the motor part.

The relationship among λ, β and wind capacity utilization coefficient C_p is as following.

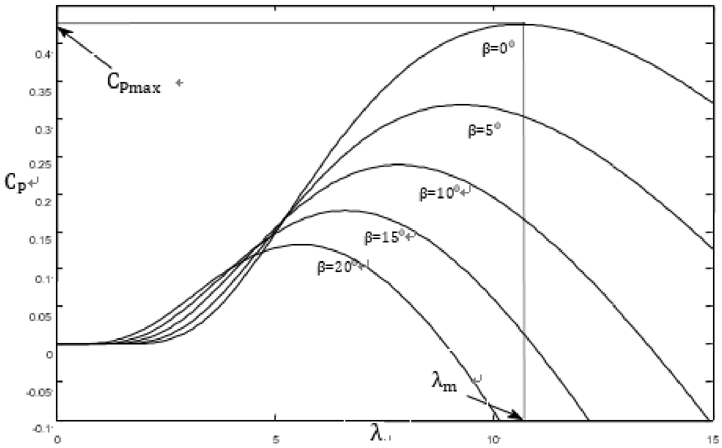

Fig 5. Wind energy utilization coefficient

In the figure, we can see that when β is constant, there is always a leaf tip speed ratio λ corresponding to the maximum wind energy utilization coefficient. At a certain tip speed ratio λ, when β is equal to zero, the wind energy utilization coefficient reaches the maximum. And with the increase of β, the utilization coefficient of wind energy will gradually decrease when the λ is maintained.

When the wind speed is below the rated value, the pitch angle β of the fan is zero, and the maximum power tracking MPPT of the fan is achieved by adjusting the tip speed ratio λ. When the wind speed exceeds the rated wind speed, it is necessary to adjust the maximum power point dynamically by adjusting beta, so that the output power of the fan is maintained at the rated value. When the wind speed is fixed, the Eq. 4 shows that the blade tip speed ratio is relative to the speed, and the wind energy utilization coefficient C_p is related to the power of the fan. At this time, the curve shown in Fig. 5 is also applicable to the relationship between the power P and the rotational speed ω of the fan, so in the fan system, it is necessary to dynamically adjust the rotational speed ω to achieve the maximum power output.

The common maximum power tracking control algorithms of fans mainly include optimum tip speed ratio method, power signal feedback method and disturbance observation method. The variable step size disturbance observation method is used to realize maximum power tracking of wind in this study. The control structure diagram is shown below.

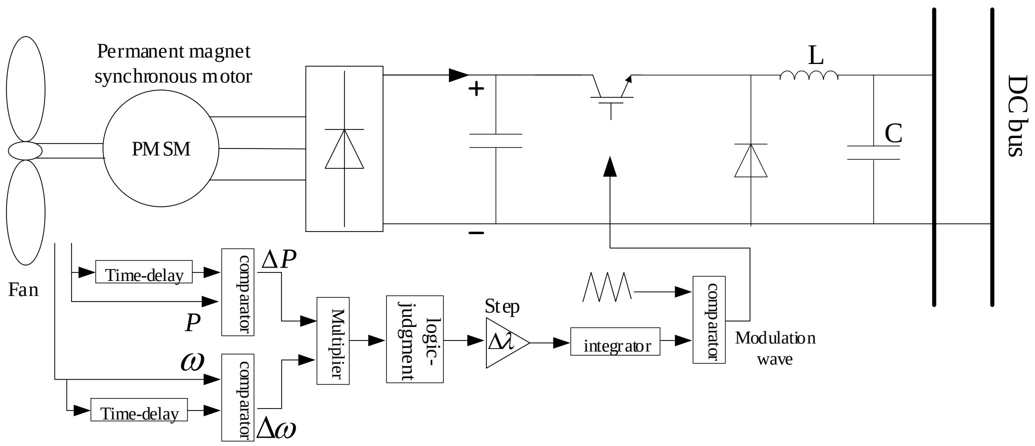

Fig 6. Maximum power tracking of wind turbines.

2.3 Charge and Discharge Control of Battery

In the hybrid wind-PV-diesel DC microgrid system, the battery is an indispensable part of energy storage, and it can stabilize the DC bus voltage within a certain range and adjust the system power balance. Compared with other batteries, lead-acid batteries have been widely used due to their low operating temperature, reliable performance, low price, safety and efficiency. This article uses a lead-acid battery.

Overcharging or over-discharging of the battery will cause a large deviation of the bus voltage directly connected to it, resulting in the system not functioning properly, and at the same time, the battery may be irreparably damaged, so it is necessary to control its charging and discharging. The common charging methods of the battery include constant voltage charging, constant current charging, and constant voltage limiting three-stage charging which can make up for the shortage of these two charging modes. As shown in Fig. 7, the constant voltage current limiting charging curve of the battery is shown. Constant current charging is performed at the initial stage of charging, and constant voltage charging is performed later. This charging method has better charging performance, does not cause overshoot current, and enables fast and efficient charging.

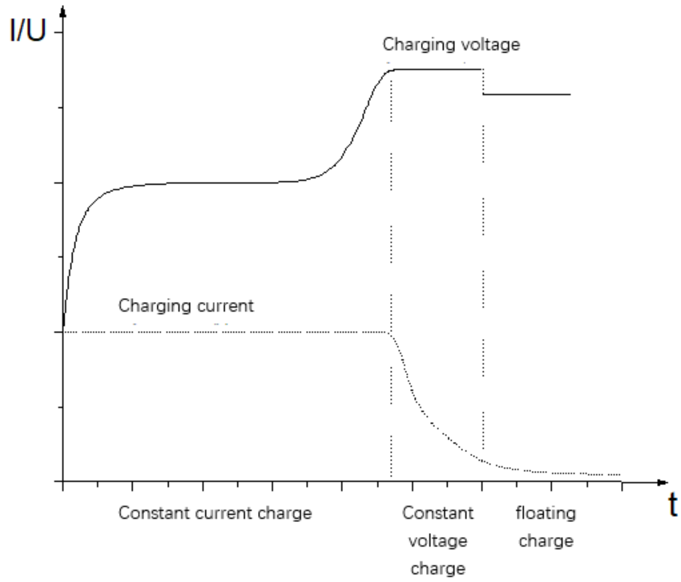

Fig 7. Constant-voltage limitary-current three-stage charging

In this paper, the optimal charging curve control of the battery is realized by controlling the output power of the diesel generator (see Section 2.4). When the battery is fully charged, if the renewable energy supply is too much, in order to prevent the battery from overcharging, it is necessary to put in the unloading load; when the battery energy is insufficient and the renewable energy cannot provide sufficient power, in order to prevent the battery over-discharge voltage from being too low It is necessary to start the diesel generator in time to provide load power and charge the battery. The battery model in this paper uses the lead-acid battery module that comes with Simulink.

2.4 Diesel Generator Control

In this paper, a synchronous motor is used to simulate a diesel generator to supply power to the system. The normal supply of the load and the charging of the battery are achieved by controlling the output of the three-phase synchronous motor. At present, the mainstream scheme adopted by the DC microgrid is to control the discharge of the battery by adding a DC/DC bidirectional converter between the battery and the DC bus to manage the flow of energy. According to the actual demand, based on the low-voltage DC microgrid of 48v bus voltage, the battery is directly connected with the busbar, and the ideal charging curve of the battery is realized by controlling the DC/DC converter of the synchronous motor end, thus eliminating the need to save the battery. The circuit switching process that needs to be continuously operated when the battery is bidirectionally flowed in the battery enables better system stability during charging and discharging of the battery.

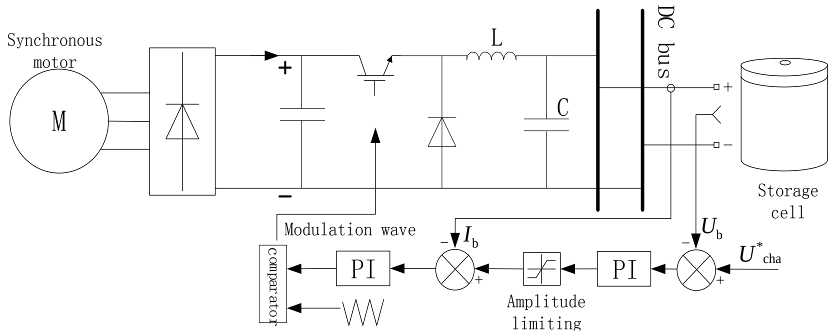

Fig 8. Generator output control structure diagram

The generator output control structure is shown in Fig. 8. At the beginning of charging, the battery voltage is low, so the error of the battery voltage U_b and the given charging voltage U^*_{cha} is still large after PI adjustment, which can not be used as the current inner loop reference value. At this time, the limiter link is added, and the limit value is the maximum allowable charging current, thereby constant current charging is achieved. As the charging progresses, the battery voltage gradually rises, when the error is lower than the limit value, the current limiting link will no longer function, the system enters the constant voltage charging phase, and the charging current is gradually reduced until the battery is full.

2.5 Energy Management Control Strategy

For the DC microgrid, the charge and discharge control of the battery is usually realized by a DC/DC bidirectional converter, and the system needs to adjust the main power in real time according to the supply of renewable energy. When the renewable energy is sufficient, the control is switched to the main power mode to stabilize the bus voltage. At this time, the battery is charged as a load; when the renewable energy is insufficient, the battery is used as the main power source to stabilize the bus voltage; when both the remaining energy of the battery and the renewable energy is insufficient, the backup power supply is activated to supply power to the system. This traditional practice often requires frequent switching of the controllers of the distributed power supplies, thereby greatly increasing the complexity of the system control.

Based on the actual project, this paper proposes a set of energy management control strategy based on low-voltage DC microgrid. By connecting the 48v voltage class battery directly to the DC bus, the bidirectional converter of the battery is omitted, and the control is used as the backup power source. The output of the diesel generator is used to achieve constant voltage current limiting charging of the battery. For the renewable energy part, it is always controlled to the maximum power output. When the system energy has a margin, it is put into the unloading load for consumption. The control strategy is shown in Fig. 9.

There are three important system parameters in Fig. 9, there are the minimum voltage U_{min} and the maximum voltage U_{max} of the battery, the diesel engine shutdown voltage threshold U_{th}. Since the voltage of the battery is always positively related to its charge, it is possible to monitor its residual charge by detecting its voltage. When the system is in normal operation within the normal voltage range, the fan and photovoltaic always work in the maximum power output mode, and the charge and discharge of the battery is determined by the supply of renewable energy. When the renewable energy is sufficient, the excess power is supplied to the battery for charging, and when it is insufficient, the battery is required to make up the insufficient power of the load. When the bus voltage is lower than U_{min}, the diesel generator is started to charge, and the voltage reaches the diesel shutdown voltage threshold U_{th}, the engine stops. When the bus voltage is higher than U_{max}, the unloading load is added.

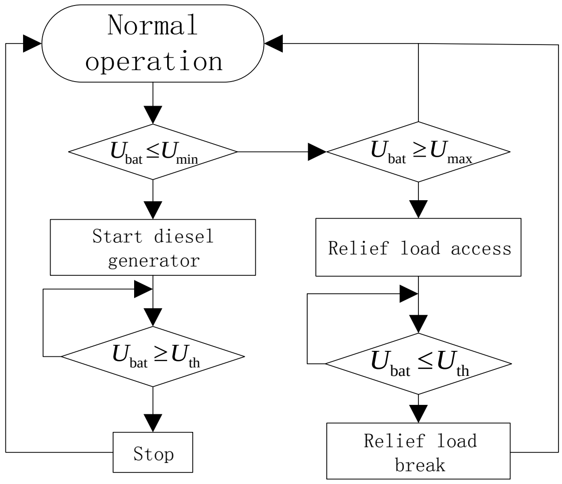

Fig 9. Energy management control strategy based on low-voltage DC microgrid

3. System Simulation and Results Analysis

According to the above system structure, the simulation model of the wind-PV-diesel DC microgrid system is built on the Matlab/Simulink simulation platform as shown in Fig. 10.

The simulation parameters of the hybrid wind-PV-diesel DC microgrid system are shown in Table 1.

Table 1. Simulation parameters configuration of the hybrid wind-PV-diesel DC microgrid system.

Power supply	Fan[kW]	PV[kW]	48V Battery[Ah]	Diesel generators[kW]	Load[kW]
Power	2	1.5	1500	15	2.7

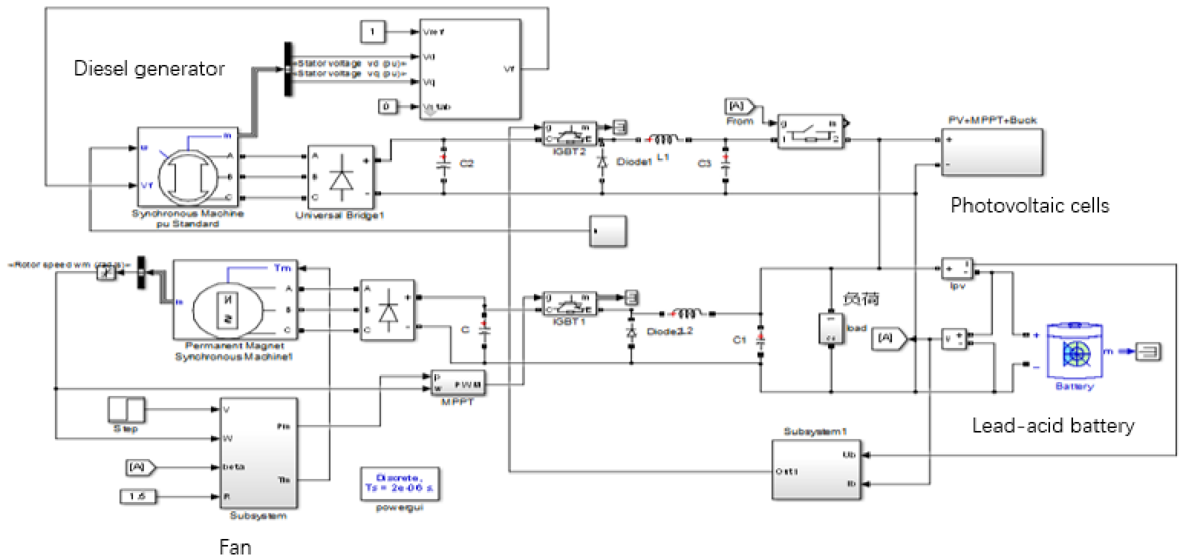

Fig 10. Simulation model of hybrid wind-PV-diesel DC microgrid system

Set the ambient temperature to $25°C$, photovoltaic cell rated sunshine intensity is 1000W/m^2, the rated wind speed of the fan is 7m/s. The initial sunshine intensity and wind speed are set to 800 respectively. W/m^2, 5 m/sThe simulation waveform is shown in Fig. 11.

It is assumed that the system is in stable running state at t=0.5s. It can be seen from the Fig. 11 that the system can maintain stable operation at the beginning, and the output of the fan and photovoltaic cell is stable. As the renewable energy is not sufficient to provide enough power to maintain the load operation at this time, battery discharge is required to maintain power balance. Balanced power P_{bal}

in the figure represents the algebraic sum of the output power and load power of all parts of the system, which value can be basically stabilized at zero. It can be seen that the system can maintain power balance, and the bus voltage is stable. At t=2s, the intensity of sunshine is increased to the rated value and the wind speed is increased to 6 m/s. It can be seen from the diagram that the dynamic adjustment of the fan and PV battery has reached a new output steady state, and the adjustment process is rapid and meets the expected requirements. As renewable energy increases, excess energy will be generated to charge the battery, and the bus voltage can be seen rising synchronously.

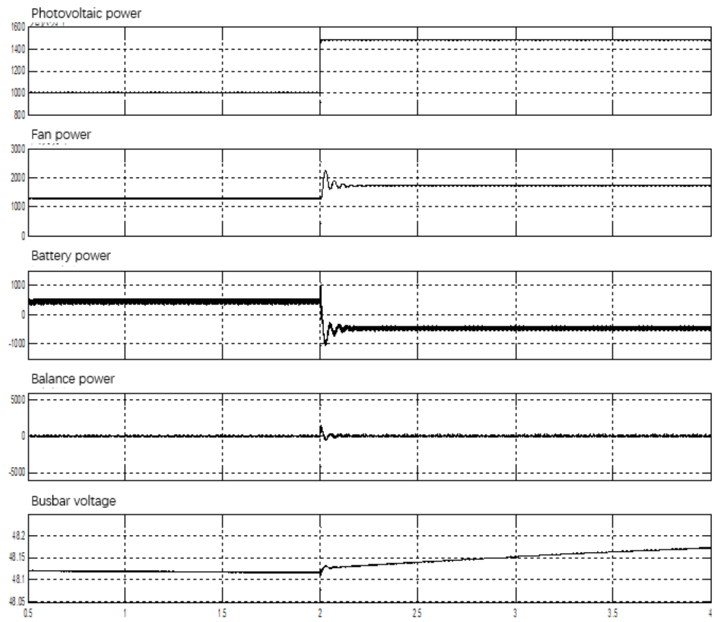

Fig 11. Wind and light diesel DC micro-network simulation waveform.

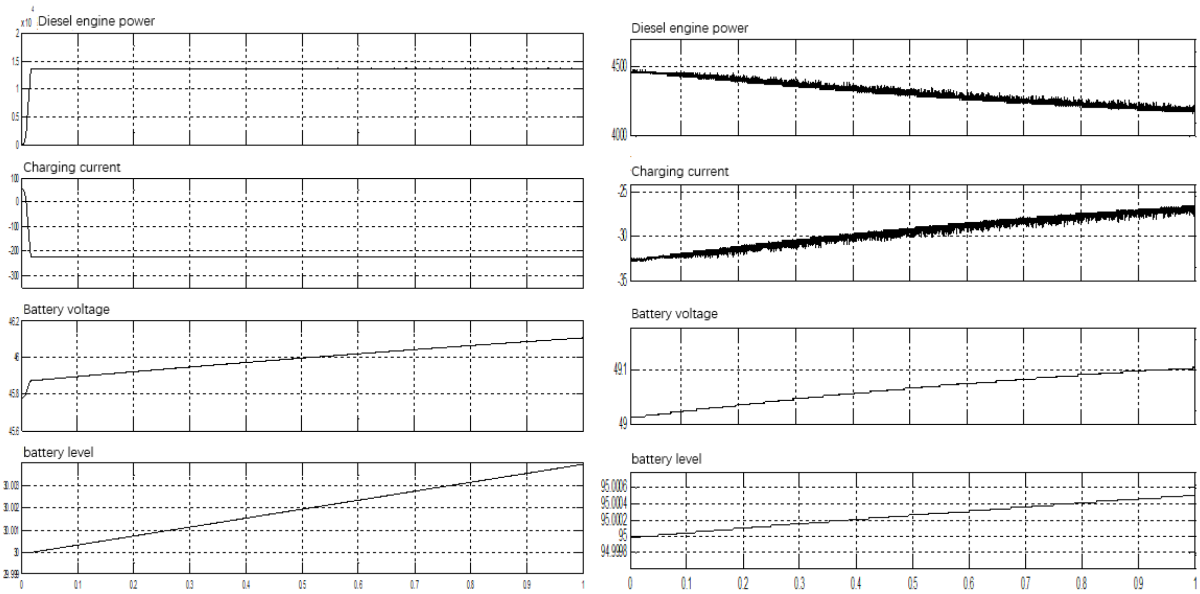

Fig 12. Diesel engine charging control output waveform.

In the normal voltage range of the battery, the system can operate stably according to the established control strategy, the switching fluctuation of the battery charging and discharging process is small, and the system power can be maintained stable.

When the battery voltage is too low to reach the warning line, it is necessary to activate the backup power diesel generator to charge the battery. According to the charge of the battery C=1500Ah, select the charging current limit value $I_{lim} = 0.15 * C = 225A$ Therefore, the charging power is $P_b = U_b * I_{lim} = 48 * 225 = 10.8kW$. Considering the load power of 2.7 kW, a 15kW rated diesel generator is used. The simulation results show that the diesel engine charging control output waveform is shown in Fig. 12.

It can be seen from the figure that in the initial stage of charging, the output power of the diesel generator is stable, the charging current of the battery is gradually increased to reach the current limiting amplitude, and then charged with a constant current, and the battery voltage and the charge amount are simultaneously increased. As the charging progresses, the charging current will gradually decrease in the later stage of charging, the corresponding diesel generator output will gradually decrease, and the battery voltage and the charge current will rise synchronously, thereby completing the charging control of the battery.

4. Conclusion

In this paper, a simulation study on the energy management control strategy of small off-grid wind-PV-diesel DC microgrid system is proposed. The 48v battery is directly connected with the busbar, which eliminates the need to add bidirectional flow between the battery and the DC bus. The device simplifies the control mode switching process of each distributed power source during the battery charge and discharge control process, which makes the system control simpler and more efficient. At the same time, a control strategy of diesel generator output is proposed to realize the ideal charging control of the battery. In addition, the paper also introduces the system modeling, output characteristics and corresponding power output control strategies of fans and photovoltaic cells.

The simulation results show that the power output control of the renewable energy of this system is stable and efficient, the system can maintain the power balance, and the ideal charging curve of the battery is realized in the charging control part of the diesel generator to the battery. This verifies the feasibility of the energy management control strategy of the hybrid wind-PV-diesel DC microgrid proposed in this paper, which meets the expected requirements.

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