Study on Stability of Hand-in-hand Structure of Multi-terminal DC Hydrogen Production System

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Abstract. Multi-terminal DC (MTDC) hydrogen production systems are becoming one of the important forms of power distribution systems with the increasing growth of distributed renewable energy sources (such as PV and wind turbines), energy storage devices, and DC loads. To explore the key factors in stability analysis, the circuit diagram of MTDC hydrogen production system in hand-in-hand structure composed of voltage source converters (VSCs), DC lines, renewable energy and DC hydrogen production load was established in this paper. The overall state space model of the system was put forward, taking the master-slave converter control strategy into consideration. Then, the small-signal stability analysis of the MTDC hydrogen production system was carried out by comparing and analyzing the moving trajectories of the dominant eigenvalues in different system parameters. The key factor affecting the stability of the system such as DC capacitance of the converter and the electrolyzer power in the DC bus are determined. On this basis, a simulation model of the low-voltage MTDC hydrogen production system was built based on MATLAB/Simulink to verify the correctness of the theoretical analysis.

1. Introduction
With the massive access of renewable energy, multi-terminal DC (MTDC) power distribution system has been becoming one of the important networking forms for the power distribution system [1]. The MTDC structure provides an efficient approach to improve the comprehensive utilization efficiency of renewable energy by reducing conversion link of power electronics [2]. The problem of wind and solar power generation and consumption could be solved with rational configuration of wind/PV/hydrogen in a small power system. Furthermore, the increasing production of green hydrogen could support the energy sustainable development [3].

The traditional hydrogen production method is steam reforming of fossil, while producing a huge amount of CO₂, which is not conducive to achieving the goal of carbon neutrality. DC hydrogen production is a more feasible and green way to achieve large-scale hydrogen production without CO₂ emissions [4]. The form of DC coupling hydrogen production is that the DC bus and the electrolytic cell are coupled through a DC/DC converter. The structure of the DC hydrogen production system is also more diverse, mainly divided into radiation, star, grid and hand-in-hand structure [5]. The hand-in-hand structure is a double-ended power supply mode which is widely used in today's urban distribution network. The hand-in-hand structure is more reliable and flexible than the radial structure.
powered by a single-ended power supply. High-quality power could be provided to special users in this structure [6]. Meanwhile, the small disturbance stability of the MTDC hydrogen production system is also one of the research hotspots. The control methods could be droop control and master-slave control [7]. The hydrogen production system generally selects master-slave control to directly control the DC bus voltage [8].

This paper proposed a state space model of MTDC hydrogen production system with a hand-in-hand structure. Then, small-signal stability analysis was conducted. By drawing the movement trajectory of the dominant eigenvalues, the relationship between dominant eigenvalues and different key system parameters was analyzed. Finally, a simulation model was built to verify the correctness of the theoretical analysis.

2. MTDC Hydrogen Production System Model

The stable operation of MTDC hydrogen production system after disturbance relies on the flexible and coordinated control of the converter station accessed renewable energy. Due to its multi-terminal interconnection feature, the MTDC hydrogen production system can supply power to multiple hydrogen production electrolyzers at the same time, which effectively increases the hydrogen production output. The structure of a DC multi-terminal DC hydrogen production system is shown in figure 1. Where, the AC voltage of the gridVs passes through a Voltage-Source Converter (VSC), VSCm is connected to the DC network, and energy storage unit, renewable energy (like PV and wind power), and DC hydrogen production load are connected to the DC bus. In terms of control, the DC hydrogen production system shown in figure 1 adopts a master-slave control mode, that is, the master station VSCm adopts a constant DC voltage control mode, and three hydrogen production electrolyzers are connected to the VSC side and the DC side respectively.

![Diagram of MTDC Hydrogen Production System](image)

**Figure 1.** Multi-terminal DC hydrogen production system structure

In figure 1, \( r_i \) and \( L_i \) represent the resistance and reactance of the \( i \)-th DC link of the system, respectively. \( C_i \) and \( C_{dc} \) represent the DC capacitance of DC/DC converter accessed the \( i \)-th each electrolyzer and DC capacitance of the DC bus, respectively. \( P_{0} \), \( P_{1} \) and \( P_{2} \) represent the hydrogen production power of each electrolyzer respectively. \( P_{load} \), \( P_{beess} \) and \( P_{DG} \) represent energy storage power, DC load power, and renewable energy power, respectively. The equivalent power is \( P_{eq} \), which is calculated by \( P_{eq}=P_{load}+P_{beess}-|P_{DG}| \).

2.1. Modeling of Constant DC Voltage Station

When the system selects master-slave control, the master station VSCm adopts constant DC voltage control, which aims to maintain the DC voltage stable in the entire DC system. This control mode
Figure 2. Control strategy diagram of constant DC voltage station.

Combining linearization of controller equation, the mathematical model of the VSC station of the constant DC voltage can be obtained in (1):

$$\frac{d\Delta X_m}{dt} = A_m\Delta X_m$$

Where, $X_m$ is the state variable in the converter model of the constant DC voltage station, $A_m$ is system matrix of the converter module of the constant DC voltage station. Among of $A_m$, $L_s$ is the filter inductor, and $R_s$ is the equivalent resistance of constant DC voltage station. The expression of the $A_m$ is as follows:

$$A_m = 
\begin{bmatrix}
-k_{pq}k_{q}I_{pq}d_0 & -k_{pq}k_{q}I_{pq}d_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_{pq}k_{q}I_{pq}d_0 & -k_{pq}k_{q}I_{pq}d_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{L_s}(k_{pq}k_{q}I_{pq}d_0) & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
k_{pq}k_{q}I_{pq}d_0 & k_{pq}k_{q}I_{pq}d_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & k_{pq}k_{q}I_{pq}d_0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}$$

2.2. Network Modeling

In the low-voltage MTDC hydrogen production system, renewable energy, DC hydrogen production load and energy storage unit play an important role in the power balance and voltage regulation of the system. When each slave station absorbs power from the DC network in a constant power mode, both the renewable energy and DC hydrogen production load are equivalent to a constant power load (CPL). The mathematical model can be expressed as:

$$C_{dc} \frac{d\Delta U_{dc}}{dt} = \frac{P_{bess} + P_{load} - P_{DG} + P_0}{U_{dc}^2} \Delta U_{dc}$$

$$-\frac{\Delta P_{bess} + \Delta P_{load} - \Delta P_{DG} + \Delta P_0}{U_{dc}}$$

$$+\Delta i_{dcm} - \Delta i_{dc1}$$

2.3. State Space Model of the System

Combining the mathematical models of inverter, DC line, renewable energy and DC hydrogen production load above, the small signal model of the system can be obtained in (4).
\[
\begin{bmatrix}
\frac{d\Delta X}{dt}
\end{bmatrix} = A\begin{bmatrix}
\Delta X
\end{bmatrix}
\]  

Where, the state variable \(\Delta X = [\Delta X_m, \Delta U_{dc1}, \Delta U_{dc2}, \Delta U_{dc}, \Delta i_{dcm}, \Delta i_{dc1}, \Delta i_{dc2}]^T\), the system matrix \(A\) is a 13th order square matrix.

3. Theoretical Analysis

The parameters of the multi-terminal DC hydrogen production system are shown in Table 1. The rated voltage of the main station VSCm DC side is 800 V, the PI parameters of the inner loop are 22.56 and 6, and the PI parameters of the outer loop are 30 and 1500. It is assumed that the power consumption of the VSC side electrolyzer, electrolyzer No.1 and No.2 are 70 kW, 180 kW and 200 kW respectively. The frequency of the three-phase AC system is 50 Hz, the rated voltage is 380 V, and the rated capacity of the renewable energy unit is 20 kW.

Table 1. Multi-terminal DC hydrogen production system parameters

| Symbol      | Value         | Symbol      | Value         |
|-------------|---------------|-------------|---------------|
| \(R_s\)    | 0.00015\(\Omega\) | \(L_s\)    | 0.0008H       |
| Line Resistors | 0.033\(\Omega/km\) | Line inductors | 0.433mH/km   |
| \(U_{dc\text{mref}}\) | 800V      | \(C_m\)    | 3500\(\mu F\) |
| Line m/1/2 | 0.4km        | \(C_1\)    | 1000\(\mu F\) |
| \(P_{\text{load}}\) | -80kW      | \(C_2\)    | 1000\(\mu F\) |
| \(P_{\text{bess}}\) | -70kW      | \(C_{dc}\) | 1000\(\mu F\) |
| \(P_{DG}\) | 20kW        |             |               |
| \(P_1\)    | -180kW       | \(P_0\)    | -70kW         |
| \(P_2\)    | -200kW       |             |               |

Theoretical trajectory

\(\text{Figure 3. Eigenvalue trajectory}(C_{dc}\text{ from }1000\mu F \text{ to }1300\mu F)\)

\(\text{Figure 4. Eigenvalue trajectory}(P_0\text{ from }70kW \text{ to }120kW)\)
The small disturbance stability of the DC hydrogen production system is analyzed using the eigenvalue analysis method. The system matrix in equation (4) is solved by eigenvalue analysis, and if the eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$ are all negative in the real part, the system is asymptotically stable. If the real part of the eigenvalues has positive values, the system is judged to be unstable. According to the participation factors between the eigenvalues and each state variable, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, $\lambda_5$ and $\lambda_6$ are identified as the dominant eigenvalues representing the dominant modes of the system.

Figure 3 depicts the trajectory of the dominant eigenvalues when the DC bus equivalent capacitance $C_{dc}$ gradually increases from 1000$\mu$F to 1300$\mu$F. As can be seen from figure 3, except $\lambda_5$ and $\lambda_6$, the rest of dominant eigenvalues move to the left half-plane and the stability margin of the system increases. Therefore, as the $C_{dc}$ increases, the stability margin of the system accordingly for the same hydrogen production load, will increases which also means that the maximum capacity of hydrogen production load in the system can be further increased.

Figure 4 depicts the trajectory of the dominant eigenvalues when the power of VSC side DC bus electrolyzer increases from 70kW to 120kW. As can be seen from figure 4, the DC bus electrolyzer power on the VSC side has a great influence on the system stability, and as the power increases, except $\lambda_5$ and $\lambda_6$, the rest of dominant eigenvalues move rapidly to the right half-plane and the system stability margin decreases. It indicates that the stability of the DC hydrogen production system is negatively correlated when the hydrogen production increases.

Figure 5. Eigenvalue trajectory ($P_1$ from 180kW to 230kW)  
Figure 6. Eigenvalue trajectory ($P_2$ from 200kW to 250kW)

Figure 5 depicts the trajectory of the dominant eigenvalues when the power of No.1 electrolyzer increases from 180kW to 230kW. As can be seen from figure 5, the dominant eigenvalues, especially $\lambda_5$ and $\lambda_6$, move rapidly to the right half-plane and as the power increases, the system stability margin decreases.

Figure 6 depicts the trajectory of the dominant eigenvalues when the power of No.2 electrolyzer increases from 200kW to 250kW at the $C_{dc}$ of 1300$\mu$F. As can be seen in figure 6, the dominant eigenvalues, especially $\lambda_5$ and $\lambda_6$, move to the right half-plane as the power increases and the system stability margin decreases. Compared with figure 5, it can be seen that the stability margin of the No.2 electrolyzer is greater when increasing 50 kW at the same time, indicating that increasing the DC bus capacitance on the VSC side can improve the hydrogen production of the electrolyzer.

4. Simulation Verification
In order to verify the potential of using a multi-terminal DC hydrogen production system to enhance the production of hydrogen from renewable energy sources, this paper verifies the results of the above analysis by building a simulation model in MATLAB/Simulink based on the parameters of a low-voltage multi-terminal DC hydrogen production system. The following figure shows the simulation waveforms of the corresponding DC bus voltage and DC side port power of the constant DC voltage station.
Figure 7 depicts the simulation results when the DC bus equivalent capacitance $C_{dc}$ is increased from 1000μF to 1300μF. From figure 7, it can be seen that both the DC bus voltage and the DC side port power curve become smoother when $C_{dc}$ is increased to 1300μF, and the stability of the DC hydrogen production system is improved, which is consistent with the improved stability margin of the system reflected in figure 3.

![Graphs showing DC bus voltage and DC side port power](image)

(a) DC bus voltage ($C_{dc}$=1000μF)  (b) DC side port power ($C_{dc}$=1000μF)  
(c) DC bus voltage ($C_{dc}$=1300μF)  (d) DC side port power ($C_{dc}$=1300μF)

**Figure 7. Simulation results when DC bus equivalent capacitance increases.**

Figure 8 depicts the simulation results when the DC bus electrolyzer power on the VSC side is increased from 70 kW to 120 kW and $C_{dc}$ = 1000μF. As can be seen from figure 8, the DC bus voltage always remains stable with the increase of $P_0$, which does not affect the system operation. It can be seen from figure 4 that there is still a large stability margin at $C_{dc}$=1000μF with $P_0$ of 120kW, so the maximum capacity of the hydrogen production load is larger than 120kW. Therefore, when $P_0$ reaches 120kW in figure 8, the system still has a large stability margin and no instability occurs. The results shown in figure 8 are consistent with the intrinsic mechanism revealed in figure 3 and figure 4.

![Graphs showing DC bus voltage and DC side port power](image)

(a) DC bus voltage  (b) DC side port power

**Figure 8. Simulation results when VSC side DC bus electrolyzer power increases.**

Figure 9 depicts the simulation results when the power of No.1 electrolyzer is increased from 180kW to 230kW with $C_{dc}$ =1000μF. It can be seen from the figure 9 that the DC bus voltage can remain stable when $P_1$ is increased without affecting the normal operation of the existing system when $P_1$ reaches 230kW. This phenomenon is consistent with the results shown in figure 5.

![Graphs showing DC bus voltage and DC side port power](image)

(a) DC bus voltage  (b) DC side port power

**Figure 9. Simulation results when No.1 electrolyzer power increases.**
Figure 9. Simulation results when No.1 electrolyzer power increases.

Figure 10 depicts the simulation results for increasing the power of No.2 electrolyzer from 200kW to 250kW with $C_{dc}=1300\mu F$. From the figure 10, it can be seen that the DC bus voltage can be kept stable when $P_2$ increases up to 250kW, and compared to Fig 9, the DC bus voltage is smoother and the system stability is improved. This phenomenon is consistent with the results shown in figure 6.

5. Conclusion

Renewable energy complementary hydrogen production can enhance the full consumption of renewable energy to produce hydrogen while reducing the abandonment of renewable energy. Integrating renewable energy and hydrogen production through existing multi-terminal DC systems can reduce the construction of new power lines and save equipment investment. This paper proposes a new scheme of integrating renewable energy/hydrogen energy into the ready-to-use multi-terminal DC system.

1) Under the premise that the parameters of the hand-in-hand structure are determined, the inclusion of the VSC DC-side capacitance and the power of each hydrogen production electrolyzer are the key parameters affecting the stability of the system.

2) Integration of renewable energy/hydrogen in a multi-terminal DC system can increase the hydrogen production potential of renewable energy without affecting the normal performance of the existing system.

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7. References

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