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Research on the Control Strategy of Urban Integrated Energy Systems Containing the Fuel Cell

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Abstract: As a new type of energy with the advantages of high efficiency, clean and pollution-free, fuel cells have attracted the attention of many experts and scholars. The efficient utilization of fuel cells will certainly become the mainstay of energy transformation and environmental protection. However, fuel cells have low power density, soft electrical output characteristics, and significantly delayed response to sudden load changes. When fuel cells are used as power supply energy alone, the output voltage fluctuates greatly, and the power supply reliability could be higher. To increase the fuel cell's service life in real world applications, a DC converter and an appropriate auxiliary energy storage power supply are combined to form a fuel cell hybrid power supply system that makes efficient use of the auxiliary energy storage system's availability, enhances the power supply system's adaptability through dynamic reconfiguration, and provides better flexibility overall. This work proposes a method for managing the energy produced by an urban integrated power supply system that includes fuel cells, supercapacitors, and solar cells. Applying the IF-THEN rule of load power and the state of charge of the supercapacitors, the power balance is adjusted between the su-percapacitors, photovoltaic cells, and fuel cells according to the defined fuzzy logic control. The intermittent nature of solar power production and the erratic nature of fuel cell output may both be mitigated using this technique, allowing the load power to operate more reliably. The simulation results show that the control strategy adopted in this paper is able to not only meet the load requirements but also reasonably allocate the functional requirements and improve the working efficiency of the system, resulting in a clear optimization effect on the system's control. In this paper, we focus on the fuel cell hybrid power supply system design, and then we use the idea of fuzzy logic control energy management to build the structure of the fuzzy logic control system, design the fuzzy controller, determine the functions, and verify the solutions through simulation and experimentation.

Keywords: fuel cell; urban integrated energy system; control strategy; fuzzy logic control

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1. Introduction

In recent years, numerous researchers have shown great interest in the development of fuel cells. Compared with traditional fossil fuels, fuel cells have many advantages such as high efficiency, no pollution, and long service life, and are widely used in the aerospace field [1]. However, fuel cells have a drawback of low power density, which requires the addition of converters and energy storage sources to ensure efficient and stable power supply.

Energy management strategies are the core of fuel cell stable operation and reliable power supply. A reasonable energy management strategy can not only achieve optimal energy allocation, but also meet the power requirements of load operation. Literature [2] proposed a parameter estimation adaptive update control strategy for fuel cell load tracking, which optimized the utilization of fuel cells but did not allocate energy reasonably. Literature [3] is based on literature [2] and proposed real-time power allocation between fuel cells and supercapacitors. Although this strategy allocated energy reasonably, it affects the long-term operation of the system. Literature [4] used differential theory to achieve reasonable energy allocation, but it is difficult to model, computationally expensive, and structurally complex. Literature [5] proposed a fuel cell embedded energy management method based on fuzzy theory but cannot guarantee the stability of DC bus voltage. In literature [6], Jiang et al. used a genetic algorithm to develop an energy management strategy that improved the efficiency of fuel cells. Kaya et al. in literature [7] investigated the impact of control strategies on the lifetime of system components. In literature [8], a fuzzy adaptive PI controller was designed to control the fuel cell and was compared with the traditional PI controller. The results showed that the fuzzy adaptive PI controller could reduce saturation time and overshoot. Additionally, in literature [9], a fuzzy logic approach was used to design a control model for the output voltage of fuel cells and supercapacitors, which improved the output performance of fuel cells by making the average output voltage close to the set point. While these methods have achieved certain effects, the issue of unequal power distribution still exists.

Therefore, this paper proposes an energy management strategy for a city comprehensive power supply system composed of fuel cells, supercapacitors, and photovoltaic cells. Based on a specified fuzzy control, IF-THEN rules are applied to optimize power balance distribution between the supercapacitors, photovoltaic cells, and fuel cells based on load power and supercapacitor state of charge. This method can achieve stable operation of load power and effectively solve the problems of fuel cell output instability and intermittent photovoltaic power generation, with significant optimization effects.

2. Background

With the formulation of the goal of "carbon peak and carbon neutrality", while pursuing benefits, more attention is paid to environmental protection, especially in the face of the shortage of fossil energy, global warming, air pollution, and other problems [10–12]. In this regard, governments worldwide attach great importance to it and formulate sustainable development strategies committed to the research, development, and use of efficient and clean new energy such as fuel cells.

A hybrid power supply system with a fuel cell as the core has been used in aerospace, heavy industry, light industry, electric power, communication, transportation, and other fields. In the civil field, fuel cell research is most widely used in electric vehicles. Then, the energy management strategy is particularly important in the urban energy management system. Effective energy management strategies can improve the efficiency of fuel cells and auxiliary energy storage devices and the reliability of the operating system as a whole. Different energy management strategies have different effects on the energy distribution of the system. Specifying reasonable and effective energy management strategies for power supply systems with varying sources of energy is one of the keys to the long-term stable operation of the system [13,14]. Therefore, the industrialization process of hybrid power supply systems powered by fuel cells that is now under development will speed up. The research on its energy management strategy is of social value and practical significance.

3. Design of Urban Integrated Energy System Containing the Hydrogen Fuel Cell

3.1. Urban Comprehensive Energy Power Supply Structure

The topology of the urban comprehensive energy power supply system chosen for this paper's fuel cell research is shown in Figure 1. The load side is composed of DC/AC converters and loads, while the power side is composed of fuel cells, supercapacitors, photovoltaic cells, unidirectional DC/DC converters, and bidirectional DC/DC converters. All modules are fed back to the energy manager. An energy management controller is used to control and distribute energy supply, thus forming the structure of an urban comprehensive energy power supply system. There are a large number of devices and many energy supply channels. As energy sources, fuel cells, supercapacitors, and photovoltaic cells provide the required power to the load side through DC/AC converters managed by the energy monitoring and control system.

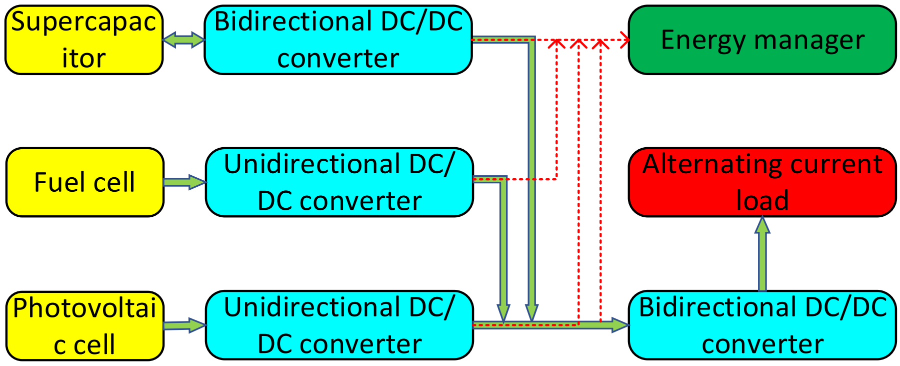

Figure 1. Integrated energy and power supply system topology based on fuel cells.

The power side of the aforementioned topology structure includes an alternating current (AC) load and a bidirectional direct current (DC) to direct current (DC/DC) converter that is wired into both the DC bus and the AC bus. In the power supply test, the supercapacitor and the fuel cell or photovoltaic cell are both connected to the DC bus via unidirectional DC/DC converters so that the voltage from the energy source can be increased or decreased, respectively, at the DC bus to meet the power supply system's power source output voltage level requirements.

The supercapacitor is coupled in series with a bidirectional DC/DC converter and the DC bus to act as an auxiliary energy storage system. The connection of the conversion device increases the flexibility of the supercapacitor in charge and discharge control. The fuel cell system uses a unidirectional DC/DC converter connected in series with the DC bus as the primary power supply unit. By linking the conversion unit, the fuel cell's output may be regulated, eliminating the phenomenon of fuel hunger during system operation [15–18], and reducing the situation of large fluctuations in energy output. An energy management controller is responsible for distributing the electricity generated by the power grid, and then the DC/AC converter is controlled to provide the required power for the load side. Based on the comprehensive energy power supply structure of fuel cells, energy management involves regulating the flow of power from sources such as fuel cells and ultracapacitors to achieve optimal distribution while giving full play to the electrical characteristics of energy sources according to the energy output and load demand changes of the power supply side of the system as state variables.

3.2. Fuel Cell

This article focuses on hydrogen energy storage as the energy source for fuel cells. Conventional energy storage technologies include pumped storage, battery storage, superconducting storage, and compressed air energy storage. Among them, superconducting energy storage has the advantages of fast response speed and high response power, but superconducting materials are expensive. Maintaining low tem-perature refrigeration operation requires a lot of energy; Low energy density (second level only). Pumped storage belongs to physical storage, with high conversion efficiency, and has been widely used in areas with conditions, as its construction scale depends on specific geographical features and environmental conditions and is greatly influenced by climate and region. To integrate it with wind and solar complementary power generation systems, pumped storage power stations need to be able to accommodate large-scale and seasonal abandonment of electricity, which is challenging [19,20]. The compressed air energy storage has higher safety risks, while chemical batteries have lower energy density, a short cycle life, and require complex maintenance. Moreover, they are difficult to decompose and can cause environmental pollution when reaching the end of their service life [21].

Conventional energy storage technologies such as pumped storage, batteries, superconducting energy storage, and compressed air energy storage all face challenges in meeting the requirements for ultra-large capacity and long cycle periods. In contrast, hydrogen storage has advantages such as large capacity, ease of transport, and simple maintenance. Additionally, hydrogen storage is not typically limited by time constraints, unlike some other storage methods such as lead-acid batteries and flywheels, which may experience self-discharge and mechanical losses during long-term operation that affect system energy storage efficiency. Hydrogen storage can be well matched with wind and solar power generation systems and can adapt to different environmental conditions and operate normally, making it an optimal choice for system energy storage. The entire hydrogen storage process mainly includes hydrogen production, hydrogen storage, and hydrogen fuel cell power generation, completing the conversion between electrical and hydrogen energy. If the front end is a grid-connected wind and solar power generation system, using this storage technology can smooth out the output of the generation system, ensuring the stability of the power supply system. The entire process is free of carbon emissions. In terms of application scenarios, hydrogen storage stations have no land requirements and take up a small area. Pumped storage stations need to be built in areas with abundant water resources and are greatly affected by climate and geography. During the peak load period, the hydrogen gas generated by electrolysis can be used as the energy source for power generation, and the stored hydrogen gas will not escape. Therefore, hydrogen fuel cells can be a reliable power source and one of the best solutions for developing storage and utilization under the green development concept in new energy generation [22].

At present, basically tends to mature, the most widely used fuel cells can be divided into three types, alkaline fuel cells, proton exchange membrane fuel cells, solid oxide fuel cells. As shown in Table 1 below, the operating temperature of alkaline fuel cells ranges from 80 °C to 230 °C. Because it can operate at a lower temperature (about 80 °C), it starts up quickly, but its power density is ten times lower than that of proton exchange membrane fuel cells. It is mainly used in aerospace field and is not suitable for building large and medium-sized power stations. The operating temperature of proton exchange membrane fuel cells is between 80 °C and 230 °C, which can be quickly started at room temperature and can quickly change the output power according to the load requirements. It is the best candidate for electric vehicles, submarine power sources independent of air propulsion, various mobile power sources and distributed power generation equipment. The operating temperature of solid oxide fuel cells is usually between 800 °C and 1000 °C, and the current research takes the SOFC operating temperature of 700 °C as the leading direction. The power of solid oxide fuel cells can reach more than 2000 kW, and the cheap preparation technology is especially suitable for the construction of large and medium-sized power stations.

Table 1. Characteristics of three fuel cell electrolytic cells.

Cell Type	**Alkaline Cell**	**Solid Oxide Electrolyzer**	**Proton Exchange Membrane Electrolyzer**
Electrolyte	20–30%KOH	Y_2O_3/ZrO_2	Proton exchange membrane
Operating temperature/°C	70–90	600–1000	70–80
Energy consumption/(kWh·Nm^{-3})	4.5–5.5	3.8–5.0	2.6–3.6
Operating characteristics	Start and stop very fast, corrosive liquid, high cost of operation and maintenance.	Start and stop unchanged, mainly laboratory research.	Quick start and stop, simple operation and maintenance, low cost.

To generate electricity, fuel cells use the chemical energy stored in the fuel. They have the advantages of high efficiency, no pollution, low noise, and only water and heat as incidental products. They are especially suitable for use in dense urban centers. There are three types of commonly used fuel cells. Solid oxide fuel cells are selected in this paper.

The ability of proton exchange membrane fuel cells to adapt to variations in load is its main benefit, and they are insensitive to environmental changes with a fast response speed.

The dynamic model equation of the fuel cell established in this paper is as follows and the total voltage can be expressed as:

$$\begin{cases} V_{cell} = E - V_{ohm} - V_{conc} - V_{act} \\ V_{fc} = N \cdot V_{cell} \end{cases} \tag{1}$$

where V_{cell} is the fuel cell's output voltage in a single unit; E is the theoretical electromotive force; V_{ohm} is the electromotive force that dissipated by ohm; V_{conc} is concentration loss electromotive force; V_{act} is the electromotive force loss upon activation; V_{fc} is the fuel cell's discharge voltage; N is the number of individual fuel cells.

3.3. Supercapacitor

Supercapacitors are a high specific power energy storage device that can quickly switch between charging and discharging due to their response speed. During system functioning, the unexpected shift in load will affect the life of cells and photovoltaic cells. Therefore, supercapacitors are added to cushion the impact of load on fuel cells and photovoltaic cells [23–25]. This system uses a carbon material double-layer capacitor as the supplementary energy source to meet the needs of the whole system, absorb the voltage fluctuation of the bus, and provide short-term power shortage to maintain the voltage stability of the bus. In this paper, the equivalent circuit model is adopted for the supercapacitor. The output voltage of the ultracapacitor is expressed as follows:

$$V_{sc} = \begin{bmatrix} \frac{R_c}{R_e+R_c} & \frac{R_e}{R_e+R_c} \end{bmatrix} \cdot \begin{bmatrix} V_b \\ V_c \end{bmatrix} + \begin{bmatrix} -R_t - \frac{R_c R_e}{R_e + R_c} \end{bmatrix} \tag{2}$$

where R_c is capacitance resistance, unit Ω; R_e is zero resistance, unit Ω. The simplified circuit model of the equivalent RC circuit for supercapacitors is shown in Figure 2, where C_b is a static capacitor; C_c is a dynamic capacitor. In the diagram, R_t is the terminal voltage of stationary capacitor; V_b is the terminal voltage of stationary capacitor; V_c is the terminal voltage of dynamic capacitor C_c. Compared with storage batteries and traditional physical capacitors, supercapacitors have the characteristics of high-power density, a long cycle life, no memory problems, wide operating temperature limit, they are maintenance free, they have green environmental protection, and so on. Supercapacitors have the characteristics of high current fast charge and discharge of ordinary capacitors and the energy storage characteristics of batteries. This model is simple in structure and can be well coupled with fuel cell output power, which is convenient for practical application. In the diagram, we see the RC version of the supercapacitor.

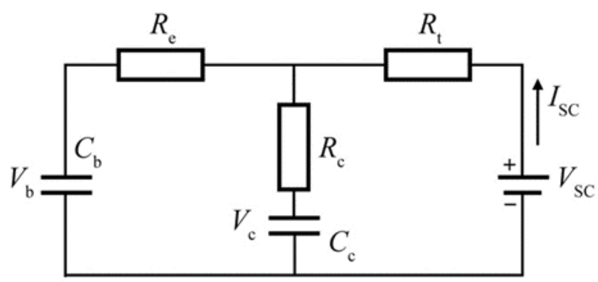

Figure 2. Supercapacitor RC model.

It is possible to think of the ultracapacitor in this paradigm as being analogous to both a resistance R and a perfect capacitor, where the current I_{SC} and voltage V_{SC} will change dynamically under different load conditions. Therefore, the current can be expressed if the resistance changes in real time:

$$I_{\mathrm{sc}} = \frac{V_{\mathrm{C}} - V_{\mathrm{sc}}}{R} = -C\frac{\mathrm{d}V_{\mathrm{C}}}{\mathrm{d}t} \tag{3}$$

where V_{sc} is capacitance voltage; I_{sc} is the current output of the supercapacitor.

The charged state SOC_{SC} of the supercapacitor can be defined as:

$$SOC_{\mathrm{sc}} = \frac{V_{\mathrm{sc}}}{V_{\mathrm{max}}} \tag{4}$$

where V_{max} is the maximum voltage allowed by the supercapacitor.

3.4. Photovoltaic Cell

Photovoltaic power generation is a technology that directly converts light energy into electric energy by utilizing the photogenerated volt effect at the semiconductor interface. The key component of this technology is the solar cell [26]. After the solar cells are packaged and protected in series, a large area of solar cell modules can be formed, and then combined with the power controller and other components to form a photovoltaic power generation device. The voltammetry characteristic relation of photovoltaic cells is:

$$I = I_{\mathrm{ph}} - I_{\mathrm{D}} - \frac{U_{\mathrm{D}}}{R_{\mathrm{sh}}} = I_{\mathrm{ph}} - I_0\left\{\exp\left[\frac{q(U + IR_{\mathrm{s}})}{AkT}\right] - 1\right\} - \frac{U + IR_{\mathrm{s}}}{R_{\mathrm{s}}} \tag{5}$$

$$I_{\mathrm{sc}} = I_{\mathrm{ph}} - I_{\mathrm{D}} - \frac{U_{\mathrm{D}}}{R_{\mathrm{rh}}} - \frac{U_{\mathrm{D}}}{R_{\mathrm{r}}} \tag{6}$$

$$U_{oc} = \frac{AkT}{q}\ln\left(\frac{I_{sc}}{I_0} + 1\right) \tag{7}$$

where I_{sc} is photovoltaic cell current during a short circuit; I_0 is the reverse saturation current; I_{ph} is photogenerated current; q is the charge of the electron inside; U_{oc} is open-circuit voltage; I_{D} is the current that flows through the diode; U_{D} is the voltage at both ends of the diode; R_{sh} is the parallel resistance; R_s is the series resistance; A is the characteristic constant of photovoltaic cells; T is the operating temperature of the photovoltaic cell and k is the Boltzmann constant.

This paper assumes that the PV module always operates with the maximum power point.

4. A Fuzzy Logic-Based Energy Management Strategy

Concept is one of the basic forms of thinking, which reflects the essential characteristics of objective things. In the process of cognition, human beings abstract out the common characteristics of perceived affairs and summarize them, and then the concept is formed. The so-called fuzzy logic theory is that the extension outside this concept has uncertainty, or its extension is unclear and fuzzy. Now it refers to the accumulation of expertise and knowledge. For the original logic, especially the problems which are difficult to be described and dealt with by mathematics, the fuzzy object is taken as a fuzzy object, and then the membership function and fuzzy set are applied to the fuzzy object and fuzzy inference to solve the uncertain problem. The idea of fuzzy logic is the basis of the control approach known as fuzzy logic control, especially for nonlinear control systems with good robustness. Fuzzy logic, fuzzy set theory, and fuzzy language variables all come together in this clever control mechanism [27,28]. The fuel cell integrated energy system has added nonlinear components, which leads to the nonlinear variables of the system. The fuzzy logic control strategy can achieve a good control effect for this kind of system. In this research, we use fuzzy control theory to design the energy management and controller for a fuel cell based urban integrated energy system.

4.1. Fuzzy Logic Control System Structure

Figure 3 shows the structure of the fuzzy logic control system, which carries out identification, extraction, fuzzy reasoning, and unambiguation of input.

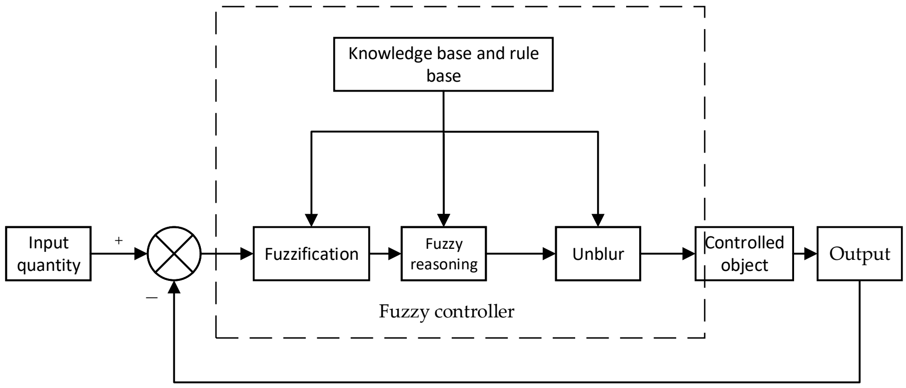

Figure 3. Structure diagram of fuzzy logic control system.

4.2. Composition of Fuzzy Logic Controller

4.2.1. Design of Fuzzy Controller

The use of a fuzzy logic controller involves the primary means by which energy is managed in a fuel cell urban integrated energy system. The fuzzy controller description provides the basis for a five-stage process to create the system model. Firstly, determine the input and output variables for the system design. Next, select a suitable and reasonable fuzzy method for the system, process the fuzzy variables reasonably, and evaluate the input and output variables, as well as the effective range of the fuzzy controller's settings. Thirdly, formulating fuzzy rules based on the ideal outcomes envisioned by individuals' or experts' experience requires figuring out the membership functions of each input and output variable. Fourthly, choose the optimal and reasonable method for defuzzification to obtain accurate output variables. Finally, select a reasonable fuzzy control sampling time and verify the rationality of the fuzzy controller in energy management using simulation software [29,30].

Once the input and output variables are determined in the design of the fuel cell urban, comprehensive energy system, they cannot be changed among all the uncertain factors. Only the membership functions and fuzzy control rules can ultimately affect the results of energy management. Therefore, it is necessary to make reasonable adjustments based on the design requirements of an integrated energy system powered by fuel cells and select the appropriate membership functions and fuzzy control rules. The simulation results reflect the performance of fuzzy logic energy management controller.

The design of the fuzzy controller utilizes the supercapacitor's SOC capacity Q_{SOC} and the power required by the load side P_{load} as the input variables for the controller. The signal at the output is the product of the power generated by the fuel cell, the power generated by the solar cells, and the required power, denoted by K_{FC}. The variables' fuzzy truth value range is set through proportional factor calculations as $P_{load} \in [0, 1]$, $Q_{SOC} \in [0, 1]$, $K_{FC} \in [0, 1]$. VL, ML, L, M, H, MH, and VH represent the very low, medium-low, low, medium-high, high, and very high states, respectively. This fuzzy controller is a dual-input system, and when designing a fuel cell integrated energy system, it is important to take into account the properties of each energy source. The energy management system's output is set to be the fuel cell system's power output, denoted by the symbol P_{fc}. Based on the input membership functions of P_{load} and SOC and the IF-THEN rules, P_{fc} regulates the fuel cell power plant to respond flexibly to load fluctuations. The fuzzy controller used in this paper is shown in Figure 4. i_{fc} is the current output of the fuel cell; V_{fc} is the voltage output of the fuel cell.

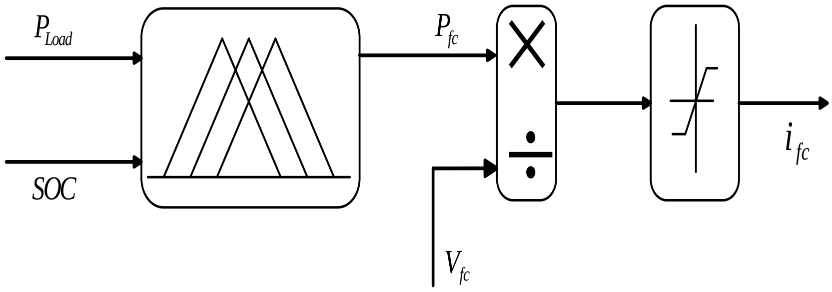

Figure 4. Designing a fuzzy-logic controller.

The fuzzy logic controller can achieve the following two basic goals [31,32]:

1. The output power of the fuel cell and solar cell must be calculated using the load side power demand and the supercapacitor capacitance in order to ensure the system operates smoothly, allocates power efficiently, and maintains its own energy.
2. Maintain the fuel cell's output current within a legitimate range, the lower end of which allows the fuel cell to produce the least output power at that current and the higher end of which allows the fuel cell to maintain stable system functioning even under strong load demands. This constraint also avoids the impact of high current output on the battery's lifespan.

4.2.2. Determination of Membership Functions

When determining membership functions, the sensitivity of parameters varies across different fuzzy sets, and numerical variables belong to different range sets, with only their degree of membership being different. Additionally, a numerical variable can have a fuzzy union in different sets, and the membership function can represent the degree of membership of the numerical variable over the entire range [33]. The membership functions are the pivot for the conversion between precise and fuzzy quantities, which determine the sensitivity of the control. Suitable membership functions are selected based on the output of the fuel cell and supercapacitor, as well as the demand of the load. At point P_{load}, it is basically within a certain range, so trapezoidal membership functions are chosen for the VL, ML, L, M, H, MH, and H fuzzy subsets. Since point P_{load} may change at any time and the supercapacitor only exists as a gradient power source, the SOC will not change significantly. Therefore, a Gaussian membership function is chosen for the M fuzzy subset, and trapezoidal membership functions are adopted for the remaining fuzzy subsets of SOC to improve the control accuracy. The control objective of the fuel cell is to operate in the medium to high load range. Therefore, trapezoidal membership functions are chosen for the VL, ML, L, M, H, MH, and VH fuzzy subsets of point P_{fc}. The membership functions obtained by applying the fuzzy controller in the simulation system are displayed in Figure 5 on the fuzzy controller interface.

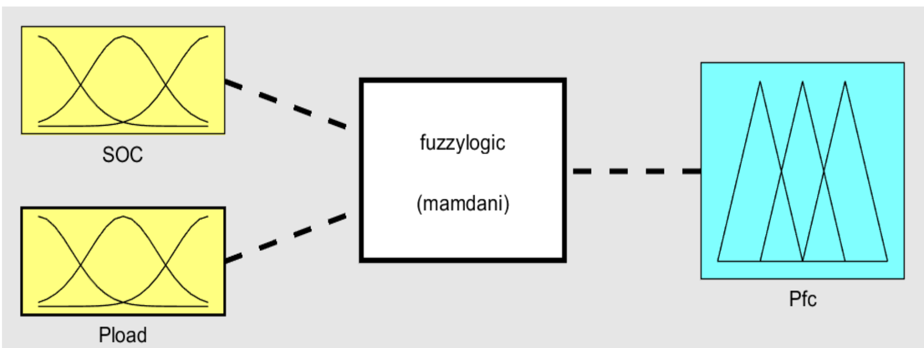

Figure 5. Fuzzy controller interface.

Figure 6 shows the membership functions of the input variables, power demand P_{load} and SOC of the U_C, as well as the output variable P_{fc}.

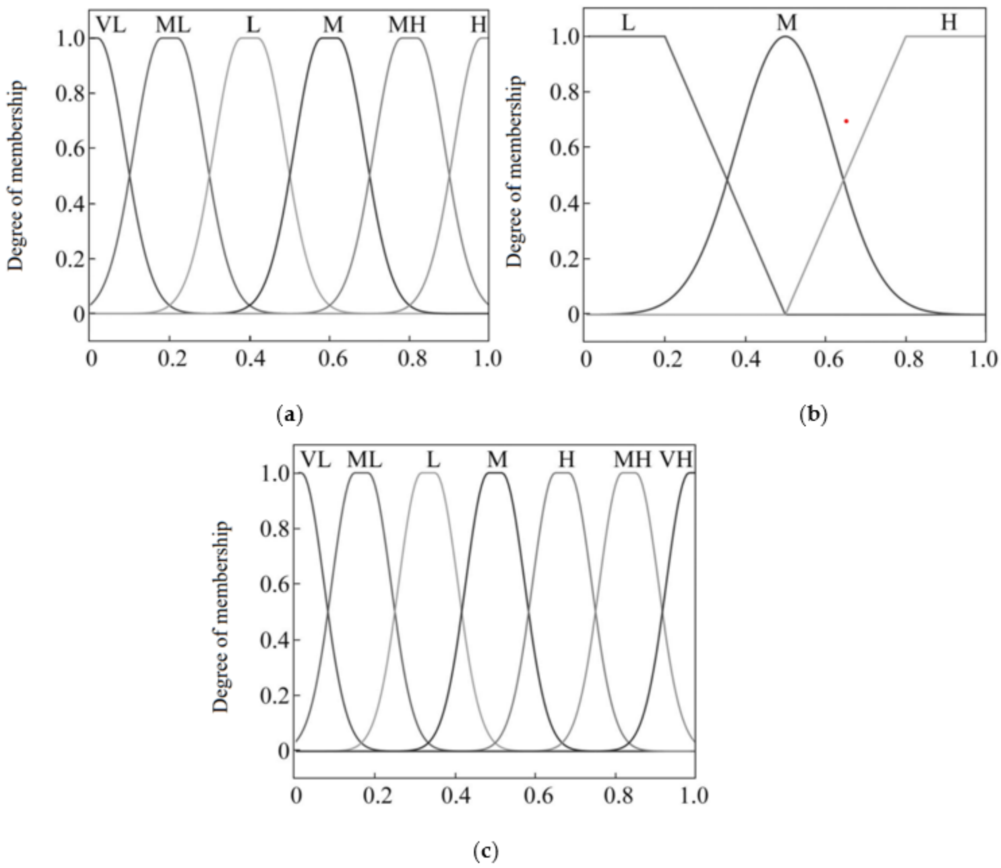

Figure 6. Membership functions of input/output variables: (**a**) The membership function translation of P_{load}; (**b**) The membership function translation of Q_{SOC}; (**c**) The distribution of the P_{fc} output variable's membership function.

4.2.3. Methods for Establishing Fuzzy Rules

Table 2 displays the rules matrix. When the load's power demand is high, the fuel cell and the solar cell should both produce their maximum levels of output. While at the same time, if the supercapacitor's load is low, the fuel cell's power should be boosted to the maximum achievable level for safety reasons. On the other side, the supercapacitor immediately compensates for the fuel cell by providing most of the power when the load power is low. The fuel cell and photovoltaic cell are the primary sources of energy during times of low load demand and supercapacitor charging. Keeping the supercapacitor within an appropriate energy storage range is necessary to better avoid overcharging and over-discharging of the supercapacitor and to prevent the sudden mutation of the fuel cell output power in light of the various energy allocation scenarios discussed above [20].

The power allocation of the fuel cell and supercapacitor needs to meet the changing load demand. First, to regulate the bus voltage, a unidirectional converter is required to achieve fast regulation. Second, the unidirectional converter not only needs to provide all steady-state load power and meet the requirements of the supercapacitor, but also needs to ensure that the supercapacitor is fully charged. Based on the above ideas, the control strategy can be divided into the following two types according to IF-THEN fuzzy control rules:

(1) When the load power exceeds the rated power of the fuel cell, a positive current reference is generated by the supercapacitor. Since the supercapacitor is in a discharging

state at this time, when the power reaches a certain level, the current reference of the fuel cell is clamped at the rated current, and the fuel cell outputs its rated power.

(2) When the load power is lower than the rated power of the fuel cell, the current of the supercapacitor is positive, indicating that it is charging. The operation of the fuel cell depends on the current of the supercapacitor. When the feedback current of the supercapacitor is negative, the fuel cell outputs energy at its rated power. When the feedback current of the supercapacitor is zero, the fuel cell outputs an appropriate amount of energy according to the load power demand.

Table 2. Fuzzy rules table.

SOC	P_{load}	P_{fc}
L	VL	L
M	VL	L
H	VL	VL
L	L	M
M	L	M
H	L	VL
L	M	H
M	M	H
H	M	L
L	H	VH
M	H	H
H	H	M
L	VH	VH
M	VH	VH
H	VH	H

The fuzzy inference form employed in this article is as follows, taking into account the practical charging and discharging range of supercapacitors and the finite power available from a fuel cell system due to its poor efficiency:

$$\text{“IF } P_{\text{load}} = \text{AAND SOC} = \text{B, Then } P_{\text{fc}} = \text{C”}$$

By analyzing the energy allocation during the system operation, to account for the uncertainty in the connection between power system inputs and outputs throughout a wide range of operating circumstances, the fuzzy rules shown in Table 1 were formulated.

4.2.4. Defuzzification

Energy management control techniques is aimed to obtain the final output value of fuzzy inference. However, since the output variable is fuzzy, a defuzzification technique must be applied to it. To ensure that the selected defuzzification method accurately expresses the calculation results of the output membership function, common defuzzification methods include the median, center of gravity, maximum membership degree, and weighted average methods, among others [34]. The Min-Max center of gravity approach is one such defuzzification technique, and it works by finding the center of mass of the region bounded by the membership function curve and the horizontal axis, and then extrapolating that value [35]. Compared with other methods, the advantage of the Min-Max centroid method is that it can produce output fluctuations within the effective range even with small changes in the input variables, and the output fluctuations are smooth. Therefore, choosing the Min-Max centroid method as the calculation method for defuzzification is reasonable. In the case of a continuous domain, the defuzzification process can be represented as the centroid of the fuzzy set, which is the weighted average of the input values based on their degrees of membership in the fuzzy set:

$$m_0 = \frac{\int_M m\mu_m(m)dm}{\int_M \mu_m(m)dm} \tag{8}$$

The equation is defined as follows: m is a membership function; M is the range of membership function values; m_0 is the "center of gravity" of the fuzzy set, which is also the accurate output value needed; $\mu_m(m)$ is the corresponding membership degree.

In the discrete domain:

$$m_0 = \frac{\sum_{i=1}^{n} m_i \mu_m(m_i)}{\sum_{i=1}^{n} \mu_m(m_i)} \tag{9}$$

in the formula, n is the number of quantization levels, m_i is the corresponding quantization level value, and $\mu_m(m_i)$ is the membership degree of a certain discrete point. The obtained m_0 through solving the formula is the required output value, and the actual value of energy produced by the fuel cell is obtained through multiplication with a proportion factor.

5. Energy Verification and Result Analysis

5.1. The Verification of Energy Management Strategies

An energy management simulation was run on a 40-kW proton exchange membrane fuel cell power generating system with a 210 V supercapacitor voltage and a 500 V DC bus voltage reference value to validate the fuzzy theoretical analysis of the energy management approach. In this paper, the key parameters of the fuzzy reasoning system designed on the simulink platform are shown in the following Table 3:

Table 3. Basic parameters of the system.

Parameter	Description	Numerical Value
P_{load}	Load demand power	50 kW
U_{dc}	Dc bus voltage	500 V
U_{sc}	Supercapacitor terminal voltage	210 V
C_{SC}	Capacity of the supercapacitor	99.5 F
V_{fc}	Fuel cell terminal voltage	250 V

With this regulation in place, the DC bus voltage U_{dc} can vary in response to changes in the alternating current (AC) load, while the fuel cell can smoothly track the load change and the supercapacitor can maintain its most efficient energy-storage state at all times. The load power may be adjusted in this manner by the power-producing system to match the actual operating circumstances.

The DC bus voltage's swings throughout a cycle are seen in Figure 7. The DC bus voltage may experience transient fluctuations when a sudden load demand changes. A coordinated power supply scheme with a fuel cell and supercapacitor can be employed to address this issue. The fuel cell is responsible for the bulk of the power generation, while the supercapacitor smooths out voltage dips caused by load transients. This approach can improve the stability and reliability of the system, reduce load fluctuations of the fuel cell and extend system life, U_{dc}, quick recovery to rating. According to Figure 8, when U_{dc} fluctuates, the ultracapacitor voltage U_{sc} also changes significantly.

Figure 9 shows how the load demand affects the current from the fuel cell and the supercapacitor. Changes in current may be used as a proxy for understanding the variations in output power across different energy sources. Figure 10 shows how the power from the fuel cell and the supercapacitor are distributed as the load demand varies. Thus, it is clear that this imbalance between supply and demand is what causes the transient fluctuations in the DC bus voltage. To address this issue, a fuel cell and a supercapacitor may work together to provide the load with the necessary energy while simultaneously storing the feedback energy in the supercapacitor. This can effectively balance the power difference between the load and the energy supply and improve the stability and reliability of the system.

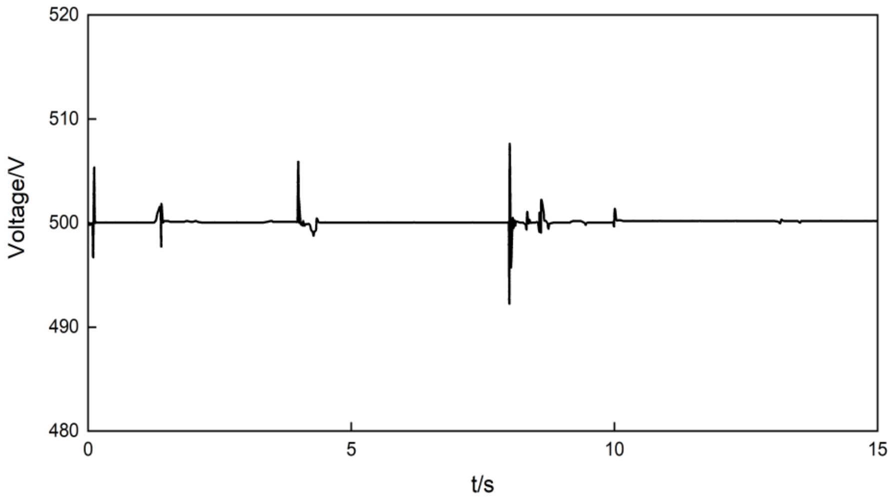

Figure 7. Volts on the DC bus.

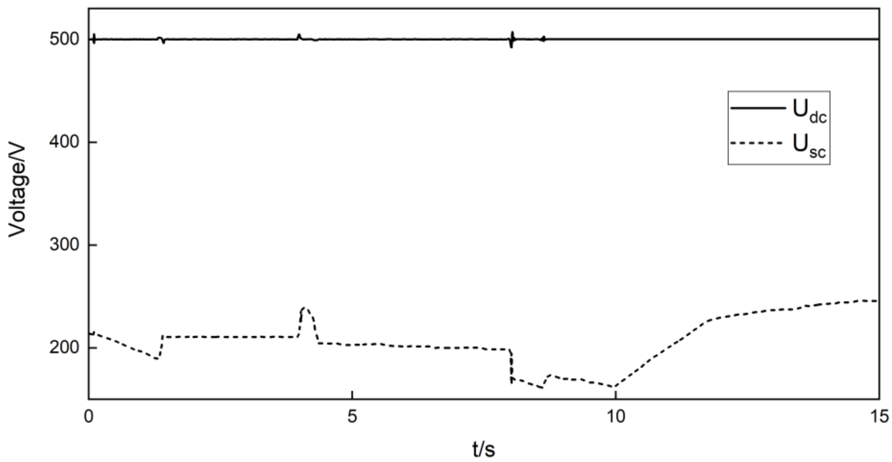

Figure 8. Ultracapacitor voltage and DC bus voltage.

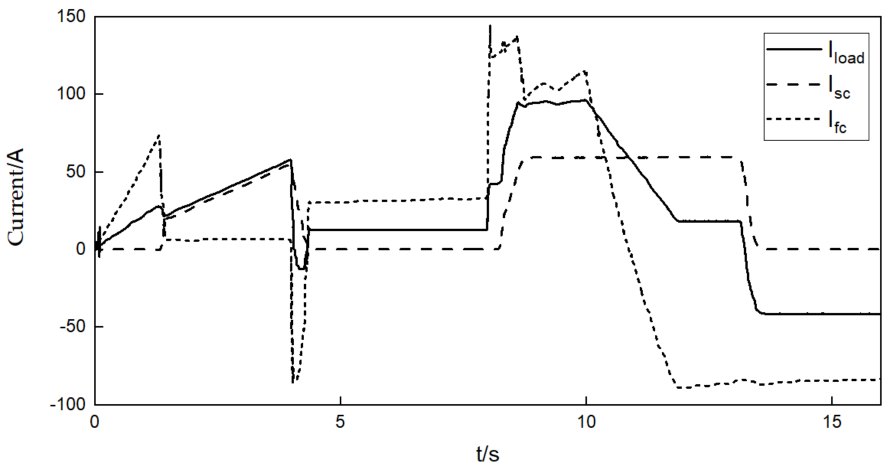

Figure 9. Change in output current.

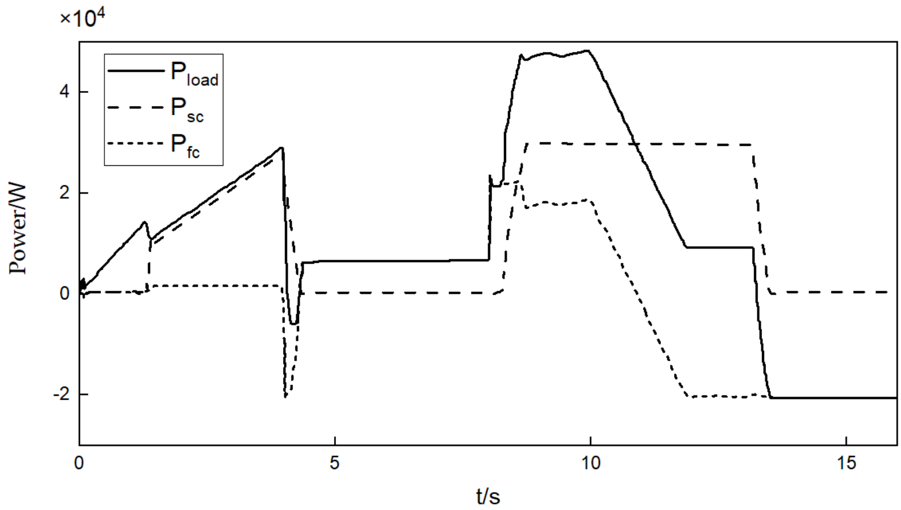

Figure 10. IF-THEN rule output power distribution.

At the initial moment, with no output power, the supercapacitor's output current is constant, while the variables I_{load} and I_{fc} exhibit noticeable changes. The fuel cell smoothly tracks the changes in load and supplies all the necessary power. At t = 1.3 s, the variable I_{fc} undergoes a sudden drop and I_{sc} tracks the variation of I_{load}. The load power undergoes slight fluctuations before continuously changing until t = 4 s. During this transient process, the supercapacitor rapidly discharges, mainly bearing the imbalance caused by the load demand, whereas the fuel cell's modest output follows changes in demand.

To keep the supply and demand in equilibrium while charging the supercapacitor, the fuel cell output was adjusted at time t = 4 s when the load power rapidly decreased. As the fuel cell took over carrying the load, the supercapacitor's output power eventually dropped to zero. Up to time t = 8 s, the fuel cell swiftly reacted to the unexpected load requirement, and the supercapacitor swiftly discharged in concert with the fuel cell to fulfill the load need. Although there was a brief fluctuation, the system eventually returned to a stable state. However, the fuel cell still outputs power to charge the remaining energy of the system into the supercapacitor, supplementing any missing energy during the transient load process until time t = 13 s, when the fuel cell and supercapacitor return to a stable operating state.

5.2. Comparative Analysis of Results

Compare with the current distribution under the most classical and accurate PI control, as shown in Figure 10.

At 4 s in Figure 11, the load power drops suddenly. The fuel cell responds accordingly to maintain the supply-demand balance while charging the supercapacitor. After this process, the output power of the supercapacitor reaches zero and is entirely supported by the fuel cell. At 8 s, when the load power changes dramatically, the fuel cell responds quickly to the sudden increase in demand, and the supercapacitor discharges rapidly to assist the fuel cell in meeting the load requirement after a brief response. The DC voltage experiences a short-term fluctuation but eventually returns to a stable value. However, the fuel cell continues to output power, charging the remaining energy in the system into the supercapacitor to supplement the missing energy during the load change process until t = 13 s when the fuel cell and supercapacitor return to a stable operating state.

The power supply system operates in a favorable environment with a supercapacitor SOC of approximately 60%. However, the supercapacitor has a relatively large output ratio, and repeated operation at a high discharge power for an extended period can cause irreversible damage to its charging and discharging system. Compared with power allocation without the fuzzy control strategy, it can be observed that fuzzy logic control optimizes energy regulation between different sources and increases the fuel cell system's output power ratio while reducing the supercapacitor's output pressure, thereby avoiding over-discharge of the supercapacitor.

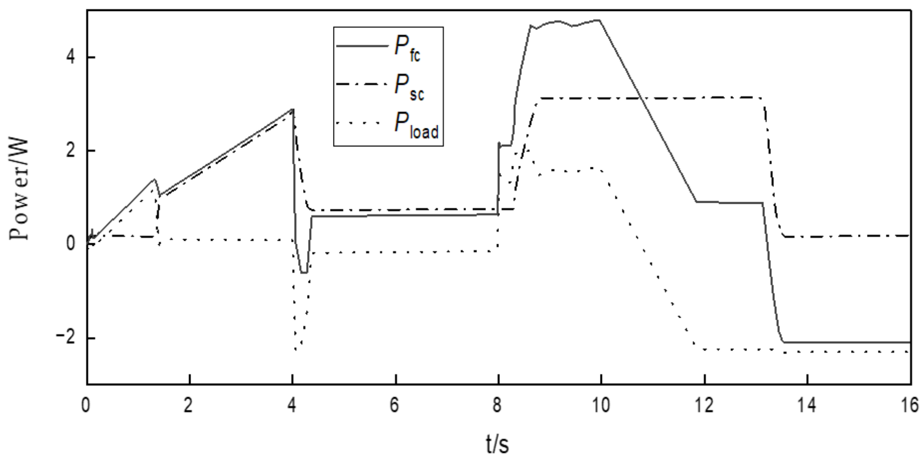

Figure 11. Power distribution under PI control.

In this research, we present a control technique based on fuzzy logic that can adapt to unexpected shifts in load demand by considering the fuel cell and super-capacitor in their various operational states. Energy is distributed most efficiently between the fuel cell and supercapacitor, with no overshoot or degraded performance from the reverse correction. The created simulation model of the hybrid power supply system powered by fuel cells demonstrates the system's regulation capabilities for load variations while also improving fuel usage and addressing difficulties with fuel cell lifetime. This proves that the control technique is proper and superior, and the optimization has a considerable impact.

6. Conclusions

In order to improve the functionality of fuel cell hybrid power systems, the author of this article suggests an approach for energy management based on fuzzy logic. The fuel cell's output power is calculated using the energy storage system's state of charge (SOC) and the load demand P_{load}, and then the power from each module is allocated optimally so that the fuel cell follows load changes smoothly while the supercapacitor provides or absorbs dynamic energy to boost the system's efficiency. The authors created a simulation model of a fuel cell hybrid power system and regulated the DC/DC converter to accomplish fast charging and discharging of the super-capacitor and efficient and smooth power production from the fuel cell to validate the viability of the suggested technique. The fuel cell's working pressure was lowered, the SOC was kept within an optimal range, the DC bus's energy and voltage were kept steady, and the system's dynamic performance was guaranteed by this method.

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