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Photovoltaic Hydrogen Storage Combined with DC Microgrid System and Energy Allocation Optimization Strategy

Ruohan Li

Department of Faculty of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing, China
15128275828@163.com

Abstract: This study focuses on the design and energy management optimization of a photovoltaic hydrogen storage DC microgrid, aiming to improve the utilization efficiency of renewable energy and solve the intermittent and unstable problems in traditional energy systems by integrating solar and hydrogen energy technologies. With the intensification of global energy depletion and climate change issues, finding sustainable clean energy solutions has become an urgent task for governments and all sectors of society around the world. The article first establishes a photovoltaic hydrogen storage microgrid model, analyzes the key technologies of photovoltaic power generation, battery energy storage, and hydrogen energy storage, and then proposes an energy management strategy based on cascaded fuzzy control to optimize power allocation and improve the overall efficiency of the system. The purpose of this article is to provide theoretical support and practical guidance for the research of photohydrogen integrated microgrid systems through the construction of system models and the proposal of optimization strategies, promoting the efficient utilization and development of renewable energy.

Keywords: DC microgrids, Energy distribution management, Photo-hydrogen storage model

1. Introduction

With the increasingly serious problem of energy depletion, energy transformation is urgent. Globally, addressing climate change and reducing carbon emissions have become urgent tasks for governments and all sectors of society. Among them, solar energy, as the most promising form of clean energy, has achieved significant results in its development and utilization. However, in actual operation, due to the inherent randomness and intermittency of photovoltaic power generation, it has led to a series of problems such as increased difficulty in peak shaving of the power grid and a surge in energy storage demand. Hydrogen energy, as an ideal energy storage medium and clean fuel carrier, [1-3]is widely regarded as one of the effective ways to solve the above contradictions due to its unique advantages such as high energy density, good conversion efficiency, and zero pollution emissions. Thus, the combination of photohydrogen storage and microgrid system emerged.

The photovoltaic hydrogen storage combined microgrid system is a comprehensive energy system that combines renewable energy and hydrogen technology. The system consists of photovoltaic modules, hydrogen production equipment, and corresponding energy storage devices [4], to solve the

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pain points of intermittent and unstable photovoltaic power generation.[5] Many scholars have studied the photovoltaic hydrogen storage combined microgrid system, and its core lies in its efficient energy conversion and storage capabilities, which can ensure the stability and reliability of power supply in unstable renewable energy production environments. Reference [6] used a hybrid electrolytic cell to solve the problem of slow reaction and difficulty in adapting to the intermittency and uncertainty of photovoltaic power generation in traditional alkaline electrolytic cells; Reference [7] describes the replacement of traditional fuel cells with proton exchange membrane fuel cells to improve energy utilization efficiency; Reference [8] proposes an energy management strategy for electric hydrogen coupled DC microgrids based on cascaded fuzzy control for power allocation in DC microgrids. This article proposes a wind solar hydrogen integrated energy microgrid system based on the above literature to improve energy utilization efficiency.

The research on the photovoltaic hydrogen storage combined microgrid system has high application prospects and adaptability, especially suitable for remote areas or mobile application scenarios. Its flexible allocation capability and green energy characteristics provide innovative solutions for the future energy structure transformation.

2. Wind solar hydrogen energy system model

2.1. Wind solar hydrogen integrated energy system

This article establishes the use of photovoltaic power generation as energy supply, and produces hydrogen gas using alkaline electrolysis cells or PEM electrolysis cells. The hydrogen gas is stored in hydrogen storage tanks and used in conjunction with fuel cells and batteries for comprehensive use.

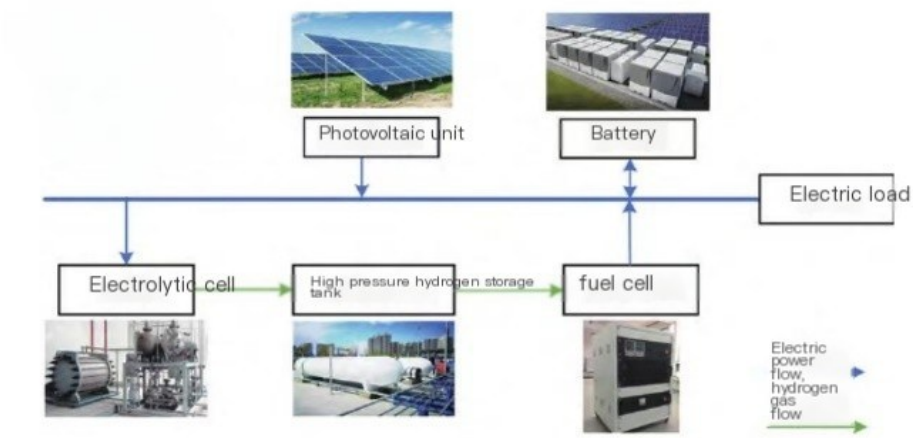

Figure 1: Structure of photovoltaic hydrogen storage microgrid system [9]

The operation mode of microgrids should cover multiple scenarios, including islanding mode and grid connected mode. In islanding mode, the system relies on the combination of wind solar hydrogen to achieve stable power supply through flexible scheduling. The grid connected mode focuses on the interaction with the main power grid, maximizing economic benefits through the grid connected generation of wind energy.[10]

2.2. Photovoltaic power generation model

Photovoltaic arrays are usually composed of a series of semiconductor photovoltaic cells connected in parallel based on the principle of photovoltaic effect, which directly convert solar radiation into

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electrical energy using the photovoltaic effect. The typical photovoltaic cell model and photovoltaic array model are shown in the following figure.

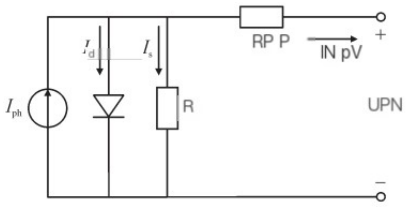

Figure 2: Photovoltaic array equivalent circuit [11]

Based on the equivalent circuit of photovoltaic array, the relationship between output current and output voltage can be obtained

$$\begin{cases} I_{pv} = I_{ph} - I_d - I_s \\ I_d = I_0 \left\{ exp\left[\frac{q(U_{pv}+I_{pv}R_p)}{\alpha_0} \right] - 1 \right\} \end{cases} \tag{1}$$

In the formula, $R_p$is the series impedance of the photovoltaic cell;I_{ph} Representing the current generated by the photovoltaic array due to sunlight exposure;I_{pv} For load current; I_0For saturation current;U_{pv} For the output voltage of photovoltaic cells; α_0As a time factor.

The calculation method for the application of photovoltaic power output engineering is as follows

$$P_s = \eta_s A_s I \tag{2}$$

$$\eta(I, T_s) = \left(a_1 + a_2 + a_3 lnI\right) * \left[1 - 0.005\left(T_s - 25\right)\right] \tag{3}$$

In equation (2), (3), $A_s$is the total area of the photovoltaic panel array; ITotal irradiance received by photovoltaic panels; η_sTo improve the photoelectric conversion efficiency of photovoltaic panels; T_sOperating temperature for photovoltaic panels; a_1, a_2, a_3The irradiation parameters received by photovoltaic panels.

2.3. Battery Energy Storage System model

The main body of the Battery Energy Storage System (BESS) is a lithium battery, which stores and releases energy through the conversion of internal electrical and chemical energy. The energy storage level and operating state of BESS are determined by the state of charge (SOC) of the lithium battery. The DP model is chosen for the mathematical model of the lithium battery, and the Coulomb counting method is used for SOC estimation.The details are as follows [12-13]

$$\begin{cases} U_{bat} = U_{oc-bat} - I_{bat}R_0 - U_{p-bat} - U_{s-bat} \\ I_{bat} = \frac{U_{p-bat}}{R_p} + C_p \frac{dU_{p-bat}}{dt} \\ L_{SOC} = L_{SOC,0} - \frac{\int P_{bat,t} dt}{C U_{bat,t}} \end{cases} \tag{4}$$

In the formula: U_{bat}, I_{bat} are the output voltage and output current of the lithium battery, respectively; $U_{oc-bat}, U_{p-bat}, U_{s-bat}$They are the open circuit voltage, electrochemical polarization voltage, and concentration polarization voltage of lithium batteries, respectively; R_0, R_pThey are the ohmic resistance and electrochemical polarization resistance of lithium batteries, respectively; C_pElectrochemical polarization capacitance for lithium batteries; L_{SOC}State of Charge (SOC) for

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lithium batteries; $L_{SOC,0}$Initial SOC value for lithium batteries; C is the rated capacity of the lithium battery; $U_{bat,t}, P_{bat,t}$The voltage and power of the lithium battery at time t are respectively.

2.4. Hydrogen energy storage system model

The energy absorption and release of the hydrogen energy storage system (HESS) mainly rely on two parts: the electrolytic cell and the fuel cell, which are separately operated and isolated by the hydrogen storage tank.

2.4.1. Mixed electrolytic cell model

Hybrid electrolysis cells include alkaline electrolysis cells and proton exchange membrane (PEM) electrolysis cells, which combine the advantages of simple operation, low cost, and fast response capability of the former, and can better adapt to the intermittency and uncertainty of wind and solar power generation.

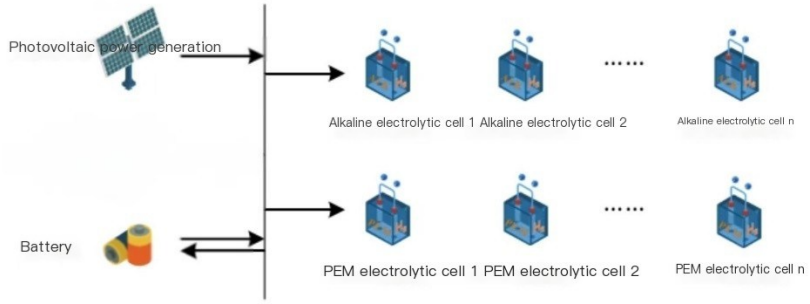

Figure 3: Alkaline-PEM hybrid production system [14]

The main components of an alkaline electrolytic cell are bipolar plates, gaskets, anode and cathode electrodes, and separators, which produce hydrogen and oxygen based on electrolysis of water or electrolyte solutions containing alkaline solutions.

The voltage equation is

$$U = N * U_{cell} = N * \left[U_{rev} + \frac{r_1 + r_2 T}{A_{cell}} I + (s_1 + s_2 T + s_3 T^2) lg \left(\frac{t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}}{A_{cell}} I + 1 \right) \right] \quad (5)$$

In the formula: N- number of modules connected in series with a single battery; U_{cell}- Voltage of a single cell in an electrolytic cell; U_{rev}- Internal reversible open circuit voltage; T - Temperature of electrolytic cellA_{cell}— Electrode area; r_1, r_2- Electrolyte Ohmic Resistance Parameterss_1, s_2, s_3— Electrode overvoltage coefficient; t_1, t_2, t_3- Electrolyte overvoltage coefficient.

The hydrogen production is

$$n_J = \eta_F \frac{NI}{2F} \quad (6)$$

In the formula, z represents the gas compression coefficient Faraday efficiency, where F is the Faraday constant.

The main components of a PEM electrolytic cell, from inside to outside, are proton exchange membrane, anode cathode catalytic layer, anode cathode gas diffusion layer, anode cathode plate, etc.

The hydrogen production rate of PEM electrolytic cell is

$$n_{PEM} = \eta_F \frac{N_{el} I_{el}}{2F} \quad (7)$$

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2.4.2. Fuel cell model

As a device that converts chemical energy into electrical energy, fuel cells are typically classified into different types based on the type of electrolyte. Among them, proton exchange membrane fuel cells (PEMFCs) have attracted increasing attention in practical engineering applications due to their long service life, ability to operate continuously for a long time, low operating temperature, and high power density.

The hydrogen consumption rate of PEMFC is

$$n_{PEMFC} = \eta_F \frac{N_{fc} I_{fc}}{2F} \tag{8}$$

The output voltage of a fuel cell formula can be expressed based on Srinivasan's experience as [15]

$$E_{fc} = U - E_{act} - E_{ohm} - E_{conc} \tag{9}$$

(9) In the equation, U is the Nernst voltage, $E_{act}$is the activation E_{ohm}overpotential, $E_{conc}$is the Ohmic overpotential, and is the concentration overpotential

2.4.3. Hydrogen storage tank model

The hydrogen storage capacity in the hydrogen storage tank is determined by both the hydrogen production rate of the electrolytic cell and the hydrogen consumption rate of the fuel cell. When the hydrogen storage tank meets the following requirements: (1) there is no leakage during the hydrogen storage process; (2) The temperature of the hydrogen storage tank remains constant; (3) The mathematical model of the hydrogen storage tank remains unchanged in terms of its volume.It can be expressed by following formula.[16]

$$\begin{cases} M = M_0 + \int \frac{\eta_F I_{el} N_{el}}{2F} dt - \int \frac{\eta_F I_{fc} N_{fc}}{2F} \\ p_{tank} = \frac{R T_{tank}}{V_{tank}} M \\ L_{SOH} = \frac{p_{tank}}{p_{tank-max}} \times 100\% \end{cases} \tag{10}$$

(10) In the formula, M represents the hydrogen content in the hydrogen storage tank at time t, and M_0represents the hydrogen content in the hydrogen storage tank at the initial time.T_{tank} is the temperature of the hydrogen storage tank; .$V_{tank}$is the volume of the hydrogen storage tank; .L_{SOH} Hydrogen storage state for the hydrogen storage tank; .P_{tank} is the internal pressure of the hydrogen storage tank; $P_{tank-max}$ is the maximum pressure that can be withstood inside the hydrogen storage tank.

3. Device level control model

3.1. Overview of microgrid control model

The microgrid operates in a coordinated manner through layered control of the source load storage devices to ensure stable operation of the microgrid. The microgrid connects the DC bus and various equipment devices through a DC/DC converter to achieve lower level control; By monitoring the operating status of each device through an energy management system (EMS) and providing power reference values for each DC/DC converter, upper level control is achieved.[17] To achieve the coordinated regulation of the DC microgrid mentioned above, this paper proposes a hierarchical control method. The upper level is a system level control based on fuzzy logic controller interpolation

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method (FLC-IM), which can monitor and collect real-time information of each device in the microgrid, analyze and optimize data, and allocate power to each device in the lower level; The lower level is device level control, which can adopt matching inverter control strategies according to the different working characteristics of each device.[18]

3.2. Operation control of photovoltaic arrays

The photovoltaic array adopts maximum power point tracking (MPPT) control, whose core idea is to regulate the operating point of the photovoltaic array to ensure that the photovoltaic power generation system always operates at the maximum power point, thereby achieving the highest energy conversion efficiency. The commonly used photovoltaic MPPT methods include conductance increment method, open circuit voltage method, short-circuit current method, and disturbance observation method. In this paper, MPPT control based on perturbation observation method is selected. [19-20] MPPT continuously detects I_{pv}, U_{pv} and calculates the voltage reference value corresponding $U_{mppt-ref}$ to the maximum power point. U_{pv} After the difference between this value and the PI controller, a PWM duty cycle signal is generated and D_{pv} applied to the boost converter.

3.3. Operation control of lithium batteries

$I_{bat} U_{bat-ref}$ After the reference voltage of the lithium battery generated by EMS is passed through the PI controller, a current reference value is generated $I_{bat-ref}$. The difference between this value and the current is passed through the PI controller, and a PWM duty cycle signal is generated to D_{bat} act on the buck boost converter.

3.4. Operation control of fuel cells

The output power of fuel cells during operation is I_{fc} nonlinearly positively correlated P_{fc} with. $I_{fc} P_{fc-ref}$ After the fuel cell reference power generated by EMS is passed through the IM controller, a current reference value is generated I_{fc-ref}. The difference between this value and the current is passed through the PI controller, and a PWM duty cycle signal is generated to D_{fc} act on the boost converter.

3.5. Operation control of electrolytic cell

The output power of the electrolytic cell during operation is I_{el} nonlinearly positively correlated P_{el} with. $I_{el} P_{el-ref}$ After the reference power of the electrolytic cell generated by EMS is passed through the IM controller, a current reference value is generated I_{el-ref}. The difference between this value and the current is passed through the PI controller, and a PWM duty cycle signal is generated to D_{el} act on the buck converter.

4. Upper level control model

4.1. FLC-IM energy management system

Bus capacitance can smooth out voltage fluctuations in microgrids caused by small power fluctuations in distributed power sources or loads. However, when there are significant fluctuations in distributed power sources or loads, a hybrid energy storage system is needed to compensate for power shortages in microgrids and suppress bus voltage fluctuations. The dynamic equation of DC bus voltage and the power balance equation of microgrid are as follows

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$$\begin{cases} C_{dc}\frac{dU_{dc}}{dt} = I_{pv} \pm I_{bat} - I_{el} + I_{fc} - I_{load} \\ \frac{1}{2}C_{dc}\frac{dU_{dc}^2}{dt} = P_{pv} \pm P_{bat} - P_{el} + P_{fc} - P_{load} \end{cases} \tag{11}$$

(11) In the formula, the subscript dc represents the relevant parameters of the DC bus, the subscript load represents the load related parameters, the subscript pv represents the photovoltaic array related parameters, the subscript bat represents the lithium battery related parameters, the subscript el represents the electrolytic cell related parameters, and the subscript fc represents the fuel cell related parameters.

The expression for the net power of a DC microgrid is

$$P_{net} = P_{pv} - P_{load} \tag{12}$$

The controllable power expression of the hybrid energy storage system is

$$P_{hyd} = \pm P_{bat} + P_{el} - P_{fc} \tag{13}$$

The core of DC microgrid EMS lies in the P_{net}power distribution between various devices. When the photovoltaic output exceeds the load demand, that is, when it is greater than 0, in order to reduce the waste of light, the hybrid energy storage system is activated to absorb the energy of the photovoltaic surplus; When the photovoltaic output is exactly equal to the load demand, that is, P_{net}equal to 0, the hybrid energy storage system stops working; When the photovoltaic output is insufficient to meet the load demand, i.e. P_{net}less than 0, the hybrid energy storage system is activated to compensate for the power shortage of the source load.[20] The power allocation process of the FLC-IM energy management system is shown in the following figure:[21]

Condition 1: The $P_{net} \geq 0$system is in a charging state; L_{SOH}When the fuel cell is out of operation, the hybrid energy storage system determines the LSOC of HESS and BESS during charging power allocation. When both LSOH and LSOC reach their upper limits, considering the safety of the hybrid energy storage system, the light is discarded.

Condition 2: The $P_{net} \geq 0$system is in a charging state; L_{SOC}If the upper limit is not reached, the energy storage system corresponding to the device will absorb the remaining electricity.

Condition 3: The $P_{net} \geq 0$system is in a charging state; L_{SOC}If the upper limit is not reached, the energy storage system corresponding to the device will absorb the remaining electricity.

Condition 4: The $P_{net} \geq 0$system is in a charging state; L_{SOC}When neither reaches the upper limit, the first level fuzzy controller (FLC-I) is used to allocate the initial power of the hybrid energy storage system, obtaining the reference values for the primary charging power of the electrolytic cell and lithium battery. Then, the second level fuzzy controller (FLC-II) is used to correct the reference values and obtain the final charging power reference values for the electrolytic cell and lithium battery.

Condition 5: The $P_{net} \leq 0$system is in a discharge state; L_{SOC}When L_{SOH}both are reduced to the lower limit, considering the safety of the hybrid energy storage system, the hybrid energy storage system will be shut down.

Condition 6: The $P_{net} \leq 0$system is in a discharge state; When it does L_{SOC}not reach the lower limit, the energy storage system corresponding to the device will supplement the shortfall.

Condition 7: The $P_{net} \leq 0$system is in a discharge state; When it does L_{SOH}not reach the lower limit, the energy storage system corresponding to the device will supplement the shortfall.

Condition 8: The $P_{net} \leq 0$system is in a discharge state; The initial power allocation of the hybrid energy storage system is carried out through FLC-I to obtain the reference values of the primary discharge power of the fuel cell and lithium battery. Then, FLC-II is used to correct the reference values and obtain the final discharge power reference values of the fuel cell and lithium battery.

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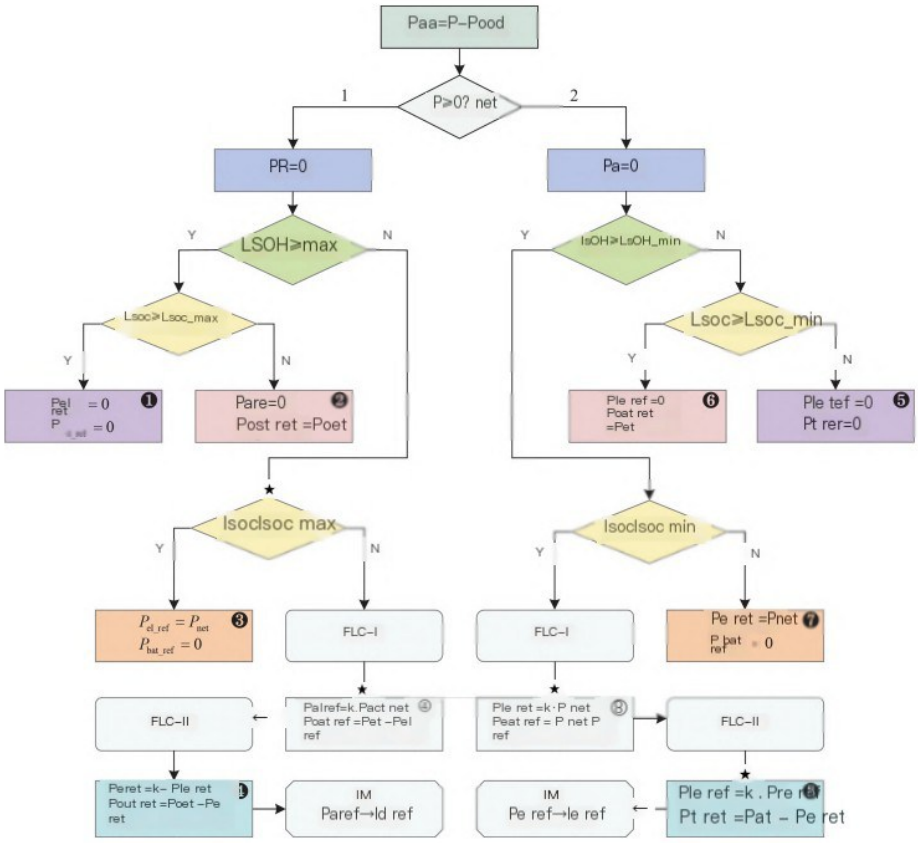

Figure 4: Power allocation flowchart of FLC-IM energy management system

4.2. Power allocation strategy based on cascaded fuzzy control

The cascaded fuzzy controller consists of two levels of fuzzy controllers. In the systemL_{SOH}, and $L_{SOC}$are two input variables of FLC-I. Through the calculation of first-order fuzzy logic rules, the HESS primary power allocation factor k is obtained, and then P_{net}multiplied to obtain the HESS primary charge/discharge power reference value$P_{HESS-ref}$;P_{net} The $P_{HESS-ref}$difference between and is the primary power reference value of BESS$P_{bat-ref}$. The calculation expression of FLC-I is as follows:

$$\begin{cases} P_{el-ref} = k * P_{net} \\ P_{bat-ref} = P_{net} - P_{el-ref} \end{cases} \tag{14}$$

$$\begin{cases} P_{fc-ref} = k * P_{net} \\ P_{bat-ref} = P_{net} - P_{fc-ref} \end{cases} \tag{15}$$

(14) The parameters with subscripts ref in equation (15) are all primary power allocation reference values.

The first power allocation result of the hybrid energy storage system obtained through a first level fuzzy control strategy can initially achieve a L_{SOH}、L_{SOC}fast transition from different interval states to reasonable intervals.[22] However, this strategy does not fully utilize the advantages of BESS's flexible dynamic response, which increases the power fluctuation of HESS to a certain extent, and does not consider the later limit exceeding L_{SOH}situation caused by HESS's same direction power throughput near the upper/lower limit.[23] Therefore, this paper uses FLC-I and FLC-II for cascaded

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control, aiming to reduce the proportion of HESS bearing fluctuating power by correcting k, slow down the upward/downward fluctuation trend of LSOH, and compensate for the difference between HESS before and after the first and second level power allocation using BESS. FLC-II takes $P_{HESS-ref}$and L_{SOH}as two input variables, calculates the HESS secondary power allocation factor through second-order fuzzy logic rules$k^{'}$, and then $P_{HESS-ref}$multiplies it to obtain the secondary charge/discharge power reference value$P_{HESS-ref}^{'}$; The $P_{HESS-ref}^{'}$difference between $P_{net}$and is the secondary power reference value of BESS$P_{bat-ref}^{'}$. The calculation expressions for FLC-II are shown in equations (16) and (17)

$$\begin{cases} P_{el-ref}^{'} = k' * P_{el-ref} \\ P_{bat-ref}^{'} = P_{net} - P_{el-ref}^{'} \end{cases} \tag{16}$$

$$\begin{cases} P_{fc-ref}^{'} = k' * P_{fc-ref} \\ P_{bat-ref}^{'} = P_{net} - P_{fc-ref}^{'} \end{cases} \tag{17}$$

5. Conclusion

This article delves into the design and optimization of a wind solar hydrogen integrated energy microgrid system, with a focus on analyzing its potential in improving the efficiency of renewable energy utilization and addressing the intermittency and instability of wind solar power generation. By establishing a system model and proposing an energy management strategy based on cascaded fuzzy control, this paper demonstrates the flexibility and reliability of the system in various application scenarios, significantly improving the stability of power supply.

(1) The research integrated technologies such as hybrid electrolysis cells and proton exchange membrane fuel cells to optimize the production and storage efficiency of hydrogen energy. The application of these technologies not only improves the energy conversion efficiency of the system, but also provides new solutions for the efficient utilization of renewable energy.

(2) We have established an FLC-IM energy management strategy, which can optimize power allocation under different operating conditions and improve the effective power and energy utilization of DC microgrids.

Looking ahead, the wind solar hydrogen integrated energy microgrid system has broad application prospects in remote areas, mobile applications, and urban energy structure transformation. With the continuous advancement of technology and policy support, this system is expected to play an important role in achieving sustainable development goals. However, the promotion and application of the system still face some challenges, including the economic viability of hydrogen energy storage technology, the complexity of system integration, and adaptability under different climatic conditions. Future research directions should focus on optimizing the economy and reliability of the system, exploring the application of new materials and technologies to further enhance the overall performance of the wind solar hydrogen integrated energy microgrid system.

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