

Analysis of high-frequency interference characteristics of UHVDC converters

Chaonan Ying¹ ✉, Zheng Xu¹, Chenxi Luo¹¹Department of Electrical Engineering, Zhejiang University, Hangzhou, People's Republic of China

✉ E-mail: 417042242@qq.com

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Abstract: The converter is the main component of the converter station and the main noise source of the PLC interference. The accurate modelling of the high-frequency characteristics of the converter is the foundation for the design of the ± 1100 kV UHVDC PLC filter. Based on deep analysis of the high-frequency characteristics of the converter valve, this paper first proposes three high-frequency models of the converter valve. Compared with a real converter valve used in similar HVDC project, model two is chosen to analyse the high-frequency characteristics. Second, the model of Zhundong–Wannan UHVDC transmission project is established in the PSCAD simulation platform to determine the actual high-frequency characteristics of the converter valve. The voltage before the smoothing reactor is calculated, and the high-frequency noise level is obtained by Fourier transform. Considering the practical application of the high-frequency model of the converter valve, this paper finally proposes a formula to express the measured noise level. The noise source expressed by the formula is more practical for research on high-frequency characteristics of the converter station.

1 Introduction

In the early development of China's power communication network, power line carrier communication (PLC) was the main means of power system communication. PLC is subject to noise interference because of its coupling with the power line. Thus, it is required to use high-frequency filter to reduce the noise level in the 30–500 kHz band [1–3]. Nowadays, all the information of the converter station is exchanged with each other through the fibre optic, and the carrier signal only exists in the AC substation which is directly connected to the converter station. Meanwhile, the costs of high-frequency filter increase as the voltage level of AC system rises. Under these circumstances, the necessity of installing AC/DC PLC filter in the converter station deserves further study [4]. If we can optimise the design of high-frequency filters, such as reducing the equipment size and the number of its components, the economy and reliability of HVDC projects can be greatly improved, especially to the ± 1100 kV UHVDC project which is now being constructed in China.

In order to study the optimal design of the high-frequency filter, it is necessary to build an accurate high-frequency converter station model, which requires modelling various high-frequency devices. It can be seen from the literature [5, 6] that during the operation of the converter station, the converter valve is switched on and off, causing the rapid change of the voltage between the electrodes and thereby causing conducted interference noise. The noise is transmitted to the DC side through the smoothing reactor and to the AC side through the converter transformer. The noise causes conducted interference to the PLC system and the noise level depends on the characteristics of the circuit and the operating state of the system. Through the modelling of the internal components of the converter, the equivalent high-frequency model of the converter can be established. Then an accurate equivalent noise source model can be obtained, which is the basis of the research on the filter of the power carrier band [7–9]. Up to now, ± 800 kV UHVDC project has been put into operation and it can be a reference for the research of ± 1100 kV UHVDC project. However, the high-frequency interference of ± 1100 kV converter station and the ± 800 kV converter station are different in essence. On the one hand, the different voltage levels of the connected AC system lead to the difference of the actual structure of the converter valve. On the other hand, the ± 1100 kV converter station adopts the hierarchical

access method. Therefore, it is necessary to do further research on the specific ± 1100 kV UHVDC project.

This paper is based on the Zhundong–Wannan UHVDC transmission project [10–12]. In section 2, this paper proposes three high-frequency models of the converter valve. In section 3, by compared with a real converter valve used in similar HVDC project [13], model two is chosen to analyse the high-frequency characteristics of the converter valve. In section 4, the model of Zhundong–Wannan UHVDC transmission project is established in the PSCAD simulation platform and the high-frequency noise level of the converter valve is obtained by Fourier transform. In section 5, considering the practical application of the high-frequency model of the converter valve, this paper finally proposes a formula to express the measured noise level. The noise source expressed by the formula is more practical for the research on high-frequency characteristics of the converter station.

2 Converter valve model

In the UHVDC transmission system, the positive and the negative poles are completely symmetrical. Thus, this paper studies the positive pole of the transmission system.

2.1 Main circuit structure

The ± 1100 kV converter station consists of high- and low-voltage valve halls, and each valve hall is arranged with six converter valve towers, which is in suspended structure. The converter station is designed in a way in which two 12-pulse converter valve is connected in series. As a reflection of the real system, the modelling of the converter station must take into account not only the bipolar two 12-pulse converter valve circuit, but also the interference from the DC and AC sides. Based on the above principles, the basic system for the converter valve simulation is shown in Fig. 1.

This basic system is based on the Zhudong–Wannan ± 1100 kV UHVDC transmission project, including the rectifier side 750 kV AC system, converter transformers, smoothing reactors, DC filters, and the inverter side 500 and 1000 kV hierarchical access model. In addition, the DC line uses a typical frequency-dependent model with tower structure. In this project, the rated transmission power is 12,000 MW, the rated current is 5455 A and the transmission distance is 3400 km. In normal operation, the rectifier adopts

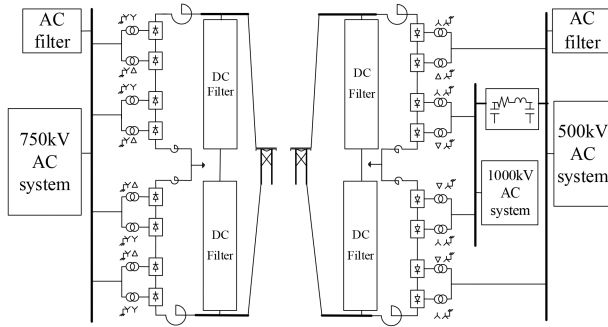


Fig. 1 Main circuit of the ± 1100 kV UHVDC project

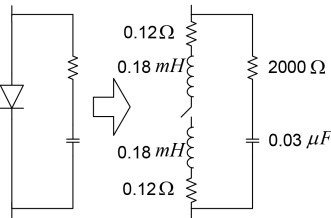


Fig. 2 High-frequency model one of the converter valve

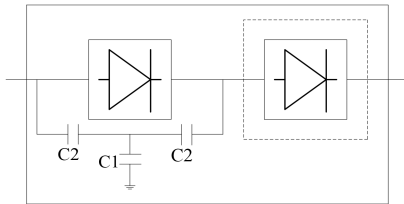


Fig. 3 High-frequency model two of the converter valve

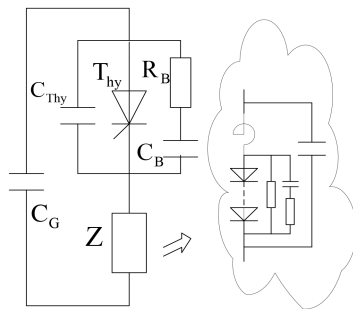


Fig. 4 High-frequency model three of the converter valve

constant current control while the inverter adopts constant extinction angle control.

2.2 High-frequency model of the converter valve

In the simulation process, in order to describe the actual working condition of the converter in more detail, the equivalent model of the converter valve is required to be more complex [14–16].

2.2.1 Model one: In [8], the converter valve is represented in its detailed structure as shown in Fig. 2, in which the resistance and inductance in series with the controllable switches are equivalent to all the resistance and inductance in series with the thyristor in each bridge arm. The values of resistance and inductance are obtained by ignoring the turn-on and turn-off effects at rated current. In parallel with the series branch is a buffer circuit consisting of a capacitor and a resistor.

The model has a simple structure. The influence of the high-frequency characteristics of the saturable reactor and thyristor in the converter valve is represented by the series and parallel circuit branch. Model one can be used to roughly estimate the influencing factors of the noise level of the converter valve. However, the model neglects the effects of conduction paths and coupling on the

noise level and only considers the high-frequency structure of a single converter valve. As a result, there will be an error when calculating the noise level of two 12-pulse converter valve.

2.2.2 Model two: The high-frequency characteristics of the converter mainly depend on the characteristics of the converter valve and its accessories, and the capacitive coupling between components provides a complicated path for high-frequency interference. For the commonly used indoor converter valve, the capacitive coupling between the valve hall and the valve is also an important factor affecting the high-frequency characteristics. As for ± 1100 kV converter station, though high-voltage valve and low-voltage valve groups are in different valve halls, there is a circuit connection between them. So the high-frequency interference caused cannot be neglected. Therefore, on the basis of model one, the valve model is improved as shown in Fig. 3.

In Fig. 3, C_1 represents stray capacitance to ground while C_2 represents stray parallel capacitance between different converter valves.

$$C_1 = nC_m, \quad C_2 = C_g \quad (1)$$

where C_m represents the capacitance between a single silicon controlled rectifier and ground; n is the number of modules; C_g represents the coupling capacitance between the connected converter valves. The capacitance units are all in pF level.

The entire converter valve is a unit in model two. On the basis that the high-frequency influence between adjacent valves is approximately the same, model two uses parallel capacitance C_2 to represent the interaction between valve groups to better analyse the converter's high-frequency characteristics.

2.2.3 Model three: Based on [15], saturable reactor, thyristor, and RC circuit components are represented in the broadband structure according to the specific structure of the valve arm. The actual reactor is non-linear and its structure is complex. According to the dynamic characteristics of its operating conditions, it can be regarded as a linear element in the transient process. Here, the high-frequency structure of the saturable reactor is represented by a circuit consisting of resistance, inductance, and capacitance in order to simplify the high-frequency model of the converter valve, as shown in Fig. 4.

In Fig. 4, Z represents the equivalent high-frequency impedance of the saturable reactor; C_{Thy} is the stray capacitance between the anode and the cathode of the thyristor; T_{hy} represents the thyristor; R_B and C_B represent the grading resistor and grading capacitor; C_G is also a grading capacitor. For C_{Thy} , there is a formula according to [15]:

$$C_{Thy} = \begin{cases} a_0 + a_1 u + a_2 u^2, & u \leq 10 \text{ V} \\ k / \sqrt{|u|}, & u \geq 10 \text{ V} \end{cases} \quad (2)$$

In the formula: $a_0 = 10^{-6}$; $a_1 = -0.3331 \times 10^{-6}$; $a_2 = 0.048 \times 10^{-6}$; $k = 0.3224 \times 10^{-6}$; u is the voltage across the thyristor. Taking into account the range of u , C_{Thy} takes a fixed value of 4.13 nF here.

3 Spectrum comparison of the converter valve model

First, it is required to get the high-frequency voltage spectrum of the 12-pulse converter valve in the Zhundong–Wannan UHVDC transmission project. The voltage spectrum is used to determine which model is the best to analyse the high-frequency characteristics. Since there is no ± 1100 kV UHVDC project in operation now, it is necessary to obtain the high-frequency voltage generated by the converter in a similar designed HVDC project which has been put into operation. Then, considering the difference between the specific parameters of the reference project and the actual project, the high-frequency voltage generated by the actual project converter can be converted from the high-frequency voltage

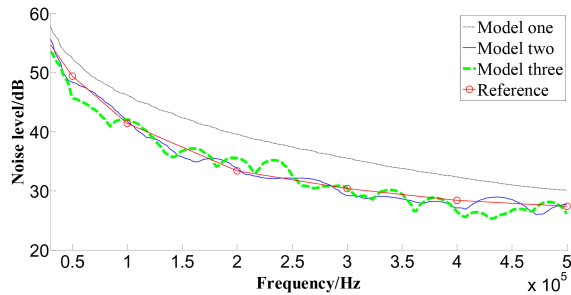


Fig. 5 Comparison of Spectrum

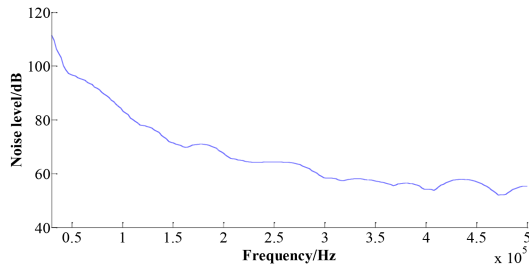


Fig. 6 High-frequency noise spectrum of two 12-pulse converter valve

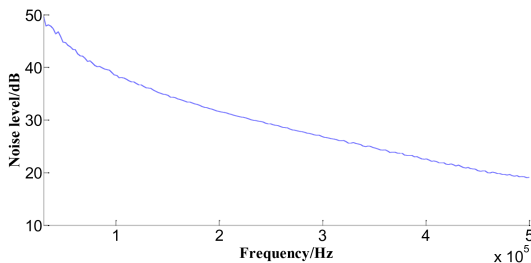


Fig. 7 High-frequency noise spectrum of single 12-pulse converter valve

generated by the reference project converter. Factors to be considered in the conversion process include: voltage applied to the valve in triggering moment, frequency bandwidth, voltage measured by the peak or RMS, resistance reference. Here, the high-frequency voltage spectrum of ± 1100 kV Zhundong–Wannan UHVDC project is calculated from the high-frequency voltage spectrum generated by the converter valve of Nuozhadu ± 800 kV HVDC project, which has been put into operation. The element parameters of the two projects are basically the same, and the difference between the resistance reference and measurement method is also negligible. Consequently, the main influencing factors of noise level are the voltage added to the valve and frequency bandwidth. The relationship between voltage and noise level is:

$$\Delta \text{dB} = 20 \lg(U_1/U_2) \quad (3)$$

where U_1 is the voltage across the converter valve to be calculated; U_2 is the voltage across the converter valve in the reference project. For the rectifier station, the ideal no-load DC voltage of the 12-pulse converter valve group is 200 kV. For the ± 1100 kV UHVDC project here, the ideal no-load DC voltage of the 12-pulse converter valve group is 275 kV. Then considering the influence of frequency bandwidth, the noise level of 12-pulse converter valve group in the ± 1100 kV UHVDC project is 4.76 dB higher than the one in the ± 800 kV converter station. Finally, the high-frequency voltage spectrum of the 12-pulse converter valve is listed in Table 1.

Put the three valve models into the rectifier station of the ± 1100 kV UHVDC main circuit in Fig. 1, respectively, and the noise spectrum of the 12-pulse converter valve group in the high-voltage valve hall can be measured. Then compare the three spectrum to the reference spectrum (listed in Table 1), the result is shown in Fig. 5.

Table 1 High-frequency noise spectrum of the 12-pulse converter valve

Frequency/kHz	± 800 kV station/dB	Converted noise/dB
30	50	54.76
50	42	46.76
100	34	38.76
200	29	33.76
300	27	31.76
400	25	29.76
500	24	28.76

According to the comparison, we can draw the following conclusions:

- The error of model one is much more than the other two models. Therefore, model one will not be used to analyse the high-frequency characteristics of the converter valve.
- Within the allowable range of error, model three has a more complex structure and its parameters to be measured are more than model two. Therefore, model two is selected as the high-frequency noise model of the converter valve to study the high-frequency noise level.

4 Analysis of the high-frequency interference characteristics

The model of Zhundong–Wannan UHVDC transmission project is established in the PSCAD simulation platform to determine the actual high-frequency characteristics of the converter valve. Apply model two to the main circuit and the high-frequency voltage before the smoothing reactor to be measured. (When measuring the high-frequency voltage level of the rectifier station, the converter valve model of the inverter station is the ideal model which is composed of a single thyristor and RC circuit in parallel. When measuring the high-frequency characteristics of the inverter station, the valve model of the rectifier station is also the ideal model). Then, the high-frequency noise level in the 30–500 kHz band is obtained by Fourier transform.

4.1 Rectifier station

Under the actual operation mode, there are two kinds of working status of the rectifier station: two 12-pulse converter valve working in series and single 12-pulse converter valve. The noise level before the smoothing reactor of these two status are shown in Figs. 6 and 7.

According to Figs. 6 and 7, in the 30–500 kHz band, when two 12-pulse converter valve groups work in series, the noise-level generated by each 12-pulse converter valve group is higher than single 12-pulse converter valve group works. The average noise difference is 5 dB. It can be concluded that high-voltage and low-voltage valve halls have mutual influence in high-frequency band. The noise spectrum has bumps in some frequency bands, which may be the result of local oscillation when a converter valve is triggered [17, 18]. It still meets the general trend that the higher the frequency is, the lower the noise level will be.

4.2 Inverter station

The inverter station adopts 500 and 1000 kV hierarchical access model. The high-frequency noise level of the high-voltage side and low-voltage side are shown in Figs. 8 and 9, respectively.

The high-frequency noise level of the 12-pulse converter valve group on high-voltage side and low-voltage side are different, which may be caused by the following reasons: on the one hand, the higher the voltage of the connected AC system is, the higher the noise level of the converter will be; and on the other hand, the difference of converter transformer impedance will lead to different commutation angle.

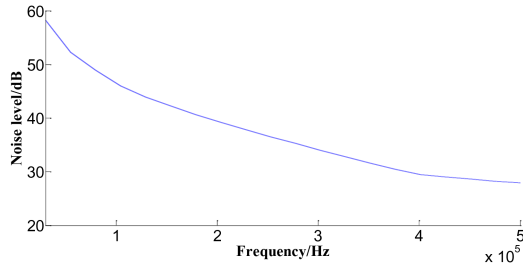


Fig. 8 Noise spectrum of the 12-pulse converter valve on high voltage side

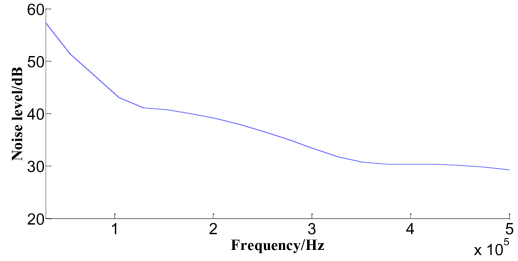


Fig. 9 Noise spectrum of the 12-pulse converter valve on low voltage side

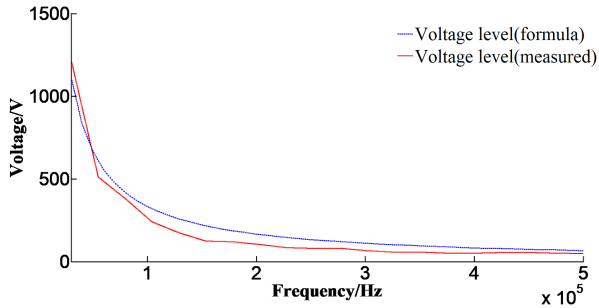


Fig. 10 Comparison of voltage level on rectifier side

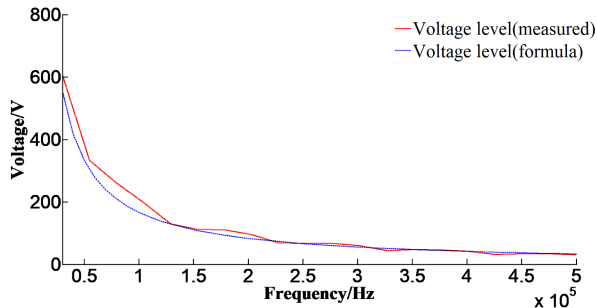


Fig. 11 Comparison of voltage level on inverter side (low voltage)

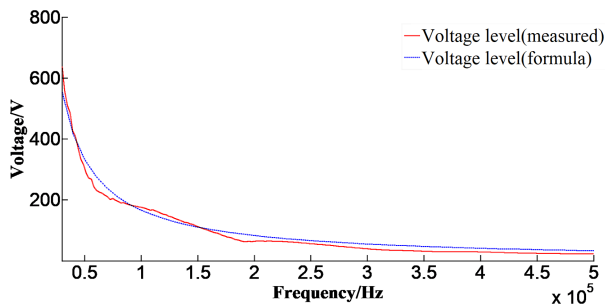


Fig. 12 Comparison of voltage level on inverter side (high voltage)

5 Equivalent noise source model

In the actual design of PLC filters, the noise spectrum of the converter station is obtained in a way in which the converter station devices are represented by their high-frequency models and the entire converter station circuit is described by its equivalent circuit. Based on this equivalent circuit, the noise level of the relevant

node is obtained by applying Kirchhoff's law. In the process of calculating the noise level, the noise source can be replaced by a voltage source or a current source. More literature prefers the voltage source [19, 20].

The noise spectrum obtained in the previous chapter cannot be directly applied to the equivalent high-frequency voltage source in the converter station circuit. So this paper finally proposes a formula to express the measured noise level for further research. Based on a large number of practical experiences and simulations, the equivalent noise source expressed by (4) can simulate the noise spectrum in PLC filter design [21].

$$U_{eq}(\omega) = \frac{6500 \times U_0 \times A(f)}{\omega \times \sqrt{1 + (\omega \cdot T_0)^2}} (V) \quad (4)$$

Where U_0 is the voltage of converter valve in triggering moment and T_0 is the commutation time of valve voltage. $A(f)$ is pulse correction factor.

For converter valve group in which two 12-pulse converter valve works in series, high-voltage and low-voltage valve halls have mutual influence in high-frequency band because there is an electrical connection. Therefore, a more accurate noise source formula is needed. Considering the relationship between pulse and frequency, $A(f)$ is a frequency-dependent linear function:

$$A(f) = k \times f + b \quad (5)$$

So we obtain

$$\frac{6500 \times U_0 \times A(f)}{\omega \times \sqrt{1 + (\omega \cdot T_0)^2}} = \frac{kf \times U_0 \times B + bU_0 \times B}{\omega \times \sqrt{1 + (\omega \times T_0)^2}} \quad (6)$$

Considering that $f \gg 1$, we obtain

$$\frac{kf \times U_0 \times B + bU_0 \times B}{\omega \times \sqrt{1 + (\omega \times T_0)^2}} \simeq \frac{kf \times U_0 \times B}{\omega^2 T_0} \quad (7)$$

where B is the frequency bandwidth of the noise (representing the bandwidth of the measuring instrument and this paper takes 3 kHz) and k is a constant.

Finally, this paper adopts (8) to express the high-frequency voltage level of 12-pulse converter valve:

$$U(f) = \frac{k_1 \times U_0 \times B}{4\pi^2 \times f \times T_0} (V) \quad (8)$$

where k_1 is an undetermined coefficient. According to the simulation fitting k_1 takes 1.55×10^{-4} (both the rectifier side and the inverter side).

The high-frequency voltage level of two 12-pulse converter valve on rectifier side and 12-pulse converter valve on inverter side can be measured in PSCAD simulation. Thus, the authors can compare the high-frequency voltage level of the equivalent noise source expressed in (8) to the measured voltage level, as shown in Figs. 10–12.

As is shown in the figures above, the high-frequency voltage spectrum expressed by (8) is almost the same as the spectrum obtained by the simulation. In Fig. 10, the maximum voltage deviation is about 100 V and the maximum converted noise-level deviation is 2.5 dB, which occurs at the frequency of 150 kHz; In Fig. 11, the maximum voltage deviation is about 50 V and the maximum converted noise-level deviation is 1.9 dB, which occurs at the frequency of 80 kHz; In Fig. 12, the maximum voltage deviation is about 42 V and the maximum converted noise-level deviation is 1.6 dB, which occurs at the frequency of 65 kHz. Therefore, the high-frequency voltage of the equivalent noise source expressed in (8) can meet the requirements of the measured noise.

6 Conclusion

(i) For UHVDC system, the capacitive coupling between the valve hall and the converter is also an important factor affecting the high-frequency characteristics. Model two uses parallel capacitance C_2 to represent the interaction between valve groups. Model two is the most suitable model to analyse the converter's high-frequency characteristics.

(ii) High-voltage and low-voltage valve halls have mutual influence in high-frequency band. In the 30 kHz–500 kHz band, when two 12-pulse converter valve groups work in series, the noise level generated by each 12-pulse converter valve group is higher than single 12-pulse converter valve group works.

(iii) The inverter station adopts hierarchical access model. The high-frequency noise level of the 12-pulse converter valve group on high-voltage side and low-voltage side are different. We can draw the conclusion that the higher the voltage of the connected AC system is, the higher the noise level of the converter will be.

(iv) The noise spectrum obtained by (8) can nearly fit the high-frequency characteristics of the actual converter. In addition, the noise source expressed by (8) is more practical for the research on high-frequency characteristics of the converter station.

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