A Study for a Hybrid Wind-Solar-Battery System for Hydrogen Production in an Islanded MVDC Network

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ABSTRACT Renewable energy hydrogen production technology is an effective way to improve the utilization of renewable energy and alleviate the problem of wind and light abandonment. However, there are many challenges in the system structure design and “Source-Load-Storage” coordination control strategy for large-scale, megawatt-scale renewable energy hydrogen production. In this paper, a hybrid wind-solar-energy storage hydrogen production system based on Medium Voltage Direct Current (MVDC) structure is proposed. HOMER software is used to plan and study the storage capacity to achieve long-term power balance and matching of the system. In addition, A decentralized coordinated control energy management system with active power following and state of charge (SOC) recovery capability is proposed and implemented for transient power regulation. An electromagnetic transient simulation was established in PSCAD/EMTDC, and semi-physical experiments were designed using StarSim to verify the effectiveness of the control strategy. Theoretical analysis and experiments show that the island MVDC network with decentralized coordinated control has technical feasibility in realizing hydrogen production from renewable energy in the 20MW level class. In addition, the power consumed by the load can realize the seconds level tracking of the output power of renewable energy.

INDEX TERMS Hydrogen production, MVDC, renewable energy, electromagnetic transient simulation, active power following control, decentralized coordination control, electrolyzer.

NOMENCLATURE

| CCM  | The continuous current mode. |
| DCM  | The discontinuous current mode. |
| HIL  | The Hardware In Loop simulation. |
| MPPT | Maximum Power Point Tracking. |
| MWp  | The PV system Mega Watt Peak power. |
| NPV  | The Net Present Value cost. |
| PSPWM | The phase-shifted pulsewidth modulation. |
| RCP  | The Rapid Control Prototype controller. |
| TPTL | Three-phase Three-level. |
| TSR  | The Tip-Speed Ratio. |
| AE   | The Alkaline Electrolyser. |
| DFIG | Doubly fed Induction Generator. |

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I. INTRODUCTION

As a renewable and clean renewable energy, hydrogen energy has become the consensus of academia and industry. The topic of “hydrogen energy” has become a research hotspot, and it has shown good application prospects in hydrogen fuel gas turbines, hydrogen fuel cells, and hydrogen internal combustion engines [1]. The World Energy Council report divides hydrogen into “gray”, “blue” and “green” by source

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of production: Green hydrogen refers to the use of renewable energy for electrolysis, zero carbon dioxide emissions, high cost, and the highest social acceptance.

In recent years, the renewable energy power system has developed rapidly, and the power supply capacity of the system has reached the megawatt level. Renewable energy hydrogen production technology has been proved to have important research value and engineering practical significance. Using renewable energy hydrogen production technology combined with medium voltage DC power distribution technology can improve the utilization efficiency of renewable energy power generation. Firstly, the energy storage capacity is reasonably designed according to the known information using the cost-optimized method and technical feasibility. On this basis, the system-level energy management strategy needs to model the characteristics of various equipment of renewable energy and the characteristics of hydrogen production load, so as to realize the matching design of power supply and load [2]. At present, there are two main types of renewable energy hydrogen production schemes: grid-connected [3] and off-grid [4].

Due to the high volatility of RES, grid-connected power generation often reduces the stability of the grid [5]. In addition, the quality of power supply and output characteristics of renewable energy will also lead to problems such as abandoning wind and light, resulting in waste of resources. At the same time, the hydrogen production load is flexible and adjustable. This problem can be solved nicely if wind and solar power are used to produce hydrogen. At present, the hydrogen production technology of distributed renewable energy power generation needs to balance the cost and benefit, and study the energy management strategy of high-capacity wind energy and solar energy independent hydrogen production. Under off-grid conditions, how to convert fluctuating renewable energy power into DC power for electrolysis and maintain stable operation under off-grid conditions is an urgent problem to be solved.

Literature [6] discusses the effects of wind power fluctuations on the efficiency and safety of the electrolyzer for hydrogen production, and proposes an adaptive control strategy for alkaline electrolyzer in combination with super-capacitors to form a hybrid energy storage system. However, the study is based on a grid-connected hydrogen production system, and PV is not considered in it.

In [7], the article designs a landscape hydrogen integrated energy system topology based on a low-voltage DC busbar network. An online energy regulation strategy is also proposed. However, the system designed in this study is only applicable to scenarios with low power levels and is not applicable to the scope of the megawatt-scale hydrogen production system studied in this paper.

In the context of the system energy storage capacity planning problem in hydrogen production from wind power, mixed integer linear programming [8], particle swarm algorithm [9], etc. are used to design the capacity of the device as well as to design energy management strategies.

In large grids, grid-connected Renewable Energy Sources (RES) can reduce system damping and cause low-frequency oscillations under conventional control strategies [10]. In particular, there are differences in the power regulation characteristics of wind power and photovoltaic power generation, and direct parallel connection may lead to system instability [11]–[13]. In off-grid mode, the grid voltage and frequency are generally provided by energy storage or diesel generators, and the grid inertia and damping are weak, so the conventional off-grid hydrogen production system has the risk of instability.

Compared with the traditional medium voltage AC power distribution system, MVDC power distribution system has more power capacity and lower power losses. The MVDC electric system is the development trend of the future power distribution system [14]. At present, the MVDC distribution network has shown good application prospects in all electric ships, industrial parks, offshore wind power and other fields. MVDC power distribution technology can reduce the technical requirements of renewable energy grid connection, and connect renewable energy sources with significantly different dynamic adjustment characteristics in parallel on the DC side. The MVDC solution realizes the decoupling of voltage and frequency on different buses on the AC side, which is convenient for system expansion. At present, although the hydrogen production topology using AC bus has certain cost advantages, the MVDC power distribution related equipment has gradually matured and will show good technical economy.

In this paper, an off-grid hydrogen production system based on the MVDC structure is proposed. The proposed system structure can avoid the direct parallel operation of renewable energy sources of different nature, which can improve the stability and scalability of the hydrogen production system. At the same time, the proposed distributed coordination control strategy can realize the real-time balance of load-side power and renewable energy source-side power, and reduce the energy consumption of energy storage in the system transient process. The main contributions of this paper are shown below.

1. An MVDC-based grid structure is proposed for the first time in an off-grid hydrogen production system. The proposed structure is easily scalable and friendly to renewable energy access.

2. Based on historical data and load data pre-processing methods, the capacity planning of grid-supported energy storage is implemented in HOMER. With the given data and conditions, at least 3MWh of energy storage is required to meet the demand of a 20MW hydrogen production system.

3. A detailed simulation model of an off-grid MVDC hydrogen production system is developed and a distributed coordination-based control strategy is proposed. The control strategy does not depend on communication and has high reliability. The SOC control of power balancing and energy storage is realized based on local information. Stable
The rest of the paper is organized as follows: The section II describes the structure of renewable energy hydrogen production system with MVDC structure. The section III studies the capacity planning of energy storage according to the system capacity configuration and hydrogen production requirements. The section IV describes the proposed decentralized control strategy for power balance and SOC recovery. In section V, simulation analysis and hardware-in-the-loop verification are carried out for various working conditions. Finally, the main conclusions of the paper are summarized in section VI.

II. STRUCTURE OF MVDC HYDROGEN PRODUCTION SYSTEM

The system structure is shown in the Figure 1, including wind and solar power supply, power storage system, transformer combined with uncontrolled rectifier using multi-pulse technology [15], hydrogen production power supply, electrolyzer cell, hydrogen production auxiliary load and emergency power supply, etc. Among them, multiple electrolyzers run in parallel on the 4000V MVDC bus, and the wind and solar power sources and their corresponding grid-supported energy storage operate in parallel on an independent AC bus. Doubly fed Induction Generator (DFIG) and photovoltaic array are used as power sources in the system, and energy storage provides voltage and frequency support for them respectively. In addition, energy storage is used to support the black-start process of wind turbines and photovoltaics. The main purpose of the system is to make full use of renewable energy to produce hydrogen which means that the electrolytic cell load follows the renewable energy power. At the same time, the energy management of the system minimizes the use of energy storage to maintain the life of energy storage. The generated hydrogen will be transported to other production links through pipelines or other technologies, so hydrogen storage equipment is not considered in this paper. Among them, the energy management system (EMS) designed in this paper contains two parts: centralized system monitoring and decentralized coordination control; centralized monitoring is not discussed in this paper. The distributed coordination control strategy is described in Section IV.

In addition, when the system capacity needs to be expanded, only a new set of 35kV buses need to be added on the AC side. A set of energy storage and RES is configured on each AC bus, and then connected to the 4000V DC system through a transformer rectifier. Since the control strategy designed in this paper is fully distributed, there is no need to adjust the control parameters and wiring of the original equipment, which will be explained later. When one set of RES is removed by a fault or human, the other RES will be unaffected.

III. CAPACITY PLANNING OF ENERGY STORAGE

HOMER Energy software has proven effective in analyzing complex distributed energy systems, both on-grid and off-grid, such as islands and remote communities [16]. HOMER software can design cost-effective and reliable microgrids that combine conventional and renewable energy sources. The optimal method based on simulation and multi-core parallel computing can quickly obtain the optimal solution in the design space and can perform sensitivity analysis on the specified parameters. The interface with Matlab/Simulink also enables the software to design better energy scheduling strategies [17].

According to the system structure proposed above, a model for the optimal configuration of system energy storage is built in the HOMER software [18]. The system composition and the location are shown in the Figure 2A and Figure 2B. It is worth noting that we have simplified the system structure. For example, multiple devices of the same type are equated to one, and the simplification does not affect the optimization results.

A. DATA ACQUISITION AND PROCESSING

The characteristics and operating constraints of the Alkaline Electrolyser (AE) is unique. When the electrolytic cell is running at low power, due to the characteristics of the material inside the electrolytic cell, the operating power of the electrolytic cell cannot be lower than a certain limit, otherwise there is a risk that the hydrogen and oxygen will cross the explosion limit. The limit is generally 20% to 25% of the rated power of the electrolytic cell. When the electrolyzer is working, its power can exceed the rated...
TABLE 1. Economic data of system equipment.

| Types         | Components Capital cost ($/kW) | Replacement cost ($/kW) | O&M cost ($/kW/yr) | Lifetime (year) |
|---------------|---------------------------------|-------------------------|--------------------|-----------------|
| Wind turbine  | 2000                            | 2000                    | 40                 | 25              |
| PV system     | 3000                            | 3000                    | 10                 | 25              |
| Converter     | 1000                            | 1000                    | 20                 | 15              |
| Battery       | 130                             | 130                     | 6                  | 5               |
| Electrolyser  | 4000                            | 4000                    | 80                 | 15              |

power for a short time, reaching 110% - 130% of the rated power. Dynamic operation characteristics of alkaline water electrolyzers ramp-up from empty to 10% of full load will take 1 second. During load shedding, the time from full load to 10% of full load is 1 second, which is faster than the power adjustment speed during the loading process.

The efficiency of power converters, namely DC/DC converter and AC/DC rectifier is 95%. Battery round-trip efficiency is 85% while the battery loss rate used is 0.0083%. Efficiency of AE considered in the simulation is 70% while 25% of the nominal electrolyser power is used as the minimum electrolyser power input. In the economic part of this analysis, a period of 25 years is assumed as the project lifetime. For all system components, replacement costs are considered equal to the initial capital costs. Additionally, 2% of the initial capital cost of wind turbines, electrolyser and converters is assumed as the Operation and Maintenance (O&M) costs per year. WT(Wind Turbine) initial capital cost is taken as 2000 $/kW ($ represents US Dollar) with a lifetime of 25 years. Initial capital cost of all power converters is taken as 1000 $/kW with a lifetime of 15 years. Battery bank should be replaced 5 times over the project lifetime due to its short lifetime assumed as 5 years, while its initial capital and O&M costs are taken as 130 $/kW and 6$/kW/year per unit of battery, respectively. Initial capital cost of the electrolyser is taken as 4000 $/kW with a lifetime of 15 years. The data of Table 1 is based on current market research and related study [16]. The data related to the economics of photovoltaics are shown in the table.

The preprocessing process of the hydrogen load data is as follows: Since there is no regulation mode in which the load follows the power supply in the HOMER software, it is necessary to preprocess the data of the hydrogen load. First, according to the project address, the local wind and solar resources and environmental data can be obtained by querying the historical data. The selected wind turbine and photovoltaic capacity are used to calculate the power of the wind turbine and photovoltaic in a year. After the summation operation, the total power curve of the renewable energy can be obtained, and then the hydrogen load curve under the current renewable energy power curve can be obtained according to the constraints of the characteristics of the Alkaline cell, including the limit of the power adjustment range, the start and stop time, and the power adjustment speed. In most cases, the hydrogen load can be matched with the output power of the renewable energy. When the constraints of the hydrogen load are not met, energy storage is required to make up for the power difference. At this time, the following procedure shown in Figure 3 can be used for calculation and processing through the homer software. Where \( NPV \) is the net present value cost.

Where \( N \) is the maximum simulation number in this optimization process, which is 10000 in this paper.

B. ENERGY STORAGE CAPACITY OPTIMIZATION RESULTS

According to the simulation conditions given above, the optimization result of energy storage capacity based on HOMER simulation is 3MWh. The one-year operation curve of the hydrogen production system obtained through data preprocessing and optimized configuration is shown in Figure 4A.

It can be seen that the hydrogen production rate of the electrolyzer changes with the wind and solar power generation, showing obvious seasonal characteristics.
The power of each device in the system within one year under the HOMER optimal solution is shown in the Figure 4B, and the charge-discharge curve of the battery shows that the battery makes up for the unbalanced power between the renewable energy source and the load.

IV. SYSTEM MODELING AND DECENTRALIZED COORDINATED CONTROL STRATEGY

In the previous section, we performed the planning of energy storage capacity using the HOMER software based on the centralized control method and the power balance principle. However, the shortcomings of the above method are that the control strategy is highly dependent on communication and has low reliability in case of system failure. Besides, due to the oversimplification of the model, the simulation results for transient power fluctuations of renewable energy are not accurate and precise enough. In addition, the HOMER software only provides a minute-level energy dispatching strategy, which is not possible for millisecond to second-level control strategies.

For this reason, this paper proposes a decentralized coordinated control strategy based on the physical modeling of each device of the hydrogen production system in conjunction with engineering practice. The proposed control strategy has features such as complete independence from communication, adaptive regulation of hydrogen production load power, automatic recovery control of energy storage SOC, virtual inertia control, etc.

A. SYSTEM MODELING

1) DFIG WIND POWER SYSTEM

The fundamental equation governing the mechanical power capture of the wind turbine rotor blades, which drives the DFIG considered in this paper [19], is given by

\[ P_{\text{wind}} = \frac{1}{2} \rho A v^3 C_p(\lambda, \theta), \]  

where \( \rho \) is the air density (kg/m\(^3\)), \( A \) is the area swept by the rotor blades, and \( V \) is the wind velocity (m/s). \( C_p \) is called the power coefficient or the rotor efficiency and is a function of tip-speed ratio (TSR or \( \lambda \)) and pitch angle \( \theta \). The details of the DFIG dynamic model is shown in Figure 5. The component and controller parameters of the DFIG are given in section 5. The output power is kept constant when wind speed is higher than the rated wind velocity even though the wind turbine has the potential to produce more power. When wind speed is higher than the cutout speed, the system is taken out of operation for protection of its components.

In the dq rotating coordinate system, the machine-side rectifier of the wind turbine generally adopts the double closed-loop control of the active power outer loop and the current inner loop for the q-axis to ensure the current follow-up [20]. To achieve fast response of the converter, the d-axis adopts a single-loop control with zero reference current.

The wind turbine grid-side converter control requires \( U_{dc} \) to be a constant value, the double closed-loop control of the d-axis adopts the DC bus voltage as the outer loop, the current as the inner loop, and the q-axis adopts the reactive power outer loop current inner loop control strategy and \( Q_{\text{convref}} = 0 \). That is, the system does not output reactive power, thereby reducing the capacity configuration of the converter and reducing the system investment cost. The virtual inertial control part of DFIG is described in Section IV D as part of the coordinated control strategy.

2) PHOTOVOLTAIC (PV) SYSTEM

At present, photovoltaic AC grid-connected technology is relatively mature, and a photovoltaic power generation system of 5MWP is selected in this paper. However, photovoltaic power generation is greatly affected by environmental factors, and the output power is highly volatile. The photovoltaic grid-connected system generally consists of photovoltaic panels, maximum power tracking boost converters, inverters and their filter circuits, and transformers. The control modes
of photovoltaic converters are divided into MPPT control under PQ control mode and constant voltage control mode. In this paper, the photovoltaic works in the MPPT mode, and the MPPT algorithm adopts the perturb and observe method. The relationship between the output voltage \( V_{PV} \) and the load current \( I \) of a PV array or a module can be expressed as

\[
I_{PV} = N_{PV}I_{SC} \cdot \left[1 - C_1 \left(\frac{c - dV}{C_2N_{PV}V_{OC}} - 1\right)\right] + dI
\]

where

\[
C_1 = \left(1 - \frac{I_m}{I_{SC}}\right) \cdot \exp\left(-\frac{V_m}{C_2V_{OC}}\right)
\]

\[
C_2 = \frac{V_m/V_{OC} - 1}{\ln(1 - I_m/I_{SC})}
\]

\[
dl = -\alpha \cdot \frac{G}{G_{ref}} \cdot (T_c - T_{ref}) + \left(\frac{G}{G_{ref}} - 1\right) \cdot N_{PV}I_{SC},
\]

\[
dV = \beta \cdot dT - R_s \cdot dl,
\]

where \( I_{PV} \) is the load current of PV array (A), \( V_{PV} \) is the output voltage of PV array (V), \( T_c \) and \( G_{ref} \) are the reference cell temperature (25°C) and given solar irradiance (1000 W/m²), \( T_e \) is the actual temperature of the PV cell, G is the solar irradiance (W/m²), and \( R_s \) is the series resistance of PV cell. The power injected by PV array into the medium voltage dc hydrogen production system could be written as

\[
P_{PV} = I_{PV}V_{PV}(1 - K_{PV-loss}).
\]

The topology and control structure of the photovoltaic power generation system are shown in the Figure 6.

3) ELECTROLYTIC CELL LOAD AND POWER SUPPLY

There are three main water electrolysis technologies: 1) AE 2) Proton Exchange Membrane Electrolyser and 3) Solid Oxide Electrolyser. Among them, the efficiency of AE is 62% to 82%, which is lower than the other [21], [22]. The main advantages of AE are maturity, large capacity, good stability and low investment cost. AE consist of a pair of electrodes immersed in an alkaline solution (usually a concentration of 25%-30% potassium hydroxide (KOH)) separated by a diaphragm to prevent gas mixing.

The models of AE mainly include electrochemical analytical model and engineering empirical model. This paper adopts the engineering model provided by the manufacturer. Due to the low voltage of the single electrolytic cell, several single electrolytic cells are connected in series to form a stack. The volt-ampere characteristics of the AE stack are:

\[
U_{cell} = U_{rev} + U_R + U_t
\]

\[
U_R = \frac{r_1 + r_2T_{el}}{A_{cell}} \cdot I_{el} = R_{elec}I_{el}
\]

\[
U_t = (s_1 + s_2T_{el} + s_3T_{el}^2)\log(\frac{I_1 + r_2/T_{el} + r_3/T_{el}^2}{A_{cell}}) + 1
\]

where \( U_t \) and \( U_R \) are the ohmic voltage and polarization voltage of the electrolytic cell, respectively; \( r_1 \) and \( r_2 \) are the ohmic resistance parameters of the electrolyte; \( T_{el} \) is the temperature of the electrolytic cell, and \( A_{cell} \) is the electrolysis module Area, \( I_{el} \), is the DC current, \( s_1, s_2 \) and \( s_3 \) are the electrode overvoltage coefficients, and \( t_1, t_2 \) and \( t_3 \) are the electrode overvoltage coefficients. The inverse voltage is shown in (8):

\[
U_{rev} = \frac{\Delta G}{zF}
\]

In (8), \( \Delta G \) is the Gibbs free energy change of the electrochemical reaction process, \( z \) is the number of electrons transferred per reaction, \( F \) is the Faraday constant. Reversible open circuit voltage \( U_{rev} = 1.228V \). The AE DC voltage is:

\[
U_{el} = N_{el}U_{cell}
\]

In (9), \( N_{el} \) is the number of serial modules in the electrolyzer, and \( N_{el} = 50 \) in this simulation analysis.

According to Faraday’s law, the hydrogen production flow rate of the stack depends on the current of the electrolyzer.

\[
\bar{n}_{H_2} = \eta_F \cdot \frac{N_{el}I_{el}}{zF}
\]

\[
\eta_F = a_1 \exp\frac{a_2 + a_3T_{el}}{I_{el}/A_{cell}} + \frac{a_4 + a_5T_{el}}{(I_{el}/A_{cell})^2}
\]

where \( I_{el}/A_{cell} \) represents current density. Electrolysis efficiency \( \eta_F \), which varies with current density and temperature. The electrical power consumed by the electrolyzer as a whole can be expressed as:

\[
P_{el} = N_{el}U_{el}I_{el}
\]

The parameters of the cell model can refer to the literature [23]. A model of the electrolyzer circuit represented by a controlled voltage source and a variable resistor is shown in Figure 7A.

The MW level electrolyzer load requires a hydrogen production power source with the characteristics of low
voltage and high current. In this paper, a three-phase three-level (TPTL) phase-shifted pulsedwidth modulation (PSPWM) dc–dc converter suitable for MVDC scenarios is adopted. The power supply has high power density, and the configured intermediate frequency transformer enables the power supply to have fault isolation capability [24]. The circuit topology of the hydrogen production power supply is shown in the Figure 7A. Three middle frequency single-phase transformers, independent to each other, are employed to obtain the required isolation between the primary and secondary sides. At the secondary side, three single-phase, uncontrolled full-wave rectifiers are connected in parallel through three output filter inductors. In the steady state of continuous current mode (CCM), when $0.08 < D_a < 0.42$, the average of the rectified output voltage is given by

$$V_o = \frac{2V_{in}D_a}{n}$$  \hspace{1cm} (13)

where $n$ is the turn ratio of the transformer. In the steady state of discontinuous current mode (DCM), some of the minimum inductor current become zero. The average of the rectified output voltage is

$$V_o = \frac{(D_a - 0.08)^2 \frac{V_{in}}{n} + \frac{V_{in}}{n} L_{Af} I_o}{(D_a - 0.08)^2 \frac{V_{in}}{n} + 2 L_{Af} I_o}$$  \hspace{1cm} (14)

where $f_s$ is the switching frequency and $I_o$ is the output current.

The controller of the proposed TPTL dc–dc converter is shown in Figure 7B. It consists of a PID controller loop and three identical current PI controller loops. The voltage PI controller feeds the same compensated error voltage to the three current PI controllers, ensuring current balance among the three. Each current PI controller generates its own duty cycle. The principle of controlling power by DC side voltage is explained in the next section.

**B. DECENTRALIZED COORDINATION CONTROL STRATEGY**

The centralized control mode based on communication may make the system unsafe in communication failure, so this paper develops and designs a decentralized control architecture independent of communication, which can realize the electrolytic cell load to follow the output power of renewable energy, reduce the charge and discharge of energy storage and extend its service life.

1) GRID SUPPORTED ENERGY STORAGE SYSTEM WITH AUXILIARY CONTROL AND FLOATING AC VOLTAGE

There are many types of batteries and many factors that affect battery performance. To predict the performance of batteries, different mathematical models exist. None of them are completely accurate, nor do any include all necessary performance effecting factors. This method is a general approach, in which an ideal controlled voltage source, in series with a resistance, is used to model the battery [25].

The open circuit voltage of the general nonlinear equivalent model of the battery is based on the actual SOC of the battery, and its mathematical relationship is expressed as:

$$E = E_0 - K \frac{Q_{Bat}}{Q_{Bat} - \int idt} + A \exp \left( -B \int idt \right)$$  \hspace{1cm} (15)

The battery voltage is:

$$U_{Bat} = E - iR_{eq}$$  \hspace{1cm} (16)
The battery SOC value is usually expressed as a percentage, and its mathematical expression is:

\[
SOC = SOC_0 - \int \frac{i}{Q_{Bat}} dt \tag{17}
\]

Among them, \(R_{eq}\) is the equivalent internal resistance of the battery, and \(U_{Bat}\) is the output voltage of the battery. \(E\) is the no-load voltage of the battery.

The total power contribution to the medium voltage dc hydrogen production system from the battery stack can be given as

\[
P_b = i_B U_{Bat} (1 - K_{B-loss}). \tag{18}
\]

The topology and control structure of battery energy storage and its converter are shown in the Figure 8. On the basis of the voltage and current double closed-loop control of the conventional grid-supported inverter [26], [27].

The outer loop of the energy storage power supply has two functions of active power zeroing control and SOC recovery control. The specific implementation method is to make the AC bus voltage float, and the \(q\)-axis voltage reference value of the voltage outer loop floats within the range of the identity value [0.9, 1.1].

The function of active power zeroing control is to prevent the energy storage from receiving active power in a steady state. All the electric energy generated by renewable energy is absorbed by the electrolytic cell load. When the sensor detects active power output from the energy storage, the AC bus voltage will increase, and vice versa.

The function of SOC recovery is to keep the energy storage SOC in a reasonable range of charge and discharge, so that it has the ability of charge and discharge. When SOC is below the set value of 0.8, the AC bus voltage will decrease, and vice versa.

In order to avoid coupling of the control loop, it is necessary to design the bandwidth of the power outer loop reasonably, in which the control bandwidth of the active power regulating control loop is 0.5Hz. The bandwidth of the SOC recovery control outer loop is designed to be 0.1Hz. Active power zeroing control \(K_{p1}K_{i1}\) coefficient are 5 and 5; The \(K_{p2}K_{i2}\) coefficients of SOC recovery control link are 0.2 and 0.1. The PI controller mentioned above adopts integral Anti-WindUp PI controller [28]. In steady state, energy storage satisfies the following relationship

\[
P_{soc1} = (SOC_{ref} - SOC_1)(K_{p1} + \frac{K_{i1}}{s})
\]

\[
\Delta u = (P_{soc1} + P_{bi})(K_{p2} + \frac{K_{i2}}{s}) \tag{19}
\]

\[
P_{bi} = 0 \quad SOC_{bi} = 80\% \tag{20}
\]

2) DFIG BLACK START AND VIRTUAL INERTIAL CONTROL

The literature [29] proposed to use an independent diesel engine to black start DFIG, but the diesel engine does not have the ability to adjust the active power in both directions. To start an off-grid DFIG, an initial excitation voltage should be provided to the DFIG in absence of a main grid, there are usually two methods to use external storage or voltage source. One is to energize the collection lines of the wind farm and then establish the external voltage of DFIG. The other is to connect a DC source to the DC link between the two PWM converters of DFIG. The first method is chosen in this paper because energy storage also needs to provide voltage support for ac bus and buffer unbalanced power.

In order to reduce the cost of energy storage, the capacity of energy storage is optimized to 3MWh as mentioned above. The rated power of the energy storage converter is configured according to the discharge rate of 2C. The C-rate is a unit to declare a current value which is used for estimating or designating the expected effective time of battery under variable charge/discharge condition. The charge and discharge current of a battery is measured in C-rate. Under extreme conditions such as sudden change in wind speed, the unbalanced power between the source and the load will increase. The drastic change of the active power of the energy storage will cause the frequency of the energy storage converter to be unstable. Therefore, on the basis of the conventional control of the DFIG, an auxiliary virtual inertial control loop is added to reduce the sudden change of wind speed and enhance the stability of voltage and frequency under weak power grids.

The classical inertial control of DFIG is shown in Figure 5. The control system of DFIG includes two additional control loops: the frequency change rate \(df/dt\) loop and the droop \(\Delta f\) loop, where \(k_{df}\) and \(k_{df}\) represent the proportional and differential coefficient [30]. The active input of the DFIG rotor-side converter consists of the maximum power tracking active output and the active output of inertial control loops. The inertial control loop obtains the active output of the loop by measuring the system frequency and comparing it with the rated frequency [31].

\[
P_{ref} = P_{opt} + \Delta P
\]

\[
\Delta P = k_{df} \frac{df}{dt} + k_{df} \Delta f \tag{21}
\]
It can be seen from the above analysis that when the system frequency changes suddenly due to factors such as wind speed change or load switching, the additional inertial control loop can respond to the frequency change according to its measured frequency and rated frequency, and adjust the wind power by controlling the active signal input by the rotor-side converter. The active power that the unit injects or absorbs into the system, so the wind turbine can respond inertially when the system is disturbed.

The analysis of the influence of virtual inertia parameters on the system is not carried out here. Other forms of virtual inertia control can also be used for the control of doubly-fed wind turbines, all of which are effective for the weak grid supported by energy storage [32].

3) ACTIVE POWER FOLLOWING CONTROL
As mentioned above, AC voltage fluctuates with the active power and SOC of the storage port, so this paper proposes to realize AC voltage regulation through DC side voltage control of MVDC bus. Double closed loop control is shown in Figure 7B.

The rated DC bus voltage is determined by the parameters of the transformer and diode rectifier and the line impedance. The dc voltage is usually 1.35 times the RMS of the transformer interface voltage. Considering the system capacity, it is reasonable to select 4kV medium voltage DC in this paper. The selection of voltage range needs to be determined according to equipment cost and technology maturity.

According to the control strategy designed in (20), when the output power of renewable energy or energy storage SOC is greater than 0.8, there is residual power on the AC side. After the ac bus voltage rises through the transformer and diode rectifier, the dc bus voltage is higher than 4000V.

Under the action of the voltage loop, a positive power reference value will be generated. The electrolytic cell tracks the current instruction according to its dynamic characteristics. And vice versa. In this way, the system achieves power balance through complete local control.

The bandwidth of PID control should be 1/10 of the bandwidth of the current inner loop. The bandwidth of the current loop is designed to be consistent with the dynamic characteristics of the electrolytic cell. The proportional integral and differential parameters of the voltage loop are designed to 0.7,0.3,0.2 through the classical controller design method.

Under the control of the voltage of hydrogen production power supply, the absorbed power of the electrolytic cell can follow the change of the output of renewable energy, and the power difference between the power supply and the load will be made up by the energy storage. In addition, the role of the differential part in the voltage outer loop control is to use the load of the electrolytic cell as a kind of energy storage on the load side, which can provide a certain inertial support for the DC bus when the DC bus voltage fluctuates due to changes in the output of the renewable energy. In the whole working range, the power of the system satisfies the eqn (22).

\[
P_{b1} + P_{b2} + P_{DFIG} + P_{pv} = P_{elec} + P_{loss}
\]

\[
P_{DFIG} + P_{pv} = P_{elec} + P_{loss}(steady\ state)
\]

\[
Q_{b1} = Q_{T&RI},\ Q_{b2} = Q_{T&RR} \tag{22}
\]

where \(P_{elec}\) represents the absorbed power of the electrolyzer and \(P_{loss}\) represents the power loss. \(Q_{T&RI}\) represents the reactive power consumed by the transformer rectifier. \(P_{b1}\) and \(P_{b2}\) represents the output active power from energy storage.

To sum up, the distributed coordinated control strategy designed in this paper is summarized as shown in the Table 2.

| TABLE 2. Composition of distributed coordination control strategy. |
|-------------------------|------------------------|
| PV system               | MPPPT control          |
| DFIG system             | MPPPT control          |
| Battery energy storage  | Voltage and frequency control |
|                        | Active Power zeroing control |
|                        | SOC recovery control    |
|                        | Auxiliary black start control |
| TPTL phase-shifted dc converter | Current loop control |
|                        | Active Power following control |

FIGURE 9. Simulation model of renewable energy hydrogen production system built in PSCAD.
TABLE 3. Simulation and experimental parameters of the system.

| Parameters                  | Value          | Parameters                  | Value          |
|-----------------------------|----------------|-----------------------------|----------------|
| DFIG rated power            | 5MW*3          | $K_p$ of pitch angle controller | 150            |
| Cui in/out) speed           | 6.2/21.3 m/s   | $T_f$ of pitch angle controller | 25s            |
| Rated speed                 | 11m/s          | $K_p$ of power controller   | 4              |
| Rated voltage               | 0.69kV         | $T_f$ of power controller   | 0.1s           |
| Stator resistance           | 0.04pu         | $K_s$ of current controller | 0.0496         |
| Rotor resistance            | 0.01pu         | $T_i$ of current controller | 0.0128s        |
| $K_p$ of speed controller   | 1              | Inertia                     | 75kg · m²      |
| $T_i$ of speed controller   | 0.1s           | Capacity of single electrolyzer | 6MW           |
| Electrolyzer operating power range | ~15% – 100% | Power consumption production | 51 kWh/kg H2 |
| Hydrogen purity             | 99.9%          | Air pressure                | 3.2 MPa        |

FIGURE 10. (A) Wind speed. (B) DFIG power. (C) Electrolyzer power. (D) DFIG energy storage power. (E) Two sections of 35kV AC bus Voltage. (F) 4kV DC bus voltag.

suddenly drops from 8 m/s to 0 in 1.5s. The simulation results are shown in Figure 10.

From the simulation results, it can be seen that according to the given parameters, the MVDC network and the decentralized coordination control strategy proposed in this paper can realize the stable operation of 10MW hydrogen production power supply system. Especially in extreme cases such as high-power wind power fluctuation (even all wind power unloading), hydrogen production power can still track the fluctuation of wind and solar output, realize the normal networking operation of the system, and the AC and DC power supply quality can meet the system requirements.

A system model of energy-based hydrogen production is built on a power electronics real-time simulation platform based on FPGA. The built HIL control strategy verification environment is shown in the Figure 11.

The experimental platform includes a rapid control prototype controller (RCP) MT1050 (MT1050 adopts CPU and FPGA high-performance hardware architecture, which can realize Simlink model into control code) and a real-time simulation system MT6016 (MT6016 is based on FPGA and can simulate power electronics model with step size of 1 μs), which can verify the effectiveness of the control strategy. The
system includes a DFIG, lithium battery energy storage and its bidirectional converter, and a multi-pulse diode rectifier device based on a phase-shifting transformer. Hydrogen production power supply and electrolyzer load. Using the source-load-storage coordinated control algorithm proposed in this paper, the system can achieve stable operation. The experimental platform and simulation results are shown in the Figure 12.

Limited by power electronics modeling accuracy and simulation resources, in the HIL simulation environment, a DC hydrogen production system with 50kW DFIG and 20kW PV module and 20kW energy storage is built. The RMS of the ac side phase voltage is 225V, the dc voltage is rated at 533V through an uncontrolled rectifier.

The designed operating conditions are as follows: DFIG is started at a wind speed of 9 m/s, the Sunshine of PV model is 500 W/m². The initial SOC values of photovoltaic and fan energy storage are 79% and 78%. At 5 s, the Sunshine of PV model is changed to 1000 W/m². At 10 s, the Wind speed of DFIG is changed to 5 m/s in 4 s.

It can be seen from the Figure 12A and B that, on the one hand, the electrolytic cell can track the power changes of PV and DFIG, and the effect of power following is satisfactory. On the other hand, the SOC of energy storage can fluctuate around the set point of 80. After reaching the quasi-steady state, the energy storage SOC basically do not change, and the energy storage output power is basically 0. Active power zeroing control and SOC recovery control are realized.

During 0-4s, the energy storage is in the SOC recovery control stage, and all PV power is used for energy storage, while DFIG power is larger and part of it is used for energy storage SOC recovery. After the SOC recovery control is completed, the energy storage active power decreases to nearly zero, and the electrolytic cell power follows the total power of PV and DFIG.

In order to verify the stable operation of the system under real environmental data, wind speed and irradiation as well as temperature data of the project site for one year were selected for simulation. It is worth noting that the real time of a year is compressed to 24 seconds in order to reduce the simulation time. The results of the simulation experiment are shown in the Figure 13.

The simulation results show that the designed control strategy can achieve the energy balance of “Source-Load-Storage”, the load power can follow the total RES power in real time, the energy storage SOC does not fluctuate much during the whole simulation process, and the charging and discharging are relatively smooth.

In order to verify the frequency domain characteristics of power response of electrolytic cell load under decentralized control strategy when wind speed and photovoltaic illumination change, small signal disturbance is added for frequency domain scanning, and the transfer functions of two channels of the system are obtained as shown in the Figure 14.

It can be seen from the frequency sweep and the estimated transfer function that both channels have high gain in low
frequency band. And the phase is also in the range of 0 to -90 degree. The power consumed by the load can realize the seconds level tracking of the output power of RES. The power fluctuation of RES can be well fed back to the load side to maximize the utilization of active power.

VI. CONCLUSION

Aiming at the problem of network structure and system control strategy design of hydrogen production in island power system, a MVDC topology structure was proposed. The paper also investigates the hydrogen production system in terms of capacity planning of energy storage and decentralized coordination control strategy. The simulation and experiment results show that the proposed control strategy has the following advantages:

1. The study shows that for megawatt-scale off-grid hydrogen production systems, MVDC-type grid structures have the advantages of scalability and stability compared to traditional AC hydrogen production systems. For a 20 MW renewable energy hydrogen system, a minimum of 3 MWh of energy storage capacity is required under specific location and economic constraints.

2. Compared with the traditional centralized control strategy, the decentralized coordinated control strategy designed in this paper has the advantages of being communication-independent and highly reliable. The energy storage active power zeroing controller and SOC recovery controller can ensure that the energy storage does not bear active power in the steady state and keep SOC at the set value to avoid overcharge and overdischarge.

3. By controlling the MVDC bus voltage on the load side, the matching of renewable energy and load power can be realized, and the load power can track the power fluctuation of renewable energy, which improves energy utilization efficiency. Studies in the frequency domain have shown that load power can be achieved with seconds-level tracking of renewable energy power.

At present, we have only completed the hardware-in-the-loop test of the controller in the laboratory environment. Next, we will study the influence of control parameters on the dynamic performance of the system and the stability analysis of the system under large disturbance conditions in conjunction with engineering practice.

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