Review of Operational Control Strategy for DC Microgrids with Electric-hydrogen Hybrid Storage Systems

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Abstract—**Hydrogen production from renewable energy sources (RESs) is one of the effective ways to achieve carbon peak and carbon neutralization. In order to ensure the efficient, reliable and stable operation of the DC microgrid (MG) with an electric-hydrogen hybrid energy storage system (ESS), the operational constraints and static dynamic characteristics of a hydrogen energy storage system (HESS) needs to be fully considered. First, different hydrogen production systems, using water electrolysis are compared, and the modeling method of the electrolyzer is summarized. The operational control architecture of the DC MG with electric-hydrogen is analyzed. Combined with the working characteristics of the alkaline electrolyzer, the influence of hydrogen energy storage access on the operational mode of the DC MG is analyzed. The operational control strategies of the DC MG with electric-hydrogen hybrid ESS are classified and analyzed from four different aspects: static and dynamic characteristics of the hydrogen energy storage system, power distribution of the electric-hydrogen hybrid ESS and the efficiency optimization of hydrogen energy storage. Finally, the advantages of a modular hydrogen production system (HPS) are described, and the technical problems and research directions in the future are discussed.**

Index Terms—**Hydrogen energy, DC microgrid, modeling method, operation control, renewable energy sources.**

I. INTRODUCTION

ENERGY crisis and environmental pollution are important factors restricting the rapid economic development of all countries throughout the world. Optimizing energy configurations, promoting energy transformation and realizing clean, low-carbon and sustainable development have become important development goals in future energy fields [1], [2]. In order to reduce carbon emissions and promote industrial development of renewable energy, many countries have promulgated various renewable energy policies and energy development plans [3]–[6]. In 2016, the National Development and Reform Commission (NDRC) issued the "Energy Production and Consumption Revolution Strategy (2016–2030)" and the "13th Five-Year Plan for National Science and Technology Innovation Plan," which proposes that by 2030, non-fossil energy power generation will account for 50% of all power generation [7]–[9]. This policy can ensure the long-term and stable development of the renewable energy industry.

In September 2020, China has put forward the development goals of "carbon peak" and "carbon neutralization," striving to achieve the peak of carbon dioxide by 2030 and carbon neutralization by 2060. Vigorously developing and utilizing the renewable energy grid connected power generation is an important measure to achieve carbon peak and carbon neutralization. According to relevant research statistics, the global cumulative installed wind power and solar photovoltaic (PV) power capacity has reached 733.276 GW and 707.495 GW by the end of 2020 [10]. With the increasing of the installed capacity of renewable energy, it cannot be used effectively, which reduces the utilization rate of renewable energy sources (RESs). According to statistics, approximately 17.2% of wind power and 10.3% of solar power was curtailed in 2016. Although the utilization rate of RESs is improved by early warning and a guarantee mechanism, approximately 4% of wind power and 2% of solar power was still curtailed in 2019 [11].

Because RESs have the characteristics of multiple time scale, wide power range fluctuation, intermittence and uncertainty, it is difficult to dynamically match the output characteristics of RESs and load characteristics. The energy storage system (ESS) must be configured to compensate unbalanced power between RESs and load, and reduce the adverse impact of RESs on power system stability and power quality [12]–[14]. Currently, supercapacitors (SC) and batteries are the most widely used energy storage units. The SC and batteries complement each other and can obtain better performance [15]–[17]. However, from the perspective of storage capacity, batteries and SC belong to short-term energy storage systems (ESSs), so they cannot continuously absorb and compensate the unbalanced power in the microgrid (MG) [18], [19]. As an energy carrier, hydrogen energy has the characteristics of high energy density, large capacity, long service life and easy

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storage and transmission. The application and development of hydrogen energy has attracted extensive attention [20], [21]. Hydrogen energy is usually used as a long-term ESS, but it has a slower time response, which is difficult to apply to microgrids requiring high dynamic regulation speed and frequent start-stop in a short time period. Therefore, the hydrogen energy storage system (HESS) should be integrated with batteries or SC to form an electric-hydrogen hybrid ESS [22], [23]. The batteries or SC are used to compensate transient unbalanced energy, while the HESS is used to compensate long-term and steady-state unbalanced power.

At present, the initial investment of hydrogen production equipment is high, and producing hydrogen by water electrolysis requires a large amount of electricity, therefore the economy of this hydrogen production method is very poor. The combination of the hydrogen production unit (HPU) and RESs cannot only increase the utilization of RESs, but also promote the economy of the hydrogen production system (HPS) [24]–[26]. The generated hydrogen cannot only be used directly and efficiently, but also provide hydrogen for fuel cells. With the rapid development of hydrogen fuel cell vehicles and the rapid layout of hydrogen refueling stations (HRSs), the strategic position of hydrogen energy development is further promoted. In order to reduce the production cost, renewable energy power generation and HRSs are combined to form a hydrogen production hydrogenation integrated business model, reducing the loss caused by power transmission and distribution, and improving the system efficiency [27]–[31]. In addition, the HPU, hydrogen storage tank (HST) and fuel cell (FC) can form a HESS, which cannot only absorb and compensate the unbalanced power, but also provide power for the MG, realizing the complementary conversion of electricity and gas.

Although the HPU improves the flexible regulation ability of MG, it also puts forward new technical requirements for the operational control strategy of MG. The operational control strategy of DC MG with electric-hydrogen hybrid ESS is one of the key technical challenges to ensure the reliable operation of the system. The scope of this paper is to provide a status overview and discuss operational control strategy for electric-hydrogen DC MG. This paper summarizes the research on operational control strategy of electric-hydrogen DC MG. Initially, the characteristics of different hydrogen production systems (HPSs) by water electrolysis are introduced, and the modeling method of electrolyzer is summarized. Secondly, the operational control architecture and operational mode of electric-hydrogen DC MG are analyzed. Thirdly, the operational control strategies of electric-hydrogen DC MG are classified and analyzed from four different aspects: static and dynamic characteristics of HESS, power distribution of electric-hydrogen hybrid ESS and efficiency optimization of hydrogen energy storage. Finally, the technical problems and research directions for the future are discussed.

II. System Structure of The Electric Hydrogen Microgrid

The electric-hydrogen MG system architecture primarily includes AC and DC type structures. Fig. 1 shows the typical structure of the AC MG.

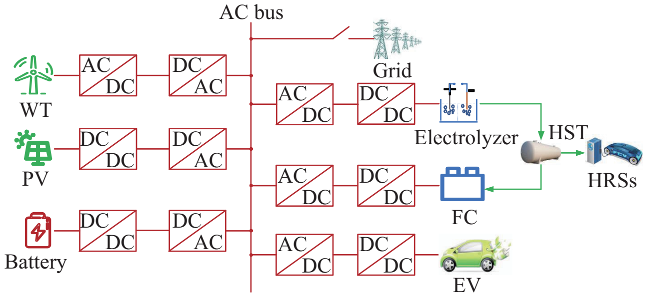


Fig. 1. Typical structure of the electric-hydrogen AC MG.

From Fig. 1, various units are connected to a common AC bus by power electronic devices. When the static switch is closed, the grid connected hydrogen production mode is selected. When the static switch is off, the MG works in an off grid hydrogen production mode. Since the PV cell, battery, FC and electrolyzer are DC units, more power electronic equipment is required to achieve energy and voltage conversion for AC MG. Therefore, the overall investment cost is higher and the efficiency is lower. In addition, the problems of frequency regulation and reactive power compensation also need to be solved for AC MG.

The typical structure of the electric-hydrogen DC MG is shown in Fig. 2.

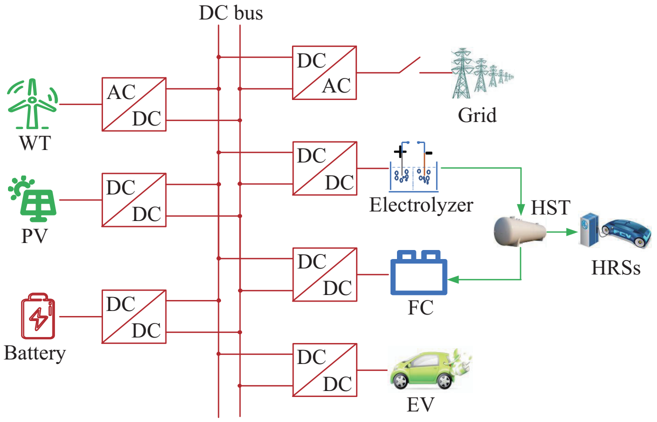


Fig. 2. Typical structure of the electric-hydrogen DC MG.

From Fig. 2, various units are connected to common DC bus by power electronic devices. The RES units, battery energy storage system (BESS) and HESS only need one energy conversion, which reduces the investment costs and improves the overall efficiency. In addition, DC MG only needs to control the DC bus voltage without considering frequency and reactive power compensation, which simplifies the control structure. Therefore, DC hydrogen production from RESs is a promising proposal for the future.

III. Classification and Characteristics of Hydrogen Production from Water Electrolysis

An electrolyzer is the core component of HPU. Different electrolyzers have larger differences in static and dynamic characteristics, energy consumption, cost, lifespan and site demand. Therefore, mastering the characteristics of different electrolyzers is beneficial to the design of renewable energy hydrogen production control proposal.

The HPSs by water electrolysis can be divided into three forms according to the type of electrolyzer: alkaline electrolyzer (AE), proton exchange membrane (PEM), solid oxide electrolyzer (SOE) [32]–[34]. Comparison of different HPSs by water electrolysis is shown in Table I. According to Table I, the characteristics of different types of HPSs by water electrolysis are analyzed as follows:

1) The main advantages of alkaline water electrolysis are mature technology, large hydrogen production, and relatively low investment cost. At present, the alkaline water electrolysis system has had a large scale promotion and application. The main defects of an alkaline water electrolysis system are a large occupation area, corrosive electrolyte, high maintenance costs in the later stages and large demand for electric energy. In addition, AE has slow dynamic response and needs to cooperate with other ESSs for hydrogen production from RESs.

2) The main advantages of a PEM water electrolysis system are high current density, small occupied area, good dynamic response characteristics and start-stop performance, and a wide operational range. A PEM electrolyzer has good matching with RESs. At present, it has been commercialized and applied in a small scale. The anode and cathode catalysts of a PEM electrolyzer uses precious metals, so the cost of a PEM electrolyzer is high. In addition, the technology of domestic manufacturers is immature, there is a large gap with international advanced technology, and the key equipment depends on importing.

3) The main advantages of a SOE water electrolysis system are high efficiency and high current density. At present, a SOE electrolyzer is primarily in the laboratory stage, so it has not been commercialized. The main defect is that the requirement of electrolysis temperature is high, and an external heat source with a large power source is required to keep the temperature stable.

IV. MODELING METHOD OF AN ELECTROLYZER

In order to provide full play to the flexible regulation ability of HPU, you need to deeply tap into the complementary characteristics of electric hydrogen hybrid ESS and ensure the efficient, reliable and stable operation of electric hydrogen DC MG, static and dynamic characteristics of the electrolyzer should be deeply understood and mastered. Mathematical modeling is an important means to obtain the working characteristics of an electrolyzer. Therefore, the research progress of modeling methods of different types of electrolyzers is summarized.

A. Modeling Method of Alkaline Electrolyzer

At present, AE modeling methods can be divided into a linear model, empirical and semi-empirical model, and physical model. Different modeling methods are summarized as follows.

1) Linear Model

Linear model is a simplified equivalent modeling method. The voltage of the electrolyzer is simulated by constant voltage source and resistance in series, which cannot accurately describe the characteristics of the electrolyzer [35]. Therefore, the linear model is usually not used.

2) Empirical and Semi-empirical Model

The empirical model does not need to establish a theoretical model and is only fitted according to the experimental measured data. Therefore, the model cannot reveal the electrochemical reaction mechanism and has no practical physical meaning [36]. For solving these problems, the method of combining theoretical modeling with experimental

TABLE I
COMPARISON OF DIFFERENT HYDROGEN PRODUCTION SYSTEMS BY WATER ELECTROLYSIS

Specification	Alkaline	PEM	SOE
Charge carrier	OH^-	H^+	O^{2-}
Cell temperature	60–90°C	50–80°C	700–1000 °C
Electrolyte	25∼30% KOH	Pure water	Y_2O_3-Z_rO_2, Sc_2O_3-ZrO_2
Overall reaction	$H_2O=H_2+1/2O_2$	$H_2O=H_2+1/2O_2$	$H_2O=H_2+1/2O_2$
Anode reaction	$2OH^-=1/2O_2+H_2O+2e^-$	$H_2O=1/2O_2+2e^-+2H^+$	$O^{2-}-2e^-=1/2O_2$
Anode catalyst	Ni_2CoO_4, La-Sr-CoO_3	Ir/Ru oxide	(La, Sr) MnO_3, Ni-YSZ
Cathode reaction	$2H_2O+2e^-=H_2+2OH^-$	$2H^++2e^-=H_2$	$2H_2O+2e^-=H_2+O^{2-}$
Cathode catalyst	Ni-Mo/ZrO_2-TiO_2	Platinum	Ni-YSZ/Ni-GDC
Dynamic response capability	Comparatively good	Good	Weak
Electrolyzer efficiency	63–71%	60–68%	100%
System efficiency	51–60%	46–60%	76–81%
Electrolyzer energy consumption	4.2–4.8 kWh/Nm^3	4.4–5.0 kWh/Nm^3	3 kWh/Nm^3
System energy consumption	5.0–5.9 kWh/Nm^3	5.0–6.5 kWh/Nm^3	3.7–3.9 kWh/Nm^3
Cell pressure	0–30 bar	0–30 bar	0–30 bar
Operating range	20%–110%	0%–160%	20%–100%
Hydrogen purity	>99.8%	99.999	99.999
Current density	0.2–0.5 A/cm^2	1.0–2.0 A/cm^2	0.3–2.0 A/cm^2
Hydrogen production per stack	<1400 Nm^3/h	<400 Nm^3/h	<10 Nm^3/h
System lifetime	55–120 kh	60–100 kh	20–80 kh
Stop/go cycling	Comparatively good	Good	Weak
Cold start-up time	>60 min	>5 min	>60 min
Warm start-up time	1–5 min	<5 s	>15 min
Technology maturity	Widespread commercialization	Commercialization	Research &Development
Investment costs	3000–12000 ¥/kW	10000–16000 ¥/kW	>16000 ¥/kW

data is adopted. First, the theoretical mathematical model is established according to fundamental thermodynamics, heat transfer theory and empirical electrochemical relationships. The main parameters in the theoretical model are determined by using the experimental data through the fitting algorithm. The parameters are modified by comparing the model with the experimental results, and then a semi-empirical mathematical model is obtained. At present, the semi-empirical model is the most commonly used modeling method, which can be divided into a static model and dynamic model. The static model can better simulate the electrolyzer voltage, hydrogen production, efficiency and hydrogen purity under specific temperature and pressure conditions [37]–[39]. However, the dynamic model pays more attention to the dynamic behavior of the electrolyzer, including the dynamic response characteristics of electrolyzer voltage, current, temperature, purity, liquid level, pressure and other parameters during the start-up process and the change of current or power reference value [40], [41].

3) Physical Model

To ensure the high accuracy of the semi-empirical model, the key parameters need to be determined by long-term experimental data. At the same time, the semi-empirical model is only applicable to one specific electrolyzer and not to other electrolyzers, so the universality is poor. To deal with these problems, a multi-physical model of an alkaline electrolyzer is proposed. This model considers the changes of all structural parameters and operational parameters of the electrolyzer, which can enhance the accurateness of the model [42]. Furthermore, the reduced order model based on equivalent circuit is proposed, which reduces the number of parameter requirements and the complexity of modeling [43]. A semi-physical model based on phenomenological theory is proposed to describe the dynamic characteristics of HPS [44].

The advantages and disadvantages of different modeling methods are shown in Table II.

TABLE II
COMPARISON OF DIFFERENT AE MODELING METHODS

Modeling methods	Description of advantages and disadvantages
Linear model	Simple and easy to implement, but it cannot simulate the working and operating characteristics of electrolyzer, so it is usually not used.
Empirical and semi-empirical model	The static and dynamic characteristics of the electrolyzer can be better simulated, but the model has poor universality and cannot clearly describe the internal physical and chemical reaction mechanism.
Physical model	Good universality and clear mechanism, but the modeling method is complex.

B. Modeling Method of PEM Electrolyzer

For the mathematical modeling of a PEM electrolyzer, different classification methods are provided in relevant literature. Literature [45] only divides the voltage and efficiency models, which is not comprehensive. Literature [46] summarizes the research on thermal effects, semi-empirical model and two-phase flow effects of the PEM electrolyzer. Literature [47] classifies the modeling methods of electrochemical model, thermal model, mass transfer model and fluidic model of a low-temperature PEM electrolyzer. The models of the PEM electrolyzer can be divided into analytical, semi-empirical model and mechanistic model [48]. In the research of electric hydrogen DC MG operational control, more attention is paid to the characteristics of voltage, current and efficiency. Therefore, it is an effective way to obtain the static and dynamic characteristics of a PEM electrolyzer through the empirical and semi-empirical models. The classification of a PEM electrolyzer modeling method is shown in Fig. 3.

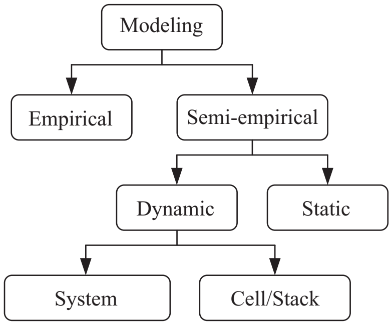


Fig. 3. Modeling methods of the PEM electrolyzer.

Similar to the AE modeling method, the empirical model of PEM electrolyzer is also directly fitted through the experimental data to obtain the static characteristics of the PEM electrolyzer [49], [50]. The semi-empirical model can also be divided into a static model and dynamic model. The difference from the AE model is primarily reflected in the physical structure of the electrolysis cell and electrochemical reaction mechanism. In the static modeling, the theoretical model is still established by thermodynamic theory, heat transfer theory and electrochemistry. However, there are main differences in the impact analysis of operating parameters and structural parameters, focusing more on the impact of different temperatures on the exchange current and charge transfer coefficient [51], [52]. In the voltage modeling of the electrolyzer, not only the open circuit voltage, activation overvoltage and ohmic overvoltage are considered, but also the diffusion overvoltage and mass transfer effects are also taken into account [53]. A new ohmic loss model is proposed, and the resistance of different components are fully considered, such as the bipolar plate, electrode and membrane thicknesses [54].

Because the PEM electrolyzer has the advantage of fast dynamic response and good matching with RESs, the PEM electrolyzer is more suitable for hydrogen production from RESs. Relevant scholars have carried out in-depth research on the accurate dynamic modeling of the PEM electrolyzer. From the model scale, it can be divided into PEM cell/stack and PEM HPS. To describe the dynamic behavior of the PEM electrolyzer, the dynamic model is established by using Simulink simulation software. The simulation model is applied to analyze the dynamic performance of electrolyzer voltage, electrolyzer current, energy efficiency, energy consumption and temperature, etc., [55]–[57]. However, the previously dynamic model is developed under the condition of a fixed parameter, so the accuracy of the model will be reduced for other input currents. To deal with this problem, an adaptive static-dynamic model is proposed, the parameters of the model can be adjusted independently under the input current change conditions [58]. Similarly, an adaptive cell voltage static-dynamic model is developed to investigate the degradation and wear effects caused by dynamic operations and current ripple [59]. The existing modeling research primarily focuses on the behavior of cells or stacks. Literature [60] developed the dynamic model of PEM HPS by using Simulink software, which can better evaluate the efficiency and loss proportion of PEM HPS.

C. Modeling Method of SOE

At present, SOE is primarily in the laboratory research and development stage. Although it has high energy efficiency, the start-stop of SOE is inconvenient and the response is slow. The modeling methods of SOE can be divided into a macro-scale model and micro-scale model [61]. In this macro-scale model, the electrochemical characteristics of SOE and SOE stack were researched, and the effects of fabrication parameters and operating conditions on SOE performance were analyzed through parametric simulations [62]–[64]. In this micro-scale model, the research primarily focused on the transport and electrochemical reactions. The purpose of the micro-scale model is to optimize the internal structure and process parameter design of SOE [65], [66].

V. MODELING METHOD OF FUEL CELL

FC is the core component of HESS. Its static and dynamic characteristics will also put forward new requirements and challenges for the operational control of the electric-hydrogen DC microgrid. According to the operating temperature, FC can be divided into low-temperature and high-temperature types.

Among all fuel cells, PEMFC are most likely to be applied for distributed generation and microgrid applications. PEMFC can provide reliable power in steady state. However, when the load rapidly changes, they cannot respond quickly due to their slow internal electrochemical and thermodynamic responses. Accurate modeling methods are needed to predict and evaluate steady-state and dynamic responses of PEMFC. Therefore, the modeling methods of PEMFC are summarized.

At present, PEMFC modeling methods can be divided into an empirical model, semi-empirical model, mechanism model and data-driven model [67]. Different modeling methods are summarized as follows.

1) Empirical Model

The empirical model of PEMFC does not need to establish a theoretical model. The unknown coefficients of the empirical model are only fitted based on experimental data. A following correlation model is proposed to predict the cell voltage. However, this model is inaccurate for high current density regions because the voltage is overestimated [68]. A mathematical correlation is established by FC testing data, and the voltage losses are evaluated [69]. An empirical equation is developed to fit the experimental cell voltage, and the exponential term is introduced to compensate for the mass transport over-potential [70].

Due to the limited experimental data, the fitting models obtained from these data are difficult to apply to all operating conditions. Therefore, empirical models are often used in situations where the accuracy of the model is not high.

2) Semi-empirical Model

The semi-empirical model is established based on the mechanism model and the parameters that are difficult to obtain in the model are determined through experimental data or parameter identification methods. The semi-empirical model is a simplification of the mechanism model. A simple dynamic model is proposed to describe the transient output characteristics of PEMFC [71]. A semi-empirical model-based prognostics method is developed to achieve degradation prediction and evaluate the remaining service life. The electrochemical surface area, equivalent resistance and recovery factor are introduced to predict the degradation trend and performance recovery of PEMFC [72]. A semi-empirical model is proposed for PEMFC, and the whale optimization algorithm is used for obtain unidentified parameters [73]. A one-dimensional, semi-empirical, and steady-state model of PEMFC is developed, and unknown parameters are obtained by using the experimental results [74]. A semi-empirical model based on online identification is proposed to improve the performances of PEMFC [75].

Although the semi empirical model is built on the basis of the mechanism model, it is still unable to describe the internal mechanism characteristics of PEMFC.

3) Mechanism Model

The mechanism model is primarily used to describe the internal electrochemical and physical properties of the PEMFC, such as the capacitance of double-layer charge effect, mass diffusion, material conservation, thermodynamic characteristics, and voltage drops inside the FC [76]–[78]. For the calculation of the mechanism model, numerical solution is generally used [79].

The mechanism model is primarily used for the optimization design of the internal structure and material selection of PEMFC. Therefore, the mechanism model is not suitable for the design and optimization of the PEMFC control system.

4) Data-driven Model

Although the mechanism model can obtain higher accuracy, the modeling is very complex and the obtained model is difficult to solve. In order to avoid complex modeling and ensure high accuracy of the model, the data-driven modeling method represents an effective solution.

The data-driven modeling method is primarily based on a large number of experimental data to obtain a high-precision model through training and learning. The data-driven models primarily include non-physics-based and physics-informed data-driven results. The data-driven (non-physics-based) models do not need to know the internal physical parameters, but rather construct the model through training, learning and statistics according to a large number of experimental data [80]–[83]. The physics informed data-driven model combines physical knowledge with the data-driven model, which can increase constraints through physical knowledge and avoid generating incorrect models [84].

Although the data-driven modeling method does not need internal parameter information, in order to obtain an accurate model, a large amount of available data is required, so the cost of the data-driven modeling method is high.

The comparison of different PEMFC modeling methods is shown in Table III.

TABLE III
COMPARISON OF DIFFERENT PEMFC MODELING METHODS

Modeling methods	Description of advantages and disadvantages
Empirical model	Simple and easy to implement, but it cannot accurately describe internal mechanism.
Semi-empirical model	It can describe part of the internal mechanism, but the model still cannot describe the complete internal reaction mechanism.
Mechanism model	It can accurately describe internal mechanism, but the modeling method is complex.
Data-driven model	It does not require knowledge about internal system parameter information, but it needs a large amount of experimental data.

VI. OPERATION CONTROL STRATEGY OF ELECTRIC-HYDROGEN DC MICROGRID

According to the current research progress and engineering demonstration application of renewable energy coupled HPS, the most widely used approach is still alkaline water electrolysis hydrogen production, such as the Guyuan dongxinying hydrogen production station (10 MW alkaline water electrolysis HPS, and the annual hydrogen production capacity can reach 17.52×10^5 Nm^3) and Chongli Wind-PV-storage-hydrogen demonstration project (3 MW alkaline water electrolysis HPS, and the hydrogen production capacity can reach 400 Nm^3/h) invested and built by Hebei Construction & Investment Group New Energy Co., Ltd.. Therefore, the following primarily takes the integration of alkaline water electrolysis HPU as an example to study and analyze an operational control strategy for the electric-hydrogen DC MG.

Currently, the research on operational control strategy primarily covers two time scales. In the research on the long-term operational scale, it does not pay attention to the control and mode switching of interface devices at the local layer, but focuses on the optimal dispatching strategy of the electric hydrogen DC MG. The main goal is to improve system economy and reduce cost and energy loss [85]–[90]. In the existing proposals, most studies primarily focus on improving the economy of HPS and reducing investment cost. However, the actual HPS and FC systems usually include multiple parts. The HESS is a power-hydrogen-heat multi-energy coupling system. In the traditional HPS, the hydrogen production power is relatively stable without significant change, and the performance evaluation of HPS is relatively easy. In the renewable energy hydrogen production system, the power of the electrolyzer and FC changes in real time, and it is difficult to evaluate the impact of wide-range power fluctuations on the performance of the electrolyzer, such as Life cycle, performance degradation and remaining life. Therefore, the economic optimization and scheduling control, considering the performance of HESS, represent the major difficulties of long-time scale control. The control goal of short-time operational scale is to balance the system power and operate stably. In the internal working process of HESS, there is mutual conversion among thermal energy, electrical energy and chemical energy, so its dynamic response is slow. Due to the mismatch of dynamic characteristics, it often cooperates with other ESS to form a hybrid ESS. The dynamic power distribution of hybrid ESS and coordinated control of multi-units will have a significant impact on system reliability, mode switching times, energy storage life, system efficiency and start-stop times. Therefore, the power allocation strategy of hybrid ESS and coordinated control of multi-units are the main difficulty of the short-time control scale. This paper pays more attention to the coordination control of multiple units in a short time scale.

A. Operational Control Structure of the Electric-hydrogen DC MG

The electric-hydrogen DC MG can be divided into two working modes: grid connected and off grid. During grid connected operations, its main task is to give priority to the output power of RESs to meet the power demand of the power grid. The HESS is similar to the control objectives of other ESSs. It is usually regarded as an auxiliary equipment to absorb or compensate the unbalanced power between RESs and power demand of the power grid, and enhance the utilization of RESs.

In the off-grid operational mode, because the system loses the external power grid, it is necessary to coordinate multiple types of sources, loads and ESSs in the DC MG to ensure the voltage stability of the DC bus. At this time, more emphasis is placed on the coordinated control of each unit interface device in multiple operational scenarios, which puts forward higher control requirements for multi-type equipment in the local layer. Its main task is to absorb or compensate the unbalanced power between the RESs and local load demand through HESS and other ESSs, fully tap the complementary characteristics of HESS and other ESSs, ensure the system power balance and DC voltage stability under multiple operational modes, and enhance the utilization of RESs.

The electric-hydrogen DC MG primarily includes two control architectures: the two-layer control architecture and decentralized control architecture.

1) Two-layer Control Architecture

At present, the developed two-layer control architecture is shown in Fig. 4, including upper layer energy management strategy and local layer controller. The energy management system (EMS) interacts with the local equipment through communication technology. The upper layer EMS generates the

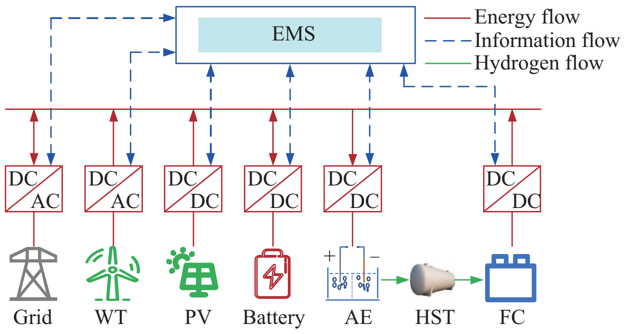


Fig. 4. Typical structure of two layer control.

control mode and power command of each unit according to the received local information, and then sends the instructions to the local device through communications. The local layer device executes the upper layer commands.

In the grid connected operational control, the current research primarily adopts the two-layer control architecture. The grid-connected converter is used to keep the DC bus voltage stability. The EMS distributes the power of electric-hydrogen hybrid ESS according to the unbalanced power between the RESs and the power grid and operational state of each unit, so as to ensure the power balance. In grid connected operations, more emphasis is placed on the research of the upper layer power management strategy (PMS), while the control method of the local layer device is relatively simple. The power only needs to be controlled according to the power command issued by the EMS, so the control mode of each interface device does not need to be switched [91]–[112]. During off grid operational control, due to the limited capacity of the ESS, once the constraints are met, it is necessary to switch the control modes of different units to maintain the system power balance. Therefore, the control strategies of the local layer equipment are more complex in island operational mode [113]–[151].

In the two-layer control architecture, more research focuses on upper layer energy/power management control. The energy management strategy primarily includes: state machine control (SMC), model predictive control (MPC), fuzzy control, equivalent consumption, minimization strategy (ECMS). The EMS based on SMC is one of the most commonly used and mature strategies. In SMC strategy, the definition of various modes is based on the status of state of charge (SOC) and hydrogen storage capacity. The power reference value and control mode of each unit are generated by SMC strategy [91]–[101]. The complexity of SMC is closely related to the type of units and the number of constraints in the system. The SMC will become complex with the increase of the types of units and the number of constraints.

MPC methodology is a good control choice for multi-parameter plant systems. The uncertainties and constraints can be handled effectively. In the MPC optimization, power reference values of the HESS and BESS can be flexibly controlled by adjusting the proper weight factors of the objective function [151]. A PMS based on distributed explicit model predictive control (DeMPC) is developed, the constraints on the current ramp rates are considered to better match the dynamic characteristics of the FC and the electrolyzer [120]. A decentralized MPC is proposed to effectively avoid frequent start and stop [136].

The fuzzy control method is very suitable for nonlinear systems. Fuzzy control does not need an accurate mathematical model, and is insensitive to the change of system parameters, and has strong robustness. In addition, energy management strategies can be constructed only according to simple language rules. Compared with the SMC, it can simplify the design process of energy management [137]–[141]. The traditional fuzzy energy management strategy uses the empirical method to design the membership function and fuzzy rules, so this strategy may not be optimal. To further improve the system performance and realize the optimal control, the fuzzy control and artificial neural network are combined to form artificial neural networks fuzzy inference system (ANNFIS). The data is trained by the artificial neural network, and the membership function can be tuned by the training data [108].

The control objective of ECMS is to ensure the minimum instantaneous hydrogen consumption. A two-level EMS is developed, and the ECMS is applied to distribute power between the battery pack and FC system [130]. Three energy management strategies (basic rule-base strategy (RB-EMS), frequency separation rule-based strategy (FSRB-EMS), and ECMS) are proposed and compared. Through contrastive analysis, the ECMS achieves a 3% improvement in hydrogen use [131]. A hierarchical EMS is developed to enhance the economy of this DC MG, and the fuel consumption is reduced by the ECMS [146].

The comparison of different energy management strategies is shown in Table IV.

TABLE IV
COMPARISON OF DIFFERENT ENERGY MANAGEMENT STRATEGIES

Existing methods	Description of advantages and disadvantages
SMC	Simple, reliable and easy to operate. But SMC will become complex with the increase of the types of units and the number of constraints.
MPC	It can effectively deal with uncertainties and constraints. However, it is difficult to determine the multi-objective weight coefficient.
Fuzzy	It does not need accurate model of the system, and the design of energy management is simple. However, the control effect depends on engineering experience.
ECMS	ECMS can minimize hydrogen consumption, but this method is limited to the optimization between fuel cell and battery.

2) *Decentralized Control Architecture*

The reliability of the two layer control architecture depends heavily on communication. If the communication fails, the bottom devices cannot receive the power command and control mode, resulting in the collapse of the whole system. To deal with these problems, the decentralized control without communication is a common solution, and this method has better reliability. Fig. 5 provides the typical structure of the decentralized control. All units in the MG adopt droop control,

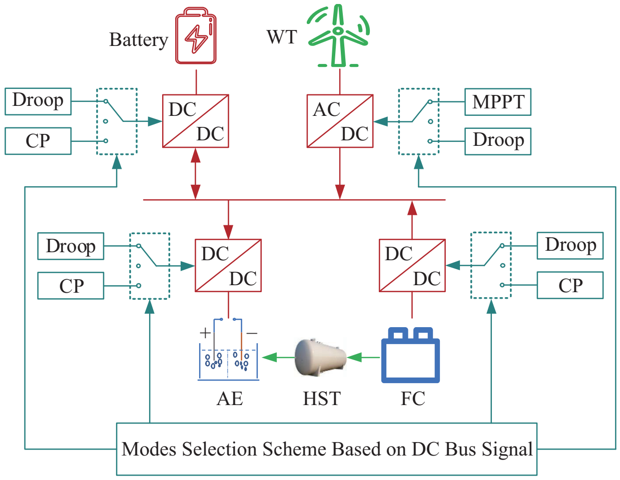


Fig. 5. Typical structure of Decentralized control.

and use the DC bus voltage signal for hierarchical division to determine the control mode of each unit. The output power of all the different devices will be adjusted independently according to the droop characteristics.

In the decentralized control architecture, more research focuses on coordinated control, smooth switching and stability control. How to combine hydrogen energy characteristics with droop control is the focus of decentralized control research. To consider the characteristics of HESS, some improved droop controls are developed [152]–[157]. A decentralized energy management strategy based on a mode-triggered droop proposal is considered, the droop characteristic curve of each unit is designed according to the three states of SOC high, medium and low [152]. The droop control based on the efficiency characteristic curve is proposed, and the efficiency of the HPU and FC units can be dynamically adjusted [153]–[155]. In addition, an active coordinated control strategy is proposed, and the power voltage reverse droop control is used to highlight the controllability of the electrolyzer [157].

B. Influence of Hydrogen Energy Storage Integration on the System Operational Mode

To analyze the influence of HPU on the DC MG operational mode, first, the static characteristics of the AE electrolyzer are analyzed, and the constraints of HPU participating in the operational control are extracted. The working characteristics of AE can be obtained according to the parameters in reference [32], as shown in Fig. 6.

Figure 6, can be summarized as follows:

1) The change of cell voltage is small, while the change of cell current is large. The voltage of the electrolyzer is greatly affected by temperature and less by pressure.

2) The purity of hydrogen is closely related to the current. To ensure the safety of HPS, the operational range of the electrolyzer needs to be limited. Hydrogen purity is affected, at the same time, by temperature and pressure changes. Hydrogen purity can be adjusted by properly adjusting temperature and pressure.

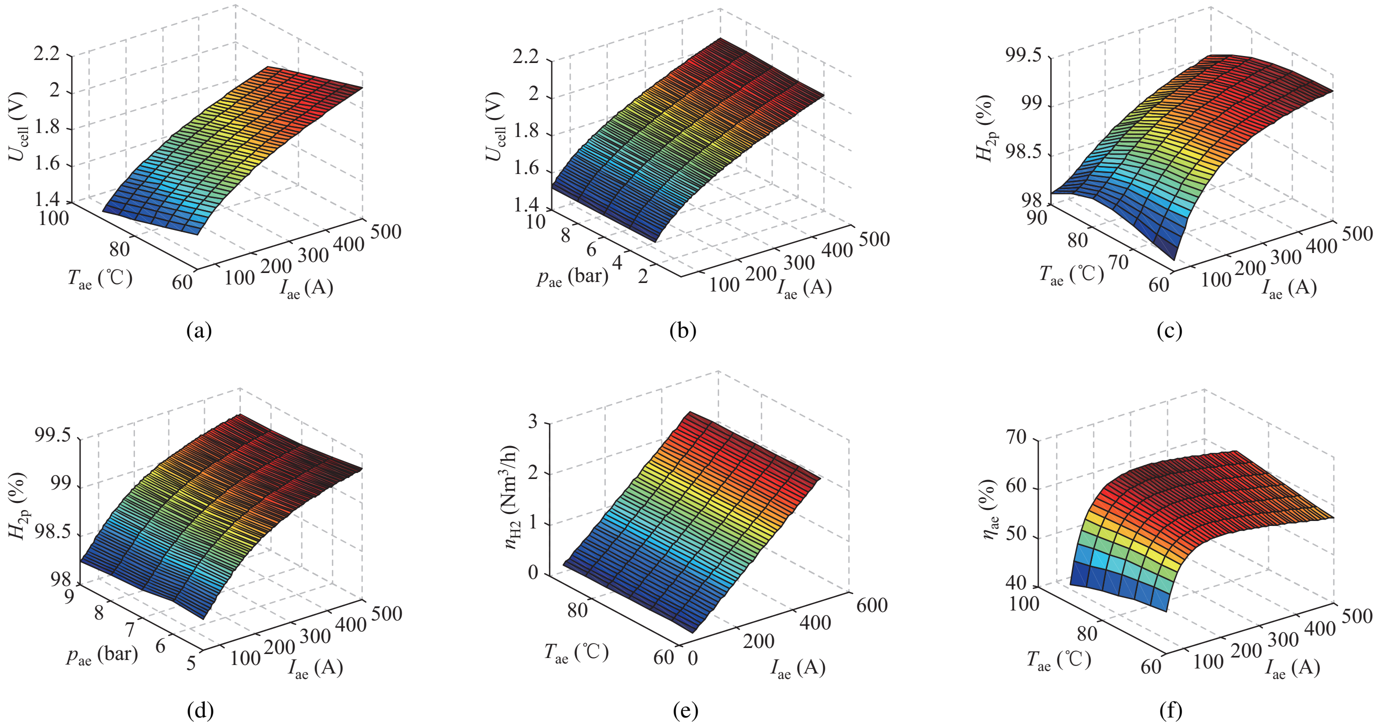
3) The hydrogen production is primarily related to current and is less affected by temperature.

4) The efficiency of AE is sensitive to temperature and current changes. Under specific temperature conditions, there is a unique current corresponding to the optimal efficiency, so the hydrogen production efficiency can be optimized by adjusting the current.

Based on the above analysis, it is necessary to restrict the working range of HPU. In addition, since the HESS also includes a hydrogen storage tank and FC, it is necessary to consider the pressure constraints of the hydrogen storage tank and the working range constraints of FC. The integration of HESS introduces three additional constraints. Compared with the traditional DC MG, its operational mode is significantly increased and more complex.

C. Operational Control Strategy Considering Static Characteristics of Hydrogen Energy Storage

From Fig. 6, the static characteristics of AE and the constraints of HESS should be fully considered in the operational strategy of electric hydrogen DC MG to meet the actual requirements. The operational control method of the grid-



(a) (b) (c)

(d) (e) (f)

Fig. 6. Working characteristics of AE. (a) U-I characteristics of AE under temperature change conditions. (b) U-I characteristics of AE under pressures change conditions. (c) Hydrogen purity of AE under temperature change conditions. (d) Hydrogen purity of AE under pressures change conditions. (e) Hydrogen production. (f) Efficiency of AE.

connected system of wind/PV/electrolyzer/SC is proposed, and four typical operating conditions are analyzed. However, only HPU is considered in the system, and the above constraints are not considered [91]–[94]. A PMS for PV/FC/hybrid energy storage DC MG is developed to maintain the DC voltage stability and power balance [95]. However, the electrolyzer is not introduced into the system. The coordinated control proposal is developed for the grid-connected hybrid renewable power system based on hydrogen energy storage [96]. The control method of HESS is proposed, and the main grid is used to compensate unbalanced power [97]. The operational control of the grid-connected RES-hydrogen DC microgrid is proposed, and five operational modes are considered [98]. However, the power grid is applied to keep DC voltage stability, and the control strategy has been greatly simplified [96]–[98]. The control strategy of the hybrid system of wind/hydrogen/FC/SC is proposed, ten operational modes are divided under the conditions of low wind speed and high wind speed, the control strategies of different units are given, but the pressure constraints of HST were not considered in the energy management strategy [99]. A coordinated control strategy is proposed for the hybrid system of wind/FC/hydrogen/battery, and the pressure constraints of HST are considered, so as to increase the operational modes of the system [100]. The test platform of the wind/PV/hydrogen hybrid system is established and an online energy control strategy is developed, and the constraints of the electrolyzer, FC and hydrogen storage tank are considered [101]. The interior point algorithm is proposed to find the optimal references for the voltage source converter (VSC) and Energy Hub. However, the energy management strategy only considers the current state and battery voltage constraints, and other constraints are not considered [102]. A semi-decentralized control strategy is proposed for electric vehicle fast charging and hydrogen production. The decentralized control strategy based on the virtual battery model and DC bus-signaling is used for photovoltaic/BESS/EV units, while decentralized control and power-based control are used for the electrolyzer to reach its hydrogen production target [109]. A HESS-priority PMS of DC MG with PV/hydrogen/FC/SC is proposed, the six operational states are considered [113]. The EMS based on a multi-agent technology is developed and the hydrogen-priority control proposal is used for autonomous hybrid system [114]. However, the supercapacitor is assumed to compensate any unbalanced power and meet the system stability, which simplifies the energy management [113], [114]. A battery-priority PMS of DC MG with Wind/PV/hydrogen/FC/battery is proposed, but the pressure constraints of HST were not considered [115]. A PMS for household solar-hydrogen power plants is designed to reduce costs [116]. A control method is proposed for an autonomous electric-hydrogen hybrid system [117]. The fuzzy controller is used to regulate the DC bus voltage, and the low pass filter is adopted to realize the power frequency division of HESS and SC. However, the inherent constraints of the electric-hydrogen hybrid ESS are not taken into account. The energy management algorithm of PV/hydrogen/FC/SC is proposed, six operational modes are divided in the system [118]. However, there is only one control mode in each unit, and the flexible regulation ability needs to be further explored. The coordinated control proposal of a wind-to-hydrogen is considered, the DC bus voltage of the WT generator is regulated by a machine-side converter and HESS. However, the FC and HPU needs frequent start-up and shut-down, which eventually degrades their performance and lifespan [110]. A fuzzy PMS based on hydrogen-priority is proposed, a large amount of power in the system is used to produce hydrogen, which reduces the service life of the battery. But the round trip efficiency is very low [119]. A PMS is designed for island DC MG to maintain DC voltage stability and power balance [127]. The control method is proposed for the microhydro power system with FC/electrolyzer/ultracapacitor. The FC and electrolyzer are used to maintain long-term energy balance, whereas the SC acts as an energy buffer for the transient compensation [133]. But the pressure constraint of the HST and SOC constraints of SC are not considered. A control strategy is proposed for a wind/FC/hydrogen/battery system for a standalone operation, and the constraints of BESS and HESS are fully considered. In the energy management and power regulation systems, eight operational modes are divided by the status of wind speed and load [134].

D. Operational Control Strategy Considering Dynamic Characteristics of Hydrogen Energy Storage

Due to the activation polarization overvoltage effect in the voltage model of AE, the dynamic response characteristics of AE voltage are slow, resulting in slow power dynamic response of HPU. In the process of load step increase, there is a fuel starvation phenomenon, resulting in instantaneous voltage reduction, even negative, which will seriously damage the performance and service life of the FC. Therefore, the current or power slope must be limited by the FC controller [158], [159]. Due to the slow dynamic response speed of HPU and FC power generation systems, the actual power cannot quickly track the power command, resulting in a short-term power imbalance. To solve the adverse impact of frequent changes in hydrogen production power on system life and efficiency, and considering the slow response characteristics of HPU, literature [103] shows how the HESS can operate stably with constant power. However, this method lacks flexibility. The coordinated control strategy of the hybrid system of PV/FC/hydrogen/SC is proposed, seven operational modes are divided, and the SC is used to quickly compensate the transient unbalanced power to enhance the dynamic response performance, so as to realize fast dynamic compensation and steady-state power stabilization [104]. Similarly, literature [105] and literature [106] still use SC to quickly compensate the unbalanced power caused by the response delay of HPU and FC for the wind-hydrogen system. An adaptive dynamic power management and control strategy is proposed for HESS and SC ESS, the power rate limit of HPU and FC are considered, the eight operational modes are divided by the status of HST and SC, and the set-reset flip-flop based fixed frequency current controller is used to accurately track the reference currents [135].

The comparison of different operational control strategies considering dynamic characteristics are shown in Table V.

TABLE V
COMPARISON OF OPERATIONAL CONTROL STRATEGIES CONSIDERING DYNAMIC CHARACTERISTICS OF HESS

Existing methods	Description of advantages and disadvantages
[103]	Simple and easy to implement, but lack of flexibility, which is not conducive to the dynamic consumption of renewable energy.
[104]–[106], [135]	The power of HPU and FC can be adjusted dynamically. The proposal has high flexibility, but other ESSs must be configured, with high cost and control complexity.

E. Operational Control Strategies Considering Start-stop Characteristics of Hydrogen Energy Storage

Frequent start-up and shut-down actions for the electrolyzer and the FC will eventually degrade their performance and reduce their lifespan. In order to solve this problem, a hysteresis band control (HBC) method is developed for BESS and HESS, the on/off switching of FC and the electrolyzer can be controlled according to the status of SOC [121]. Two PMSs based on HBC are developed to prevent excessive use of the battery, and the influence of the hysteresis band size on system performance is also discussed [123]. Similarly, a PMS with HBC is also applied for Hydrogen-Based MG [124]. A decentralized MPC is proposed to effectively avoid the frequent turning on and off of the electrolyzer [136]. The EMS with HBC is proposed to reduce ON/OFF events of the FC system and enhance the economy of the system [125]. An EMS based on HBC is proposed, the control methods of HESS, BESS, and RES unit can be designed by the status of SOC for the battery and hydrogen storage level [126]. The start-up control strategy of modular HPU is proposed in the energy management strategy design of the wind-hydrogen system. This method can not only increase the hydrogen production, but also reduce the start-stop times of HPU [107].

F. Power Allocation Strategy of Electric-hydrogen Hybrid ESS

In the electric-hydrogen DC MG, the battery or SC need to be configured to compensate for the short-term unbalanced power caused by the slow response characteristics of HESS. In the steady-state power regulation stage, the power allocation of electric-hydrogen hybrid ESS should be optimized depending on the SOC of the battery and hydrogen storage level, and then reduce the duration of deep charge and discharge of the lithium battery, the number of operational mode switching and the number of start-stop of HESS. To deal with this problem, three PMSs are developed to make sure the load requirements, and the control performance of PMSs are evaluated [122]. Four energy management strategies are evaluated, and 10% hysteresis bandwidth is selected to avert frequent switching [128]. Similarly, the battery-priority and hydrogen-priority energy management strategies are compared. Hydrogen-priority EMS achieves a smaller loss of load probability, while battery-priority EMS obtains a better global storage efficiency [129].

However, the above proposals adopt BESS and HESS to share the unbalanced power separately, while ignoring the coordination of the two ESSs. To solve the problem of optimal power allocation of electric-hydrogen hybrid ESS, a two-level EMS is developed, the nine operational states are considered, and the power of BESS and HESS are shared by a preset fitting curve [132]. But this power allocation method lacks a theoretical basis and completely depends on the defined curve. An EMS based on an adaptive neuro-fuzzy controller is proposed for the grid-connected electric-hydrogen hybrid system, the membership functions are obtained by training and testing data, and the fuzzy EMS is used to optimize the power distribution of the electric-hydrogen hybrid ESS, which can continuously ensure that the SOC of the battery and hydrogen storage levels are maintained within a reasonable range [108]. Based on both real-time and long-term predicted data of the energy generation and consumption, a fuzzy EMS is proposed to select the control mode [137]. The PMS based on a fuzzy logic controller (FLC) is developed to intelligently manage the output power of the FC system [138]. A PMS based on FLC is proposed to enhance the hydrogen production, and reduce the usage of the battery and promote the lifespan of the battery [139]. But the hydrogen storage level has not been effectively controlled in [138], [139]. A PMS based on intelligent FLC is developed to ensure a continuous power supply and maximize hydrogen production [140]. A power allocation strategy based on FLC is proposed for islanding DC MG, and this method can cause the SOC of the battery and hydrogen storage level to approach a reasonable range [141]. A hierarchical control strategy is proposed, and the fuzzy EMS is adopted for the master level to achieve power allocation of HESS and superconducting magnetic energy storage, while the nonlinear sliding mode control is used for the slave level to resist external disturbance [142]. A decentralized EMS is proposed, the power distribution mode of FC and BESS is determined based on three states of SOC. However, this method lacks a power allocation proposal for the charging process [152]. The previous research primarily focuses on the system power balance without considering the system economy. A hierarchical self-regulation control method is proposed to achieve economic operations based on the charge and discharge costs of HESS and BESS [143]. An EMS based on minimum utilization costs and an energy storage state balance is proposed to reduce running cost and optimize the energy storage state and promote the efficiency of the hydrogen energy system [144]. A hierarchical EMS with ECMS is developed to enhance the economy of DC MG [146]. A hierarchical SMC based on the minimum cost algorithm is developed to achieve economic operations [145]. An EMS based on multi-FLC is proposed, the FLC1 makes decisions about the exchange with the main power grid, while the FLC2 is used for distributing the power of BESS and HESS. The technical and economic targets are considered simultaneously [111]. A fuzzy PMS with power prediction and uncertainty is proposed to improve the HESS lifetime [147]. A methodological foundation is applied to develop a general control-oriented model. The technical and economic parameters are determined both in the short-term and long-term. Apart from optimizing electrical performance, economical parameters are also optimized [112].

The previous research primarily focuses on the power allocation of HESS and other ESSs in a microgrid, but did not consider the power distribution among multiple microgrids with HESS. To solve this problem, a hierarchical method is proposed, which gives priority to the power distribution of the hybrid energy storage system, and then distributes the obtained power between the BESS and HESS [148]. An inverse droop control strategy based on the super-twisting algorithm (STA) is developed to realize the power distribution of inverters [149]. An adaptive droop control strategy based on the hydrogen storage level is developed to achieve equilibrium control of HST [150].

G. Operational Control Strategy Considering Efficiency Optimization of Hydrogen Energy Storage

Efficiency optimization should be considered to improve the system efficiency of electric-hydrogen DC MG. As shown in Fig. 6, when the temperature is constant, there is a unique current corresponding to the optimal efficiency of the HPU. Therefore, the hydrogen production efficiency can be optimized by dynamically adjusting the current. To solve the above problems, the efficiency of HPU is evaluated, and an efficiency adaptive control is proposed to obtain optimal efficiency control [153]. Similarly, the coordinated control strategy is extended to AC MG, the operational mode is divided by frequency information, and an efficiency-frequency adaptive droop control method is proposed for HPU [154]. On the basis of reference [154], the power generation efficiency of FC is evaluated, and a power-frequency adaptive droop control strategy with efficiency dynamic adjustment capability is proposed for both HPU and FC [155]. An efficiency coordination and optimization control strategy of multi-stack FC systems was proposed to ensure the whole multi-stack system was in the optimal operational state [160]. A restriction based on a safe operating area is developed to obtain the optimal efficiency operational trajectory of the PEMFC system. And the disturbance estimation sliding mode control (DE-SMC) is adopted, which realizes optimal efficiency control of the PEMFC system [161]. An online extremum seeking-based optimized EMS is proposed to seek the maximum power and maximum efficiency points. This strategy can save hydrogen consumption and improve the stack efficiency respectively [162]. A hierarchical performance improvement control method is developed, the upper level is to seek optimal trajectory for efficient and stable operations, while the lower control level is to track optimal trajectory [163].

H. Performance Comparison and Prospects

The current operational control proposal of the electric-hydrogen DC MG has been analyzed in detail. The comparison results of different control proposals are shown in Table VI.

In the existing proposals, from the perspective of control architecture, most control proposals adopt the two-layer control architecture with communication technology, while there is less research on the operational control proposal without communication. The energy management strategy and stability performance of the two-layer control architecture are greatly

TABLE VI
COMPARISON WITH EXISTING METHODS

Existing methods	Communication	SOC management	SOC_H management	Efficiency	Power optimization allocation	Dynamic characteristics	Start-stop strategy	Operation range
[91]–[95], [115]	√	√	×	×	×	×	×	×
[96], [98]	√	×	√	×	×	×	×	√
[97]	√	×	×	×	×	×	×	×
[99]	√	√	×	×	×	×	×	√
[100], [103], [109], [114] [116], [118],	√	√	√	×	×	×	×	×
[101], [134]	√	√	√	×	×	×	×	√
[102]	√	√	×	×	√	√	×	×
[104]–[106], [120]	√	√	√	×	×	√	×	×
[107]	√	√	×	×	×	×	√	√
[108], [111], [130]–[132]	√	√	√	×	√	×	×	√
[110], [113]	√	×	√	×	×	√	×	×
[112]	√	√	√	√	√	×	×	√
[117]	√	×	×	×	√	×	×	×
[119], [128], [129]	√	√	√	×	√	×	×	×
[121]–[124]	√	√	×	×	√	×	√	√
[125]–[127]	√	√	√	×	√	×	√	√
[133]	√	×	×	×	×	√	×	×
[135]	√	√	√	×	√	√	×	×
[136]	√	×	√	×	×	×	√	×
[137]	√	√	√	×	√	√	×	×
[138], [139]	√	√	×	×	√	×	×	×
[140], [141], [151]	√	√	√	×	√	×	×	√
[142], [143], [145], [146] [147], [150],	√	√	√	×	√	×	×	×
[144], [148]	√	√	√	×	√	√	×	×
[149]	√	√	√	×	√	√	×	√
[152]	×	√	√	×	√	√	×	×
[153]–[155]	×	√	×	√	√	×	×	×
[156]	×	√	√	×	×	×	×	×
[157]	×	√	√	×	×	×	×	√
[162]	√	√	√	√	√	√	×	×

affected by communication, and the system reliability is poor. The decentralized control proposal has higher reliability, but its energy management and optimization ability are weak. From the perspective of control structure, the integration of hydrogen energy does not change the control structure of the DC MG. Therefore, the control architecture of the electric-hydrogen DC MG can still use the existing control architecture of DC MG. In the future, it is a better choice to combine the existing two control structures to form a multi-layer control architecture.

In terms of static response characteristics of hydrogen energy storage, the existing proposals consider more aspects, such as operational range of hydrogen energy storage and $\mathrm{SOC_H}$ management of hydrogen storage tanks, but there are still some literature that have not fully considered the above operational constraints. At present, the selection principle of static constraints is still based on experience, such as thresholds of SOC and hydrogen storage capacity. However, the selection of upper and lower limits of SOC and hydrogen storage levels has a greater impact on system operational reliability, cost, lifespan and benefits. Therefore, how to better formulate constraints in the future needs further evaluation and analysis.

In terms of dynamic response characteristics of hydrogen energy storage, the existing literature proposes to use lithium batteries or SC to solve the problem of the slow dynamic response of HESS. However, the real-time change of the power of the HESS has an adverse impact on the performance and service life of the electrolyzer. Therefore, in order to avoid the degradation of HESS performance, the correlation between power change and hydrogen energy storage performance should be further explored.

In the existing operational control proposals, the startup and shutdown characteristics of HPU have been widely addressed. The startup and shutdown strategy based on HBC is usually used. In this proposal, the capacity of the BESS is assumed to be large enough. However, the BESS capacity is limited in view of economy and other factors. In addition, PMSs based on battery-priority and hydrogen-priority are used, and the power allocation proposal may be poor for reducing the number of frequent starts and stops. Therefore, the start-stop strategy and advanced power allocation proposal should be further integrated.

In terms of power allocation of electric-hydrogen hybrid ESS, the most existing proposals adopt a serial sequential allocation mode, such as hybrid battery-priority and hybrid hydrogen-priority. Although there have been relevant studies on the parallel power allocation mode, these power distribution proposals are primarily based on SOC of battery, hydrogen storage level and economical parameters. In the future, more factors should be considered, such as bulk properties of fuel cell and battery.

In terms of efficiency optimization of HPU and FC, for the efficiency optimization control of the fuel cell system, there have been some valuable research results. The real-time tracking control of optimal efficiency and the power allocation strategy of the modular FC system based on optimal efficiency have been studied and addressed. Although the efficiency optimization control of HPU have also been studied, the current research primarily assumes that the efficiency curve of the electrolyzer is fixed. However, the temperature of the electrolyzer will change in real time under different operating conditions, and the efficiency of the electrolyzer is very sensitive to the temperature change, so the efficiency curve of the electrolyzer is time-varying. To ensure the effectiveness of the efficiency optimization control of HPU, the efficiency curve should be adjusted in real time according to the operating conditions. In addition, the current research is limited to the efficiency optimization of the electrolyzer. However, the actual hydrogen production system consists of many parts, and the efficiency estimation and efficiency optimization control of the whole system still need to be further explored.

In addition to the above discussion, in the current research, the HPU or FC system is usually equivalent to a power electronic device and a controlled source. However, in practice, the hydrogen production unit and fuel cell also include many other levels of control, such as gas flow rate control, liquid level control, temperature control, pressure control and so on. Therefore, these control objects and control systems also need to be taken into account to simulate the real operational scenario.

VII. FUTURE RESEARCH TRENDS AND EXPLORATION

A. *Advantages of Modular Parallel HPS*

According to the current research updates, the previous research was primarily limited to a single HPU. In the future, with the continuous increase of hydrogen production capacity, the single module hydrogen production power supply is difficult to be applied in low-voltage and high current situations, so the modular parallel HPS is usually used. The advantages of modular parallel HPS are not only reflected in the hydrogen production power supply, but also in the hydrogen production electrolyzer, as follows:

1) Increase the operational range of HPU. According to the purity characteristics of the alkaline electrolyzer, the HPU cannot operate at low power for ensuring hydrogen energy safety, and its lower limit is about 40% of the rated power of the system. Therefore, the operational range of a single HPU is narrow and cannot match the wide power fluctuation characteristics of RESs. If the modular HPS is adopted, the lower limit of operations can be reduced to 1/N (N is the number of modules), thus increasing the overall operational range of the HPS.

2) Increase the startup speed of HPU. After adopting the modular hydrogen production structure, due to the increase of the operating range, the lower limit of the starting power of the whole HPS is reduced. Therefore, the HPS can be started with less power, thus shortening the starting time.

3) Improve the operational efficiency of HPS. If a centralized HPS is adopted, according to the energy efficiency characteristic curve of the electrolyzer, when the input power is certain, the operational efficiency of a single HPS is fixed, and the efficiency cannot be optimized and adjusted. If the modular parallel HPS is adopted, multiple HPUs can optimize and adjust the operational efficiency point of the system through the power allocation method.

B. Power Allocation Strategy of Modular Parallel HPS

For the modular parallel HPS, how to optimize the power allocation of multiple HPUs is the key technical problem. In the process of power allocation, on the one hand, it is necessary to consider the capacity ratio of multiple HPUs. On the other hand, it is necessary to consider the energy consumption and energy efficiency curves of different HPUs. The power of modular HPSs is allocated depending on the overall efficiency index of the hydrogen production system. In addition, $\mathrm{SOC_H}$ management of HST shall also be considered in power allocation. Once the pressure of HST reaches the upper limit, the HPU needs to be stopped to ensure hydrogen safety. Shutdown and restart will not only bring economic losses, but also bring complexity to the operational control of DC MG. Therefore, the pressure of multiple hydrogen storage tanks needs to be intelligently managed to avoid frequent start-up and shut-down actions. Based on the above analysis, in the future, the power allocation strategy of modular parallel HPUs can be studied from the aspects of system efficiency optimization, $\mathrm{SOC_H}$ intelligent management and balance control.

C. Operational Control Strategy Considering the Start-stop Characteristics of Modular Parallel HPS

According to the research progress at home and abroad, the current research is limited to the start-stop strategy of single hydrogen production equipment, while the start-stop strategy of modular parallel HPS is rarely involved. The response time of the cold start of HPS is usually minute, which is slow. Meanwhile, the shutdown of HPUs will also affect the hydrogen production and cause hydrogen losses. For the modular parallel HPS, because the system contains multiple HPUs, when the power command is small, only one HPU is started in the system, while other HPUs may be in a shutdown or hot standby state. During the real-time change of the power command, multiple HPUs will switch frequently in hot standby, shutdown and operational states. In order to improve the response characteristics of HPUs, the cold and hot state transition time of different HPUs should be considered. In addition, the power loss caused by the hot standby state of the HPU needs to be considered to evaluate the operational efficiency of the whole system. Based on the above analysis, in the future, it is necessary to comprehensively consider the control objectives, such as hydrogen production, startup and shutdown times, energy consumption and dynamic response performance, to study the start-stop strategy of modular parallel HPS.

VIII. CONCLUSION

This paper introduces the typical structure of an electric-hydrogen MG, and analyzes the modeling methods of different types of electrolyzers. The operational control architecture of the electric-hydrogen DC MG is analyzed. Combined with the working characteristics of an alkaline electrolyzer, the influence of hydrogen energy storage access on the operational mode of DC MG is also analyzed. The operational control strategies are compared and analyzed from four aspects: static and dynamic characteristics of HESS, power allocation of the electric-hydrogen hybrid ESS and efficiency optimization of the hydrogen energy storage. From the summary and analysis of the current research, compared with the traditional DC MG, the integration of HESS will not affect the system control architecture, but the static and dynamic characteristics of HESS will have a great impact on the operational mode, energy management strategy and the coordinated control method of DC MG. The static dynamic characteristics of HESS and the complementary characteristics of the electric-hydrogen hybrid ESS should be fully considered in the operational control and energy management proposal, which is conducive to improving the adaptability of HPU to the wide power fluctuation of RESs, and the service life and operational efficiency of the system. In addition, the control strategy of electric hydrogen DC MG is analyzed and discussed. Finally, the development and advantages of the modular hydrogen production system are analyzed, and the technical problems and future research directions of DC MG with modular parallel HPS are explored.

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