Integration Control of Renewable Energy/Hydrogen Energy System Based on Flexible DC Interconnection

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Abstract. Wind/solar complementary for hydrogen production and hydrogen energy utilization have become one of the important directions for clean energy transformation and new economic growth point. This paper proposes a renewable energy/hydrogen energy system based on flexible DC interconnection and its coordinated control technology covering AC/DC voltage source converters and photovoltaic units, DC hydrogen production loads and energy storage devices. First, the typical structure of the renewable energy/hydrogen energy system with low-voltage flexible DC interconnection is proposed, and the local control strategy of each unit is analysed, including the constant DC voltage control strategy and the constant active power control strategy. Then, coordinated control methods of renewable energy/hydrogen energy under different system operation states are proposed. Finally, a corresponding system simulation model and test platform are built, and then used to simulate and verify the proposed coordinated control method.

1. Introduction

“Clean energy consumption action plan” issued by National Development and Reform Commission, National Energy Administration of China in 2018 pointed out the importance of exploring the conversion of surplus electricity generated by renewable energy into hydrogen energy and the realization of high efficient usage of renewable energy by multiple approaches. In 2019, the hydrogen energy industry was first included in the "Government Work Report" of the State Council of China. The development of hydrogen fuel vehicles is expected to bring 10 million tons of hydrogen demand and drive trillions of hydrogen energy output value. In alpine regions with abundant solar and wind energy resources, hydrogen fuel vehicles and hydrogen-powered public transportation have the advantages of long mileage endurance and good adaptation to low-temperature environments [1, 2], thus have gradually become important carriers and development trends for green transportation in cities in alpine regions. The use of large-scale hydrogen production can improve the full consumption of renewable energy and reduce wind and solar waste [3]. Wind/solar complementary for hydrogen production and hydrogen energy utilization have become one of the important directions for clean energy transformation and new economic growth points. The State Energy Investment Group, State Grid Corporation of China and other institutions have carried out a series of research and
demonstrations. Hebei Construction & Investment Group has developed China's first wind power hydrogen production industrial application project in Zhangjiakou-Guyuan 10MW wind power [4]. The related achievements cover diversified key technologies such as centralized and distributed method of hydrogen production.

The current wind/solar complementary system for hydrogen production usually adopts the renewable energy AC access method [5]. This scheme has a large number of unnecessary power electronic conversion links, which reduces the system operating efficiency and reliability, and has high control complexity. In recent years, related scientific research institutions around the world have proposed AC-DC hybrid micro-grid technology [6, 7] and multi-terminal DC system [8]. Moreover, coordinated control methods such as master-slave control and voltage droop control have been proposed accordingly [9, 10], which can effectively reduce the AC/DC conversion links, and complete the integration of renewable energy/hydrogen energy by means of flexible DC interconnection between renewable energy and hydrogen energy.

In the renewable energy/hydrogen energy integrated system based on flexible DC interconnection, there are AC/DC voltage source converters (VSCs) that undertake the power flow control between the DC network and the AC system, as well as multiple DC/DC converters for photovoltaic (PV) unit, energy storage device and DC hydrogen production load in the DC network. Generally speaking, there is relatively few research concerning coordinated control methods that overall consider the VSCs together with DC/DC converters. Based on this, this paper focuses on the renewable energy/hydrogen energy system based on flexible DC interconnection and studies the coordinated control strategy among VSCs, PV, DC hydrogen production load, and energy storage device under the master-slave control mode, which promotes the full consumption of renewable energy and realizes the stable hydrogen production.

2. System description

A typical structure of the renewable energy/hydrogen energy integrated system based on flexible DC interconnection is shown in Fig.1.

![Figure 1. The typical integrated system structure based on flexible DC interconnection.](image)

In Fig.1, the AC system feeders are flexibly interconnected through VSC1 and VSC2, the AC-side of each VSC is connected to the AC feeder, and the DC-side of each VSC is connected to the DC bus through DC line. Renewable energy such as PV, energy storage system (ESS), and DC hydrogen production load can be integrated in the DC network. When their respective working voltage is inconsistent with the DC bus voltage, DC/DC converter can be configured for voltage adaptation. DC hydrogen production load usually uses electrolysis to produce hydrogen, which includes types like alkaline electrolysis (AE), proton exchange membrane (PEM) electrolysis and so on. AE uses NaOH or KOH as electrolyte and mainly uses Ni-based catalysts. AE has advantages like simple structure and low price, but the hydrogen production speed cannot be quickly adjusted. The biggest structure difference between PEM and AE is that the former one possesses the membrane electrode formed by gas diffusion layer and the catalyst-coated membrane, and its gas cross-diffusion is small, the transmission speed of protons on the membrane electrode is faster than that in the electrolyte.
Therefore, its response speed to the load change is relatively fast, which makes PEM very suitable for renewable energy applications with large power fluctuations. Its structure is shown in Fig. 2.

![Figure 2. Schematic diagram of PEM.](image)

3. Control strategy

3.1 VSC

The typical VSC power circuit and control strategy are shown in Fig. 3. Where, $V_a$, $V_b$, and $V_c$ are respectively the grid-connected point voltages of phase A, B, and C. $I_a$, $I_b$, and $I_c$ are grid-connected currents of phase A, B, and C respectively. $L$ and $R$ are grid-connected equivalent inductance and equivalent resistance respectively. $V_{oa}$, $V_{ob}$, and $V_{oc}$ are bridge-arm voltages for phase A, B, and C respectively. $V_{dc}$ is the DC-side voltage. $I_d$ and $I_q$ are the d-axis and q-axis components of $I_a$, $I_b$, and $I_c$. $V_{od,ref}$ and $V_{oq,ref}$ are the d-axis and q-axis reference values of $V_{oa}$, $V_{ob}$, and $V_{oc}$ respectively.

![Figure 3. Power circuit and control strategy of VSC.](image)
1) Constant active power control strategy (P control strategy): VSC accepts active power dispatching, and the difference between the actual value of VSC active power $P$ and the reference value $P_{\text{ref}}$ generates the grid-connected current d-axis component reference value $I_{d,\text{ref}}$ for the inner current loop through the PI controller. Since the renewable energy/hydrogen energy system based on flexible DC interconnection usually delivers active power, the reference value of the grid-connected current q-axis component $I_{q,\text{ref}}$ is set to 0. On the basis of this, the tracking response to the power reference value is achieved through the inner current loop control.

2) Constant DC voltage control strategy (Vdc control strategy): the DC-side voltage of VSC is controlled to keep the stability of the DC network. The difference between the DC-side voltage reference value $V_{\text{dc,ref}}$ and $V_{\text{dc}}$ generates the $I_{d,\text{ref}}$ for the inner current loop through the PI controller ($I_{q,\text{ref}}$ is usually given as 0). Based on this, the constant DC-side voltage is realized by the inner current loop control.

After receiving $I_{d,\text{ref}}$ and $I_{q,\text{ref}}$, the VSC inner current loop will take the difference between $I_d$ and $I_{d,\text{ref}}$, the difference between $I_q$ and $I_{q,\text{ref}}$ by PI controller together with the feed-forward grid voltage to generate d-axis and q-axis component reference values of $V_{oa}$, $V_{ob}$ and $V_{oc}$, and further to generate the PWM signals through dq/abc conversion link.

![Figure 4. Power circuit and control strategy of DC/DC converter.](image)

### 3.2 DC/DC converter

The DC/DC converter is one of the important equipment in the DC network. PV unit, DC hydrogen production loads, and ESS are usually equipped with the corresponding DC/DC converter. Typical power circuit and control strategies are shown in Fig. 4. Where, $V_e$ is the DC voltage on the equipment side of the DC/DC converter, and $I_{dc}$ is the DC current. $g1$ and $g2$ are the drive signals of the power electronic switching devices of the DC/DC converter. Renewable energy such as PV units can adopt maximum power point tracking (MPPT) control strategy. $V_e$ and $I_{dc}$ can be used as the DC output voltage and DC output current of PV. The $V_{e,\text{ref}}$ under MPPT control strategy can be obtained by the disturbance observation method. The difference between $V_e$ and $V_{e,\text{ref}}$ can generate the corresponding duty cycle through PI controller, for DC/DC converter to realize the MPPT function.

DC hydrogen production load usually works in constant DC power control strategy ($P_{dc}$ control strategy). The difference between the DC power reference value $P_{dc,\text{ref}}$ and the actual DC power $P_{dc}$ is
used to generate the DC current reference value $I_{dc,ref}$ for the inner current loop, through the PI controller. The difference between $I_{dc,ref}$ and $I_{dc}$ is used to obtain the corresponding duty cycle by the PI controller, to realize the constant DC power control function.

When ESS provides the network power supply function, it can operate in constant DC voltage control strategy (constant $V_{dc}$ control strategy), and the difference between the DC-side voltage reference value $V_{dc,ref}$ and $V_{dc}$ is used to generate the DC current reference value $I_{dc,ref}$ for the inner current loop by the PI controller. On the basis of this, the corresponding duty cycle is calculated from the PI controller based on the difference between $I_{dc,ref}$ and $I_{dc}$. Then the DC/DC converter is controlled to establish and stabilize the DC-side voltage.

3.3 The coordinate control method under different system states

The renewable energy/hydrogen energy system based on flexible DC interconnection relies on the coordinated control of internal VSCs, PV units, DC hydrogen production load, and ESS. At the same time, the multi-terminal interconnection of VSC and DC/DC converters also provides flexible control methods for the system, enabling the system to have a variety of operating states, including grid-connected operating state, autonomous operating state, and operating states switching.

1) Grid-connected operating state: each VSC is interconnected to the AC system for grid-connected operation. One of the VSCs is used as the master station and adopts $V_{dc}$ control strategy to provide the constant DC voltage for the DC network. The other VSCs are used as slave stations with $P$ control strategy, and accept the power dispatching. This enables the AC system to carry out a bidirectional power flow transfer with the DC network, so that the mutual balance of power flows between different AC systems can also be realized through the DC network. In the grid-connected operating state, PV unit adopts the MPPT control strategy, and ESS can adopt the $P_{dc}$ control strategy to accept energy dispatching or be in the standby state. The DC hydrogen production load adopts the $P_{dc}$ control strategy. When PV unit or DC hydrogen production load encounters power fluctuations, or when the slave station VSCs adjust their output power, the master station VSC automatically balances the power flow of the DC network.

2) Operating states switching: In the event of failure, emergency, etc., the AC system cannot be normally interconnected with the DC network, and each VSC stops working. At this time, the DC network will operate independently. ESS needs to switch to the constant $V_{dc}$ control strategy, to maintain the constant DC voltage and ensure the normal operation of hydrogen production. Meanwhile, the power shortage after the VSCs exit operation will be automatically compensated by ESS.

3) Autonomous operating state: When the DC network has no electrical connection with each AC system, the DC network operates autonomously. At this time, ESS provides the network power supply, and uses the constant $V_{dc}$ control strategy to keep the stability of the DC network. PV unit adopts the MPPT control strategy, and DC hydrogen production load works in the $P_{dc}$ control strategy. When the power of PV unit and DC hydrogen production load fluctuates, ESS automatically balances the power flow of the DC network. When PV unit output power is relatively large and DC hydrogen production load is relatively small, ESS will be charged. When PV unit output power is relatively small and DC hydrogen production load is relatively large, ESS will be discharged. The higher the energy storage capacity of ESS is, the longer the autonomous operating state can be maintained.

4. Simulation analysis

A simulation model of renewable energy/hydrogen energy system as shown in Fig.1 is built using Matlab/Simulink, where the rated power of VSC1 is 150 kW, the rated power of VSC2 is 100 kW. The renewable energy uses PV unit with a rated power of 80 kW, and DC hydrogen production load fluctuates within 100 kW. The rated power of ESS is 50 kW. The frequency of the three phases AC system is 50 Hz and its rated voltage is 380 V. The rated DC voltage is 750V. In the initial state of the simulation, the system is in the grid-connected operating state (the direction of power flowing into the DC bus is considered as the positive direction).
4.1. Grid-connected operating state
After starting the simulation, VSC1 adopts the $V_{dc}$ control strategy to provide 750V DC voltage. VSC2 adopts the $P$ control strategy, which outputs 50 kW from the AC system to the DC network. The output power of PV unit is 40 kW, and DC hydrogen production load is 65 kW. ESS is in the hot standby state.

At $t=5$s, the output power of VSC2 increases to 80 kW. At $t=6$s, the output power of PV unit increases and at $t=8$s, DC hydrogen production load decreases. The corresponding simulation results are shown in Fig. 5. From the simulation results, it can be seen that the DC bus voltage changes slightly in the cases when VSC2 power dispatching command changes, or when the power of DC hydrogen production load and PV unit fluctuates. The DC bus voltage can be quickly stabilized, always within 0.99 p.u and 1.01 p.u.

VSC1 can automatically balance the power flow of the DC network, and its power follows the changes of VSC2, DC hydrogen production load and PV unit. When power of VSC2, DC hydrogen production load or PV unit changes, the influence between each other is small, which ensures the normal operation of the system.

![Figure 5](image)

**Figure 5.** The simulation results under grid-connected operating state (a) VSC1 power; (b) VSC2 power; (c) PV power; (d) DC hydrogen production load; (e) DC bus voltage.

4.2. Operating states switching
AC system fault occurs at $t=10$s, then VSC1 and VSC2 all stop working, and the system will switch its operating state. The corresponding simulation results are shown in Fig. 6. When $t=10$ s, the power of VSC1 and power of VSC2 quickly drop to 0. At this time, ESS starts the constant $V_{dc}$ control strategy in order to maintain the stability of the DC network. It can be seen from the simulation results that the
DC bus voltage has a short-term oscillation during the operating states switching process, but its variation range remains within -0.15 p.u and 0.15 p.u, and its steady state is restored within 0.1s, which guarantees the normal operation of DC hydrogen production load and PV unit. During the process of the operating states switching, power of DC hydrogen production load and PV unit has no significant fluctuation.

At the same time, after the operating state is switched, ESS automatically balances the power flow of the DC network, and the power shortage after VSC1 and VSC2 exit working is automatically compensated by it.

![Graphs showing simulation results under operating states switching](image)

**Figure 6.** The simulation results under operating states switching (a) VSC1 power; (b) VSC2 power; (c) PV power; (d) DC hydrogen production load; (e) ESS power; (f) DC bus voltage.

### 4.3. Autonomous operating state

When the system is in autonomous operating state, the output power of PV unit is set to increase at t=11 s and to decrease at t=12 s. DC hydrogen production load is set to increase at t=13s and to decrease at t=14s. The simulation results are shown in Fig. 7. During autonomous operating state, ESS automatically balances the power flow of the DC network. When the power of DC hydrogen production load and PV unit fluctuates, the corresponding power shortage is automatically compensated by ESS. It can be seen from the simulation results that ESS adopts the constant $V_{dc}$ control strategy. When DC hydrogen production load changes or PV unit power fluctuates, the DC bus voltage always remains within 0.98 p.u and 1.02 p.u.

At the same time, when DC hydrogen production load changes or PV unit power fluctuates, their mutual influence is small, and the power can quickly enter into steady state which ensures the normal operation of DC hydrogen production load and PV unit.
Figure 7. The simulation results under autonomous operating state (a) PV power; (b) DC hydrogen production load; (c) ESS power; (d) DC bus voltage.

5. Experimental test
In order to verify the effectiveness of the method proposed in this paper, a renewable energy/hydrogen energy system test platform was built. The test platform includes VSCs, DC line simulator, network topology configuration cabinet and DC sources/load. Among them, VSCs can operate under the master-slave control mode, the specific control strategy is shown in Fig. 3. DC sources can be PV unit, and DC load can be DC hydrogen production load. Test platform forms a multi-terminal DC system structure as shown in Fig.1, and the specific parameters are shown in "4 Simulation analysis".

Fig. 8 depicts the test results when DC hydrogen production load changes in autonomous operating state. Channel 1 represents the DC bus voltage, and channel 2 represents the DC current of DC hydrogen production load. It can be seen that the DC bus voltage remains stable during the whole load change process. The DC bus voltage is controlled near 750V, and the maximum fluctuation does not exceed 30V, which can guarantee normal operation of the system.

Figure 8. Experimental results when 0→50% $P_{\text{rated}}$→0.
6. Conclusion
Aiming at the renewable energy/hydrogen energy integrated system based on flexible DC interconnection, this paper establishes local control strategies for AC/DC voltage source converters and DC/DC converters for PV unit, DC hydrogen production load, and ESS. For the different system states such as grid-connected operating state, operating states switching, and autonomous operating state, a coordinate control method of renewable energy/hydrogen energy is proposed, to guarantee the normal hydrogen production under complicated conditions such as AC system failure, operating states switching, and DC network power fluctuations.

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7. References
[1] K. Tomoda, N. Hoshi, J. Haruna, M. Cao, A. Yoshizaki, and K. Hirata. "Hydrolysis rate improvement in hydrogen generation system fueled by powdery sodium borohydride for fuel-cell vehicle." IEEE Transactions on Industry Applications 50.4 (2014): 2741-2748.

[2] G. Cai, and L. Kong. "Techno-economic analysis of wind curtailment/hydrogen production/fuel cell vehicle system with high wind penetration in China." CSEE Journal of Power and Energy Systems 3.1 (2017): 44-52.

[3] Shao Zhifang, and Wu Jilan. "Capacity configuration optimization of hydrogen production from wind and PV power based on dynamic electricity price." Acta Energiae Solaris Sinica 41.8 (2020): 227-235.

[4] Luo Chengxian. "Present status of power-to-hydrogen technology worldwide using renewable energy." SINO-GLOBAL ENERGY 22.8 (2017): 25-32.

[5] Huang Dawei, Qi Deqing, and Yu Na. "Capacity allocation method of hydrogen production system consuming abandoned wind power." Acta Energiae Solaris Sinica 38.6 (2017): 1517-1525.

[6] M. Manbachi, and M. Ordonez. "Intelligent agent-based energy management system for islanded AC–DC microgrids." IEEE Transactions on Industrial Informatics 16.7 (2020): 4603-4614.

[7] M. Davari, and A. R. I. Mohamed. "Robust multi-objective control of VSC-based DC-voltage power port in hybrid AC/DC multi-terminal micro-grids." IEEE Transactions on Smart Grid 4.3 (2013): 1597-1612.

[8] W. Wang, M. Barnes, and O. Marjanovic. "Stability limitation and analytical evaluation of voltage droop controllers for VSC MTDC." CSEE Journal of Power and Energy Systems 4.2 (2018): 238-249.

[9] W. Deng, W. Pei, N. Li, X. Zhang, Y. Yi, and L. Kong. "Research on operation control of low-voltage MTDC system in a cyber-physical environment." CSEE Journal of Power and Energy Systems doi: 10.17775/CSEEJPES.2020.04240.

[10] D. Tiomo, and R. Wamkeue. "Dynamic modeling and simulation of a hybrid AC-DC microgrid with primary droop control." in IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), Edmonton, AB, Canada.