Adoption of Power Electronic Converters Multi-Module Cascade System in Power Energy Circuit Control

Junhong Li *
Guang'An Vocational & Technical College, Sichuan Province, China
*Corresponding author e-mail: 38289090@qq.com

Abstract. In order to solve the problem of system instability caused by power electronic converter in multi-module cascade operation in fields of smart grids and new energy, in this study, the impedance matching stability analysis of multi-module cascade system is presented. First, based on equivalent transfer function between the ideal input impedance and output impedance of submodule, the impedance matching stability analysis method of multi-module cascade system is put forward. Then, taking Buck circuit as an example, the two-terminal impedance model of Buck circuit is constructed, and the stability criterion of cascade system is given. Finally, the stability of single module and multi-module cascade are analyzed. The stability analysis method proposed in this study shows that the single module system in Buck circuit has good input and output. The stability analysis of multi-module cascade system in Buck circuit shows that the impedance matching stability analysis method is feasible and correct. This study provides a good theoretical basis for the stability of the multi-module converter cascade system in power energy field.

Keyword: Power energy; Power electronics; Multi-module cascade system; Circuit control; Stability analysis.

1. Introduction
In recent years, the development speed of power electronics technology is very fast. Power electronic devices are becoming more and more complex. For power electronic system, the key technologies are multi-module parallel and cascade. At present, how to ensure the stable operation of power electronic system in multi-module parallel or multi-module cascade is the focus of research [1].

Distributed power system is a relatively mature technology in power electronics system. Due to its high modularity, high redundancy, and good flexibility, it has been applied in various fields such as new energy power generation, spacecraft power supply, and communication power supply. In a distributed power system, each converter is designed independently and separately, so the converter runs at its own temperature [2,3]. Once there are two or more interconnected alternate current systems in the distributed system, these converters will affect each other, threatening the performance of the system, and even causing the collapse of the whole cascade system when there is abnormal voltage and current of the converter cascade bus [4]. In addition to the distributed voltage, the power electronic transformer is also composed of multiple modules. Currently, there are two topological structures of power electronic transformer, and the power electronic transformer with direct current link in the two topological
structures also has the problem of instability of cascade system in multi-level multimodal transport [5]. Therefore, whether it is distributed voltage or power electronic converter, it is very important to study the stability of cascade system.

In summary, in order to solve the phenomenon of cascade system instability caused by multiple modules in multi-level cascade operation in the power electronic converter, the application of multi-module cascade system of power converter in circuit control is explored. First, a method for impedance matching stability analysis of multi-module cascade system is proposed. Then the impedance model with Buck circuit as the two terminal is constructed. Finally, the stability analysis method proposed in this study is used to analyze the stability of multi-module cascade system applied in circuit control. The purpose of this study is to provide a good guidance for the application of power electronic converter in the future smart power grid [6].

2. Methods

2.1. Impedance matching stability analysis method for multi-module cascade system

When analyzing the stability of multi-module cascade system, it is conducted from the perspective of treating the sub-module as an independent individual. The idea is to build an equivalent transfer function between the ideal input impedance and the output impedance of the submodule. If the equivalent transfer function conforms to the Nyquist stability criterion, then the whole cascade system is in a stable running state, otherwise the cascade system is in an unstable state.

In the multi-module cascade system, assuming that each sub-module is independent of each other and not affected by each other, the following relationship can be obtained between each sub-module.

\[
M_{\text{ui}_j} = \frac{v_{\text{out}_j}}{v_{\text{in}_j}}, \quad M_{\text{oi}_j} = \frac{v_{\text{in}_j}}{v_{\text{out}_j}} \quad (j = 1, 2, 3)
\] (1)

Assuming that the three-module cascade system is taken as the object, the transfer function of the three-module cascade system can be expressed as follows.

\[
G = \frac{v_{\text{out}_3}}{v_{\text{in}_1}} = \frac{v_{\text{out}_3}}{v_{\text{in}_2}} \cdot \frac{v_{\text{out}_2}}{v_{\text{in}_1}} \cdot \frac{1}{v_{\text{out}_2}} = \frac{v_{\text{out}_3}}{v_{\text{in}_2}} \cdot \frac{v_{\text{out}_2}}{v_{\text{in}_1}} \cdot \frac{1}{A_{\text{ui}_2}}
\] (2)

For two adjacent submodules, the two-level cascade system can be expressed as follows.

\[
\left. \frac{v_{\text{out}_2}}{v_{\text{in}_1}} \right|_{\text{out}_2} = \frac{M_{\text{ui}_j} M_{\text{oi}_j}}{1 + Z_{\text{out}_2} Y_{\text{in}_2}}
\] (3)

\[
\left. \frac{v_{\text{out}_3}}{v_{\text{in}_2}} \right|_{\text{out}_3=0} = \frac{M_{\text{ui}_2} M_{\text{oi}_3}}{1 + Z_{\text{out}_2} Y_{\text{in}_3}}
\] (4)

Equation (4) and equation (3) can be substituted into equation (1) to obtain the equation below.

\[
G = \frac{M_{\text{ui}_1} M_{\text{ui}_2} M_{\text{ui}_3}}{(1 + Z_{\text{out}_1} Y_{\text{in}_2})(1 + Z_{\text{out}_2} Y_{\text{in}_3})}
\] (5)

To facilitate calculation, they are defined separately as follows.

\[
T_{m1} = Z_{\text{out}_1} Y_{\text{in}_2}
\] (6)
2.2 Two-terminal impedance model of a Buck circuit

In this study, Buck circuit is adopted to verify the stability analysis method of multi-module cascade system, and Buck circuit adopts single power. The main parameters of this circuit are as follows. The rated power is 300W; the input voltage is 48V; the output voltage of each stage is $V_{o1} = 24\, V$, $V_{o2} = 12\, V$, $V_{o3} = 6\, V$; the filtering inductance is 54uH, filtering resistance is 20mΩ; the filter capacitance is 470uF, the filtering resistance is 50mΩ; and the voltage loop controller parameter is 0.3.

According to the above section, the two-terminal impedance model of Buck circuit is as follows.

$$
\begin{bmatrix}
\frac{V_o}{i_o} \\
\frac{V_m}{i_m}
\end{bmatrix} =
\begin{bmatrix}
G_{11c} & Zoc \\
1/Z_{ic} & G_{22c}
\end{bmatrix}
\begin{bmatrix}
\frac{V_o}{i_o} \\
\frac{V_m}{i_m}
\end{bmatrix}
$$

(12)
Therefore, according to the analysis, the stability conditions of the three-module Buck circuit cascade system need to meet the following three conditions.

I. The source module needs to run independently and stably, that is, the cascade system of module 1 and module 2 satisfies the stability condition.

II. The load converter needs to run independently and stably, that is, module 3 can run independently and stably.

III. Impedance ratio $T_m$ meets Nyquist stability criteria.

In addition, the impedance intercept criterion can be used on the premise that the source module can operate independently and stably, that is, the cascade system of module 1 and module 2 satisfies the stability condition. The output of the equivalent impedance and the equivalent input impedance of the load transducer conform to the namely frequency characteristic curve. It needs to determine whether the source output impedance of the converter and the load input impedance of the converter intersect the frequency characteristic curve, and whether the difference between the frequency range of the section is greater than $180^\circ$. If the difference is greater than $180^\circ$, the system is in the state of flux, otherwise the system is in a stable state.

3. Results and discussion

Figure 1 is an analysis diagram of the gain frequency characteristics of the voltage control loop designed by a single module. After compensation, the amplitude of the low-frequency segment of the single-module cascade system is increased, the phase margin is $60.5^\circ$, and the crossing frequency is $12\text{kHz}$. Therefore, the single-module operation meets the design requirements. The converter works in a stable state. The output voltage waveform of Buck circuit is obtained by PSIM simulation. According to the simulation results of voltage waveform, each single Buck circuit will have stable output when running independently, as shown in figure 2.

![Figure 1. Bode before and after voltage loop gain $T_v$ compensation](image-url)
By applying the stability analysis method of multi-module cascade system to circuit control, the stability criterion can be verified. First, the influence of sub-module filter parameter L on the stability of cascade system is analyzed. According to the Buck circuit selected above, when the filter parameter is 54μH, the results of figure 3 and figure 4 are obtained. As can be concluded from Figure 3 and Figure 4, when the filter parameter is 54μH, the Nyquist curve diagram of impedance matching condition \( G_{o3} = T_{m1} + T_{m2} + T_{m1}T_{m2} \) and impedance ratio does not contain the point (-1, j0), and the frequency characteristic curves of \( Z_{out} \) and \( Z_{in} \) do not intersect. According to the analysis in figure 3, the cascade system can run stably, and the output of PSIM simulation results in figure 4 is stable, which is consistent with the theoretical analysis conclusion.

**Figure 2.** Voltage waveform output by Buck circuit when one single module runs

**Figure 3.** \( Z_{out} \) and \( Z_{in} \) frequency characteristics curves
4. Conclusion
In order to study the application of multi-module cascade system of power electronic converter in power control, its stability is mainly analysed, and an impedance matching stability analysis method for multi-module cascade system is proposed. First, the stability analysis method is proposed based on the idea of equivalent transfer function between ideal input impedance and output impedance of submodule. Then, taking Buck circuit as an example, the two-terminal impedance model of Buck circuit is constructed, and the stability criterion of cascade system is obtained. Finally, the stability of single module and multi-module is analyzed, and the impedance matching stability analysis method proposed in this study is feasible and correct.

The research has played a certain role in promoting the development of power electronic system in China, but the research still has some limitations. Other types of converters can be added to form different multi-module cascade systems, and further expand the scope of the stability analysis method in the following studies.

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