Power Sharing Control Strategy of High-Frequency Chain Matrix Converter Parallel System Based on Adaptive Virtual Impedance

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Abstract. In the high frequency link matrix converter parallel system, the impedance parameters on each line are unequal so that the output power of each converter is not equal. To solve this problem, the reason why the power cannot be divided equally under the droop control strategy is analyzed, and a power sharing strategy based on adaptive virtual impedance is proposed. This strategy introduces virtual impedance in a voltage-current dual-loop system with droop control, and uses the converter’s power information and output power factor to adaptively adjust the amplitude and phase of the virtual impedance, so that different branches have the same equivalent output impedance to compensate the voltage drop on the line impedance, while adding the droop control fine-tuning compensation link, so as to realize the load power sharing. Simulation results show that the proposed strategy can effectively improve the accuracy of output power sharing and ensure the stability of the system output voltage amplitude.

1. Introduction
The high-frequency link matrix converter is a kind of power converter that is suitable for the current era and evolved from several existing matrix converter topologies. It is also the core part of the micro-grid system to realize the AC-to-AC conversion [1-2]. Compared with other AC-DC converters, HFLMC has the advantages of high-frequency transformer isolation circuit, less energy conversion stages, and no need for large-capacity electrolytic capacitors [3-5]. It has a wide range of application prospects in various power systems, wind power generation, AC and DC transmission, etc.
Many scholars have done research on topological decoupling and switching loss of a single HFLMC. Literature [6-7] proposed a control strategy based on the idea of topological decoupling. The matrix converter topology that converts single-phase AC to three-phase AC is decoupled into two conventional three-phase voltage source inverters, which greatly simplifies the analysis process of the matrix converter. Literature [8] proposes to use the idea of decoupling to analyze
matrix converters composed of bidirectional switches from the perspective of unidirectional controllable switching converters. By improving the synthesis sequence of space vectors, high frequency and power frequency AC pulse output and positive and negative DC output are realized. Literature [9] proposed a three-port high-frequency chain direct drive wind power system grid-connected topology and its control strategy on the basis of the multi-port structure of the high-frequency chain two-stage matrix converter. Through the energy storage port control, the system has a strong smooth grid-connected power and low voltage ride-through capability. These studies analyze the similarities between HFLMC and ordinary matrix converters from the perspective of control. A connection is established between mathematical modeling and performance analysis, which provides a theoretical basis for the application of HFLMC. However, there are few researches on the power sharing problem of multiple HFLMC parallel systems in high-power applications. Since HFLMC can be equivalent to a voltage source, the multi-HFLMC parallel system can learn from the power sharing strategy of the multi-inverter parallel system. For the power sharing of multi-inverter parallel system, literature [10] proposes a flexible droop control method based on load changes, but the load distribution accuracy has a large error under light load conditions. Literature [11] eliminates the influence of line impedance by changing the droop coefficient, but it will bring the disadvantages of voltage sag and affect voltage stability. Literature [12] uses the integral value of the outlet voltage change rate to improve the power sharing control accuracy, but it affects the response speed of the system. Literature [13] uses the recursive method to correct the output voltage to gradually reduce the power distribution error, but under the condition of load fluctuations, the adjustment time is longer, and the transient process of the entire system is aggravated. Literature [14-15] introduces virtual impedance to make the output equivalent impedance appear inductive, but the change of operating parameters brings difficulties to the value of virtual impedance. Literature [16-17] uses a resistive droop control strategy, but due to the existence of the equivalent inductance of the converter, the power sharing accuracy is affected.

Based on the above research, this paper introduces an adaptive virtual impedance in the voltage-current double-loop system with droop control in order to improve the power sharing accuracy of the multi-HFLMC parallel system. The power information and output power factor of the matrix converter are used to adaptively adjust the amplitude and phase of the virtual impedance. At the same time, the droop control fine-tuning compensation link is added and the droop control coefficient is reasonably selected to meet the accuracy and stability of power sharing. Further simulation is used to verify the correctness and effectiveness of the proposed strategy.

2. High-Frequency Link Matrix Converter Parallel System

The topology of the HFLMC parallel structure is shown in Figure 1. The two-way switch in the figure can realize the two-way flow of energy. HFT stands for high-frequency transformer, which can reduce the volume and weight of the parallel system compared to ordinary transformers. It can also achieve electrical isolation, which is conducive to engineering applications. L1 and C1 are the three-phase inductance and capacitance of the filtering link; Zr1 and ZL are the equivalent impedance of the line and the equivalent impedance of the load respectively. Adopting the decoupling integrated modulation strategy can not only realize the safe commutation of the two-way switch, but also further realize the parallel operation of HFLMC, which provides a theoretical basis for the parallel operation of HFLMC.
When adopting the decoupling integrated modulation strategy, since the high-frequency chain matrix converter can be equivalent to the positive and negative two sets of ordinary matrix converters, it can be equivalent to the voltage source for analysis. Figure 2 shows the parallel equivalent model of two HFLMCs [18], where the common connection point voltage is set to \( U \angle 0^\circ \). R1 and X1 represent equivalent output resistance and inductance, respectively, and IL is the current flowing through the load. At the same time, for ease of analysis, the HFLMC output port is equivalent to a voltage source, denoted by \( E_{n1} \angle \phi_{n1} \) and \( E_{n2} \angle \phi_{n2} \).

The active power and reactive power output by HFLMC can be expressed as

\[
P_n = \frac{U E_n}{Z_n} \cos \phi_n - \frac{U^2}{Z_n} \cos \theta_n + \frac{UE_n \sin \phi_n}{Z_n} \sin \theta_n
\]

\[
Q_n = \frac{UE_n}{Z_n} \cos \phi_n - \frac{U^2}{Z_n} \sin \theta_n - \frac{UE_n \sin \phi_n}{Z_n} \cos \theta_n
\]

where, U and En are the AC bus voltage amplitude and the output voltage amplitude of the converter n respectively. Zn and \( \theta_n \) are the equivalent output impedance amplitude and argument of the converter n.

3. **Droop control strategy based on adaptive virtual impedance**
3.1. Traditional droop control analysis

In the HFLMC parallel system, the resistance inductance of the output impedance is relatively large [19], making $R_n \gg X_n$, $\cos \theta_n = 1$, $\sin \theta_n = 0$, because the value of $\varphi_n$ in practice is generally small, it can be approximated $\sin \varphi_n \approx \varphi_n$, Equation (1), (2) Simplify to

$$
\begin{align*}
    P_n &\approx \frac{U}{Z_n} (E_n - U) \\
    Q_n &\approx -\frac{UE_n}{Z_n} \varphi_n
\end{align*}
$$

(3)

It can be seen from equation (3) that $P_n$ and $E_n$, $Q_n$ and $\varphi_n$ are approximately linear relationships. Through negative feedback adjustment, the $E_n$ amplitude of the inverter with large $P_n$ is reduced, so that the output voltage is in the same phase; Similarly, negative feedback is used to adjust the output of the inverter with a large output $Q_n$ to lag, so that the output voltage amplitudes are equal. The corresponding droop control equation is

$$
\begin{align*}
    \omega_n &= \omega^* + \alpha_n Q_n \\
    E_n &= E^*_n - \beta_n P_n
\end{align*}
$$

(4)

In the formula, $\omega^*$ and $E^*_n$ are the no-load output voltage frequency and amplitude, respectively. $\alpha_n$ and $\beta_n$ are the reactive power droop and active power droop coefficient.

Considering the line impedance voltage drop, the relationship between the output voltage of the micro source and the common node voltage can be expressed as

$$
E_n = U + \frac{R_n P_n + X_n Q_n}{E_n}
$$

(5)

Combining equations (4) and (5), the projection curve of the output voltage of the micro source on the POE surface can be obtained. For different droop coefficients and line impedances, the output characteristic curve of the converter is shown in Figure 3. In the figure, $y_1$ and $y_2$ respectively correspond to the curves with voltage droop coefficients and $G_j$ is the equivalent curve of the converter. It can be seen from Figure 3 that the droop coefficient is too large and the voltage deviation will be large. If it is too small, the deviation of active power will be larger, which is not conducive to power sharing. In the same way, the use of different droop control coefficients will also cause power deviation. In a parallel system, the same droop coefficient is generally used to reduce the power deviation.

![Figure 3. HFLMC parallel active power/voltage characteristic curve](image-url)
The voltage loss of the converter voltage through the line impedance is approximately expressed as

\[ \Delta E = \frac{PR + QX}{U} \]  

(6)

From equation (6), it can be seen that the line voltage loss with large line impedance is large. In droop control, the given frequency can realize tracking without static error, that \( f1 \approx f2, \ Q1 \approx Q2 \). In order to ensure the voltage at the load is still at the rated value, the output voltage of the converter must be increased. According to the droop control principle, it is concluded that the active power output by the converter should be reduced, so that the output active power of the converter is different.

### 3.2. Droop control method of adaptive virtual impedance

In order to solve the problem of unbalanced power of each branch when two HFLMCs are running in parallel, this paper introduces an adaptive virtual impedance control method. By introducing adaptive virtual impedance, the equivalent output impedance of HFLMC is reshaped, thereby eliminating the effect of equivalent wiring impedance. After reshaping, the equivalent output impedance can be automatically adjusted according to the output power information of the branch, thereby eliminating the impedance difference between the branches. The control block diagram is shown as in Fig. 4. The virtual impedance is set to \( Z_v = Z_v \angle \theta_v = R_v + jX_v \), where \( R_v = Z_v \cos \theta_v \), \( X_v = Z_v \sin \theta_v \). In this strategy, the mode of the virtual impedance is adjusted in real time by the power signal of the converter in the system. Its function is to provide additional voltage drop to compensate for the voltage difference between the matrix converter parallel systems and offset the difference in line impedance for active power distribution impact.

![Figure 4. Block diagram of adaptive virtual impedance control](image)

The voltage drop provided by the virtual impedance is

\[ \Delta E_n = \frac{X_v Q \alpha + R P \alpha}{E} \]

(7)

The design method considering the impedance angle affects the performance of the control strategy, so formula (7) is organized as

\[ \Delta E_n = Z_v \frac{S_n \cos(\theta_v - \alpha_v)}{E} \]

(8)

If the virtual impedance angle is set to a fixed value, there will always be a working point where the impedance angle and the power factor angle are equal. At this time, the voltage drop provided by the virtual impedance is always zero, and the voltage between the converters cannot be compensated. For this reason, consider adjusting the virtual impedance angle at the same time to avoid operating points that cannot be adjusted. Calculate the output power factor according to the
information on the output side of each converter, and make the virtual impedance angle equal to the power factor angle, that
\[
\begin{align*}
\cos \theta_v &= \cos \alpha_n = \frac{P_n}{S_n} \\
sin \theta_v &= \sin \alpha_n = \frac{Q_n}{S_n}
\end{align*}
\] (9)

The adaptive impedance angle method is adopted to make constant \(\cos(\theta_v - \alpha_n) = 1\). It is guaranteed that under any power factor, the modulus \(Z_v\) of the virtual impedance is a bounded quantity. The system impedance has complex impedance characteristics. According to existing research, it can still be controlled according to the resistive droop equation. The voltage drop provided by the virtual impedance should be equal to the difference between the voltage drop on the line impedance of the two matrix converters, there
\[
\Delta E = \frac{X_1 Q_1 + R_1 P_1}{E'} - \frac{X_2 Q_2 + R_2 P_2}{E''} = \frac{Q \Delta X + P \Delta R}{E'}
\] (10)

where \(\Delta R = R_1 - R_2\), \(\Delta X = X_1 - X_2\) are the difference between the resistance and reactance of the two sets of converter circuits.

Combining formula (8) and formula (10), there is
\[
Z_v = \frac{\Delta X \sin \alpha + \Delta R \cos \alpha}{\cos(\theta - \alpha)}
\] (11)

After introducing adaptive virtual impedance, a dual-loop control structure with inductor current feedback is adopted on the output side of the converter. And combined with adaptive virtual impedance compensation control, its control block diagram is shown in Figure 5. The dual-loop control structure includes a voltage outer loop and a current inner loop. The voltage outer loop is used to ensure the stability of the system, and the current inner loop can improve the response speed of the system.

The transfer function of introducing virtual impedance is
\[
u_o = G(s)u_{ref} - (G(s)Z_v(s) + Z_o(s))i_o = G(s)u_{ref} - Z_o(s)i_o
\] (12)

where, \(G(s)\) is the system gain function, and \(Z_o(s)\) and \(Z_{eq}(s)\) are the initial and equivalent output impedances after adding the virtual impedance.

The equivalent output impedance expression with virtual impedance is
\[
Z_{eq}(s) = \frac{G_{pi} k_{pi} k_{pwm} Z_v(s) + k_{pi} k_{pwm} + L_i s}{\Delta}
\] (13)
where, \( \Delta = L_i C_i s^2 + G_{pi} k_{pu} k_{pum} + k_{pu} k_{pum} C_i s + 1 \); \( G_{pi} = k_{pu} + \frac{k_{pm}}{s} \)

Substituting \( Z_v(s) = R_v + sX_v \) into equation (13), we can get

\[
Z_{eq}(s) = \frac{1}{\Delta} \left( \frac{G_{pi} k_{pi} k_{pum} R_v + k_{pi} k_{pum}}{L_v + G_{pi} k_{pi} k_{pum} L_v} \right) s
\] (14)

### 4. Simulation analysis

In order to verify the correctness and effectiveness of the adaptive virtual impedance droop control strategy proposed in this chapter, three HFLMC parallel systems with capacity ratio of S1 : S2 : S3 = 2 : 1 : 1 are selected for analysis. Three HFLMC parallel system models are built on the Matlab / Simulink software platform, and the circuit parameters and simulation parameters are shown in Table 1. The simulation step length of the system is 5 \times 10^{-6}s, and the simulation time is 1.5 s. Under stable load condition, load 1, load 2 and load 3 are all connected. In the dynamic load state, load 1 is connected at 0.3 s, load 2 and load 3 are connected at 0.6 s, and load 2 is removed at 1 s, and load 3 is removed at 1.2 s, so as to verify the correctness and effectiveness of the control strategy in this chapter.

| Table 1. Parameters of HFLMC Parallel System |
|---------------------------------------------|
| parameter                  | HFLMC1 | HFLMC2 | HFLMC3 |
|-----------------------------|--------|--------|--------|
| switching frequency (kHz)   | 10     | 10     | 10     |
| output filtering inductance (mH) | 1.5   | 1.5    | 1.5    |
| output filter capacitor (\( \mu \) F) | 25   | 25     | 25     |
| line resistance (\( \Omega \)) | 0.0805 | 0.1605 | 0.1407 |
| line inductance (\( \mu \) H) | 43.7   | 66     | 64.5   |
| active power coefficient (\( \alpha \) pu) | 1.5e-5 | 3e-5   | 3e-5   |
| Reactive power factor (\( \beta \) q \( \omega \)) | 5e-6   | 1e-5   | 1e-5   |
| Load1                       | 20kW+10kVar |
| Load2                       | 2kW+1kVar   |
| Load3                       | 18kW+9kVar   |

### 4.1. Simulation of droop control for high frequency link matrix converter parallel system

It can be seen from Figure 6 that when the load remains stable, the AC bus voltage amplitude is 307.2V, and the total harmonic distortion rate is 1.33%. The bus voltage can remain relatively stable, and the voltage drop is relatively low. It can be seen from Figure 7 that due to the difference in impedance of the three lines, when the adaptive virtual impedance is not added, the
three HFLMCs with different capacities cannot bear the load according to the set capacity ratio. The active power is equally divided. In the same way, according to the principle of consistency, the reactive power of the parallel system cannot be distributed by the capacity ratio, and the reactive power curve has large fluctuations, the transient process is lengthened, and the stability of the system is reduced.

![AC bus voltage and FFT analysis](image)

**Figure 6.** AC bus voltage and FFT analysis

![Active and reactive power distribution curve](image)

**Figure 7.** Active and reactive power distribution curve

It can be seen from Figure 8 and Figure 9 that the active power and reactive power of the HFLMC parallel system cannot share the load power in proportion to the capacity, which causes a large disturbance in the frequency of the converter. The circulating current between the parallel systems has reached 15A, occupying more system capacity. Comprehensive analysis shows that the resistive droop control strategy keeps the AC bus voltage amplitude relatively stable when the line impedance is different. However, the HFLMC parallel system with unequal capacity cannot share the load in proportion to the capacity. And it will cause a large circulating current in the parallel system, which will occupy the system capacity.
4.2. Simulation of Droop Control Parallel System Based on Adaptive Virtual Impedance

It can be seen from Figure 10 and Figure 11 that after adding the adaptive virtual impedance, the AC bus voltage is 306.5V, and the voltage total harmonic distortion rate is 1.16%. Compared with the resistive droop control strategy, the AC bus voltage sag is lower, but the parallel system can still be kept stable. It can be seen from Figure 12 and Figure 13 that after adding the adaptive virtual impedance, the active power output of the three HFLMCs can share the load in proportion to the capacity, and the degree of stability is better. The degree of active power sharing has been effectively improved, and reactive power can also share the load in proportion to the capacity. Only the reactive power sharing process has a long transient process.
(a) AC bus voltage

(b) FFT analysis of AC bus voltage

**Figure 10.** AC bus voltage waveform and FFT analysis

**Figure 11.** A phase output voltage and current waveform

**Figure 12.** Active power distribution curve
It can be seen from Figure 14 and Figure 15 that the higher the power sharing degree of the HFLMC parallel system, the smaller the circulating current between the parallel systems. Compared with the resistive droop control strategy, under the adaptive virtual impedance droop control strategy, the AC voltage drop of the HFLMC parallel system has not deteriorated. And under the adjustment of the adaptive virtual impedance, the power sharing degree of the parallel system is improved. In addition, the frequency response overshoot of the converter system is reduced, the transient time is shortened, and the circulating current of the parallel system is reduced. It can be seen that the adaptive virtual impedance droop control strategy reshapes the HFLMC equivalent output impedance. In turn, the effect of reduced power distribution accuracy caused by the difference in line impedance is eliminated.
5. Conclusion
This paper takes the HFLMC parallel system as the research object and analyzes the limitations of the traditional droop control strategy. Aiming at the problem that the output power of each converter cannot share the load in proportion to the capacity due to the unequal impedance parameters of each line, the HFLMC equivalent output impedance is reshaped by introducing adaptive virtual impedance. So that different branches have the same equivalent output impedance. Furthermore, the precision of power distribution can be improved by fine-tuning and compensating the droop control. Through theoretical analysis and simulation verification, the following conclusions are drawn:

a) When the line impedance is different, the output power of each HFLMC has a power deviation. Especially the reactive power curve has a long transient process and poor frequency stability. The voltage stability of the AC bus can only be ensured under stable load conditions.

b) Under the same conditions, the adaptive virtual impedance can adjust the output power of each HFLMC. The power distribution accuracy of the parallel system is effectively improved. The size of the system circulation is low. When the load remains stable, the AC bus voltage can be maintained near 311V.

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