Influencing Factor and Error Analysis of Operating Capacitor Voltage Transformer Harmonic Measurement

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Abstract: With the increasing demands of power quality monitoring and management, the problem of harmonic measurement error caused by the widespread operation of capacitor voltage transformers (CVT) in high-voltage power grids has been unavoidable. This paper analyses the influence of environmental factors on harmonic measurement error of CVT, and proposes a new method for analysing the harmonic measurement errors of operating CVT, which explains the unstable phenomenon of CVT measurement errors based on field comparison test, and provides a progressing screening method of effective analysis data. The CVT harmonic error characteristic analysis method proposed in this paper considers the impact of field installation conditions, electromagnetic environment, and other actual operating environment, which can reflect the actual harmonic error characteristics of CVT in field operation. A CVT harmonic measurement system is established based on the proposed method. The validation and effectiveness of the proposed method is illustrated on a field measurements of 1000kV CVT in Shandong Province.

1. Introduction
Voltage transformer is an essential core equipment for power quality monitoring in power system. In high-voltage power grid, compared with traditional electromagnetic voltage transformer (PT), capacitor voltage transformer (CVT) has the advantages of small volume, light weight and low cost. At the same time, it can also avoid the problem of ferromagnetic resonance caused by iron core saturation. In addition, the capacitor voltage divider in CVT can be used as the coupling capacitor for carrier communication, which can also weaken the lightning wave head. Due to above advantages, the share of CVT in 110kV and above level substations is as high as 53.5%[1]. However, because of its inherent characteristics, CVT has large errors in measuring harmonics. Appendix D of Chinese national standard GB/T 14549-1993 clearly stipulates that CVT cannot be used for harmonic measurement[2]. In a word, the CVT has been widely used in power system now, but it cannot accurately measure harmonics, which has become a key obstacle to analysing power quality in high-voltage power system.

Actually, a lot of research has been carried out and many research results have been obtained to solve the problem of CVT harmonic voltage measurement. On the whole, these research results can be divided into two categories. One is the direct method, that is, transform the existing CVT to make it have the ability to measure harmonics. The other is the indirect method, which uses the obtained CVT harmonic transmission characteristics to correct the harmonic measurement results. These two methods have their
own advantages and disadvantages, but neither completely solves the problem of harmonic measurement of CVT.

In the research of CVT harmonic measurement, the direct method was first considered, which has been studied as early as 20 years ago. [3,4] proposes a method to correct CVT harmonic measurement results by using the capacitor voltage divider composed of the end screen of current transformer. However, this method requires additional equipment and complex operation. Besides, the measured signal is small and the accuracy and reliability of the signal amplification device have a great impact on the accuracy of the measurement results. [5,6] gives a current measurement method of grounding circuit. By adding two current transformers to the grounding circuit of CVT, the voltage on the high-voltage side of CVT can be calculated according to the known capacitor value. This method is still in the verification stage now. What’s more, the implementation of this method involves the accurate measurement of small current signal and noise pollution, and the accuracy of calculation results needs to be evaluated. [7] introduces a method of adding capacitor $C_3$ in CVT capacitor voltage divider for on-line transient overvoltage monitoring, which can also be applied to harmonic monitoring. The harmonic component in the primary voltage can be obtained by measuring the harmonic component of the voltage at both ends of $C_3$. This method is also in the experimental stage now and its measurement accuracy in practical applications still needs to be evaluated in depth.

Compared with the direct method, the indirect method does not need power cut to transform the CVT. It only needs to accurately obtain the harmonic transmission characteristics of CVT and then correct the harmonic measurement results, so as to realize the accurate measurement of harmonics. In [8,9], by establishing the high-frequency equivalent model of CVT, its transfer function is derived and the influence law of different parameters on harmonic voltage measurement is studied. These papers define the influencing factors of measuring harmonic voltage by CVT, but do not give the elimination method of harmonic measurement error; [10] proposed that the method of using CVT harmonic transmission characteristic curve to correct the transmission error of harmonic frequency has the disadvantage that the key parameters cannot be obtained. To solve this problem, [11] built a CVT harmonic transmission characteristics and measurement error test system to test CVT in the 35kV voltage level and corrected the error based on the test results to avoid the direct measurement of key parameters. However, without considering the randomness and contingency of the test data, the obtained CVT harmonic transmission characteristics are still not accurate enough; On the basis of experiments, [12] modifies the CVT harmonic measurement results combined with neural network algorithm. The results have certain accuracy and universality, but require a large number of experimental data and the method is time-consuming and laborious.

Based on the above, this paper studies the CVT harmonic measurement error in harmonic monitoring of high-voltage power grid. The CVT harmonic equivalent model and test platform are built and the differences between different CVT harmonic measurement errors are comprehensively analysed from the perspective of mechanism and experiment. Furthermore, an analysis method for harmonic measurement error characteristics of CVT in UHV is proposed, which provides an effective way to solve the accuracy problem of harmonic signal transmitted by CVT.

2. Harmonic equivalent model of CVT

According to the design standard of CVT, the internal intermediate transformer cannot reach saturation at 1.5 times overvoltage[13], so the iron core of the intermediate transformer will not be saturated under normal working conditions and always works in linear state. Therefore, the influence of nonlinearity of excitation branch can be ignored when establishing CVT harmonic equivalent model. Besides, according to the electromagnetic field theory, it is necessary to consider the stray capacitor between CVT internal inductance coil devices when analysing the frequency characteristics[4,5,8,14]. To sum up, the harmonic equivalent circuit model of CVT shown in figure 1 is established.
As shown in figure 1, $C_1$ and $C_2$ are high-voltage capacitor and medium-voltage capacitor; $L_c$ is the inductance of compensation reactor; $R_c$ is the equivalent resistance of compensation reactor; $C_e$ is the equivalent stray capacitance of compensation reactor; $C_p$ is the stray capacitance to ground of primary winding of intermediate transformer; $R_w$ and $L_w$ are the resistance and inductance of excitation winding of intermediate transformer; $R_{r1}$ and $L_{r1}$ are the resistance and leakage inductance of primary winding of intermediate transformer; $R_{r2}$ and $L_{r2}$ are the secondary resistance and leakage inductance of intermediate transformer converted to primary side; $R_D$ and $L_D$ are loads.

According to the harmonic equivalent circuit shown in figure 1, the transfer function of each part is obtained by using cascade analysis theory:

$$H_1(s) = \frac{1}{sC_2} + \frac{1}{sC_1}$$

$$H_2(s) = \frac{1}{sC_p} \left( \frac{1}{sC_e} \right)$$

$$H_3(s) = \frac{R_w}{sL_w} \left( \frac{1}{sC_p} \right)$$

$$H_4(s) = \frac{R_D}{sL_D} \left( \frac{1}{sC_p} \right)$$

Then the transfer function of harmonic equivalent circuit of CVT is:

$$H(s) = \frac{NU(s)}{U_i(s)} = H_1(s) \cdot H_2(s) \cdot H_3(s) \cdot H_4(s)$$

3. Influence of key parameters on harmonic transmission characteristics of CVT

3.1. Influence of internal manufacturing parameters

Using the transfer function of CVT and changing the parameters by simulation, the harmonic transfer characteristic curves of CVT under different distribution parameters can be obtained, as shown in figure 2 and figure 3:
Figure 2. CVT harmonic transfer characteristic curves under different distribution parameters $C_c$ of compensation reactor.

Figure 3. CVT harmonic transfer characteristic curves under different distribution parameters $C_p$ of intermediate transformer.

It can be found from figure 2 and 3 that the change of distribution parameters has a great impact on the harmonic transmission characteristics of CVT. Thus, there will be great differences in the harmonic transmission characteristics of different types of CVT. Therefore, it is difficult to correct the harmonic transmission characteristics of different types of CVT through a certain frequency characteristic. It is reasonable to obtain different transmission characteristics to correct the harmonic measurement results for different types of CVT.

3.2. Influence of external environmental factors
For the same type of CVT, there is little difference in its internal manufacturing parameters, which provides a theoretical possibility to correct CVT harmonic transmission error by using transmission characteristics. However, the influence of field operating environment on the harmonic transmission characteristics of CVT still needs to be further analysed.
3.2.1. Influence of the temperature.

Since CVT works outdoors all year round, the influence of ambient temperature change must be considered when analyzing the harmonic transmission characteristics of CVT.

The reason for the change of voltage divider capacitor caused by temperature is that the film capacitor or all film capacitor used in CVT will be affected by temperature. When the ambient temperature changes, the capacitor value will also change correspondingly. The degree of change mainly depends on the temperature coefficient of the capacitor. Through investigation, it is found that the temperature coefficient of most types of voltage dividing capacitors is negative, that is, the high and medium voltage equivalent capacitor of CVT will decrease with the increase of ambient temperature. However, because high and medium voltage capacitors are generally made of the same material, their temperature coefficients are basically the same. Therefore, the influence law of ambient temperature on voltage dividing capacitor will be the same and the capacitor voltage dividing ratio will not change. Although the voltage divider ratio of the capacitor does not change, the overall equivalent capacitance of the capacitor voltage divider will change. In order to simplify the analysis, the equivalent capacitance of the capacitor voltage divider is changed according to the condition that the capacitance value of the capacitor voltage divider will change by about 0.25% ~ 0.5% every 25℃ change in temperature. The capacitance temperature coefficient $\alpha_c$ is taken as -200 and the definition of $\alpha_c$ is as follows:

$$\alpha_c = \frac{\Delta C}{C_0 \Delta T} \times 10^6$$

(6)

where $\Delta C$ is the change of capacitance; $\Delta T$ is the temperature difference between the current temperature and room temperature; $C_0$ is the capacitance measured at room temperature. The capacitance values at different temperatures can be obtained:

$$C' = C_0(1 + \frac{\alpha_c \Delta T}{10^6})$$

(7)

The reason for the change of stray capacitance of internal coil caused by temperature is different from that of voltage divider capacitor. The calculation formulas of stray capacitance of winding coil deduced in [16] are as follows:

$$C_s = \frac{(n-1)\varepsilon_r \varepsilon_0 l N D}{n^2 d}$$

(8)

$$C_u = \frac{4(n-1)\varepsilon_r \varepsilon_0 l D N}{3n^2 d}$$

(9)

where $N$ is the number of turns of the winding; $n$ is the number of layers of winding coil; $l$ is the average turn length of winding; $d$ is the distance between winding layers; $\varepsilon_r$ is the relative permittivity; $\varepsilon_0$ is the vacuum dielectric constant. It can be seen that the influence of temperature on the stray capacitance of the internal coil is mainly due to the change of the $\varepsilon_r$ of the winding coil with the change of temperature. Generally, within 100℃, the changes by about 1% for every 20℃, i.e.:

$$C'_s = C_{s,20℃}(1 \pm 0.0005 \times \Delta T)$$

(10)

$$C'_u = C_{u,20℃}(1 \pm 0.0005 \times \Delta T)$$

(11)

The reason for the change of the inductance parameters of the coil caused by the temperature is that the magnetic permeability of the cold-rolled silicon steel, which is the common material of the core of the CVT compensation reactor and the intermediate electromagnetic unit, changes with the temperature. In general, this change process is nonlinear, but if only qualitative analysis of the influence of temperature is required, the analysis can be appropriately simplified. It is approximately considered that the change of permeability is about 0.3% for every 25℃ change in core temperature[15], that is:

$$\mu' = \mu (1 + 0.00012 \times \Delta T)$$

(12)
Combined with the calculation formula of inductance of inductance coil, the inductance at different temperatures can be obtained:

$$L = \frac{N^2 D \mu_0}{l} \mu_r (1 + 0.00012 \Delta T)$$  \hspace{1cm} (13)

The variation law of resistance parameters of inductance coil is similar to that of inductance parameters. Generally, the resistance value of copper resistance changes by about 10% every 25℃, that is:

$$R = R_{20^\circ C} \left( 1 + 0.004 \times \Delta T \right)$$  \hspace{1cm} (14)

According to the above analysis, the frequency response curve of CVT with temperature can be obtained, as shown in figure 4.

![Figure 4. Harmonic transfer characteristic curves of the same type of CVT under different operating temperatures](image)

It can be seen from figure 4 that the change of internal parameters of CVT caused by temperature has a certain impact on the harmonic transmission characteristics of CVT, but the impact is not obvious on the whole.

3.2.2. Influence of external electric field.

The capacitor voltage divider of CVT has no capacitance shielding. Therefore, when CVT works in a complex electromagnetic environment, the capacitor voltage divider and the live parts of the substation close to each other form stray capacitance through the space electric field. These coupling capacitors at different locations will flow capacitive currents. Capacitive current will flow into the capacitor voltage divider, resulting in a change in the voltage divider ratio. However, when the main capacitor of CVT is large enough, the stray capacitance has less influence on it. Moreover, only when the main capacitor changes, it has a great impact on the measurement results of CVT at power frequency, but has little impact on the harmonic transmission ratio, so this paper will not discuss it in depth.

3.2.3. Influence of the operating conditions.

The CVT harmonic test platform is used to test various operating conditions that may be encountered by the same type of CVT, as shown in figure 5.
Figure 5. The CVT harmonic test platform

Figure 6 and figure 7 show the test results of changing the input voltage amplitude, input harmonic content and operating ambient temperature for multiple CVTs of the same batch and type.

Figure 6. Harmonic transfer characteristic curves of the same type of CVT under different input voltage amplitudes
It can be seen from figure 6 and 7 that under certain operating conditions, CVTs produced in the same batch have the same and stable frequency characteristics. Therefore, the harmonic measurement results of the actual operating CVT can be corrected by measuring the harmonic transmission characteristics in the laboratory, so as to realize the accurate transmission of harmonics by the CVT.

4. Correction method of harmonic measurement error characteristics

4.1. Error characteristic analysis method of CVT harmonic measurement based on MLE

According to the characteristics that CVT with the same model and parameters has stable harmonic error characteristics under certain operating conditions, a new analysis method of CVT harmonic measurement error characteristics is proposed in this paper. Firstly, obtain the CVT voltage test signal with comparison and analysis conditions and the voltage test signal of standard source; Secondly, each harmonic content analysis sample with time scale is obtained after harmonic analysis. Based on the number of remaining samples and the interval span of sample probability distribution, the analysis samples are screened step by step and the effective data of harmonic error analysis are obtained; Then, the effective data are analysed based on the maximum likelihood estimation (MLE) method to obtain the harmonic error characteristics of the CVT; Finally, the measured results are corrected by using the obtained CVT harmonic error characteristics. The process is shown in figure 8.
Obtain the same voltage signal of the operating CVT and the standard source.

Harmonic analysis

Filter out the harmonic content samples in $HRU_{err}$ or $HRU_{std}$ that are less than the set threshold $C_s$.

Remaining samples $\geq S_{min}$?

$C_{th} = C_{th} + C_{step}$

The number of existing CVT samples is not enough to analyze the error characteristics of the $n$th harmonic.

Obtain the ratio error $E_n$ and its probability distribution characteristic $\alpha$.

$\alpha \leq \alpha_{eq}$?

Calculating the transfer characteristics of $n$th harmonic.

Figure 8. Flow chart of CVT harmonic measurement result processing based on MLE algorithm

4.2. Field experimental verification

The 1000kV CVT of a UHV substation in Shandong Province is used for analysis and verification. A 1000kV bus tank electromagnetic voltage transformer (hereinafter referred to as bus PT) is installed in phase A, B and C of bus I and bus II in GIS, with an accuracy level of 0.5. The research shows that PT has good frequency characteristics for harmonics below 1kHz. In the verification work, the PT of A-phase bus II of GIS is used as the error characteristic analysis standard source of harmonics within 20 times measured by CVT, and the harmonic error characteristic of A-phase line CVT is obtained by using the method proposed in this paper. As mentioned above, the harmonic error characteristics of CVT with the same parameters from the same manufacturer are basically the same. Using the obtained harmonic error characteristics, the harmonic error of B-phase line CVT is corrected. Then the corrected harmonic is compared with its corresponding standard source (PT harmonic measurement value of GIS bus II) to verify the effectiveness of the proposed method.

Taking the quintuple harmonic as an example, two channels of a power quality analysis device are used to test the quintuple harmonic of 1000kV A-phase line CVT and that of A-phase GIS bus at the same time, so as to ensure that the data time scale is strictly corresponding. The analysis interval is taken as 3s. The quintuple harmonic transmission characteristic of CVT is represented by $E_5$, calculate the ratio error of $HRU_{5(CVT)}$ and $HRU_{5(PT)}$ at each same time interval to obtain $E_5$ samples at all analysis time intervals and its probability distribution is shown in figure 9.
Figure 9. Sample probability distribution of all analysis time interval of quintuple harmonic

As can be seen from figure 9, the harmonic error characteristics of CVT in field operation show normal distribution characteristics. The minimum ratio error of 95% probability interval is 1.116 and the maximum ratio error is 1.125. The set threshold is $\alpha = 0.05$ and the span value of $E_5$ analysis sample is $\alpha = 0.009$, which is far less than the set threshold. It shows that the distribution of $E_5$ sample data is relatively concentrated and the probability distribution of sample data can reflect the actual harmonic test error level. The expected value of $E_5$ sample data distribution is $\mu = 1.1205$, that is, the quintuple harmonic error characteristic of the 1000kV A-phase CVT is 1.1205 times amplification.

The above conclusions are applied to the B-phase CVT harmonic measurement results for correction. Compare the harmonic data corrected by this method with the data measured by the standard source (i.e. measured value of GIS bus B-phase PT) and obtain the comparison results of all analysis interval data, as shown in figure 10.

Figure 10. Comparison curves of quintuple harmonic before and after correction

As shown in the figure 10, the method proposed in this paper can be applied to the harmonic measurement error analysis of CVT with the same model and parameters. After analysing and correcting the error characteristics of B-phase CVT harmonic measurement data, it can be found that the results are very close to the standard source measurement data. The average relative error after correction is only 0.3% while the average relative error before correction is 10.75%.

5. Conclusions
The inevitable harmonic measurement error of CVT seriously affects the observability of power quality of power grid. Aiming at this problem, this paper takes the harmonic measurement error characteristics of UHV CVT as the research object and puts forward the analysis and test scheme of harmonic error
characteristics of CVT in operation. At the same time, the screening method and analysis method of
effective data of harmonic error characteristics are proposed. The main conclusions are as follows:

Different brands and batches of CVTs have different harmonic transmission characteristics while
CVTs of the same batch have similar harmonic transmission characteristics;

The analysis method of CVT harmonic error characteristics proposed in this paper does not need
power failure, CVT equipment transformation or additional partial voltage measurement device. The
security risk is relatively small compared to traditional analysis methods.

Compared with laboratory analysis or delivery test methods, the CVT harmonic error characteristic
analysis method proposed in this paper considers the impact of field installation conditions,
electromagnetic environment and other actual operating environment, which can reflect the actual
harmonic error characteristics of CVT in field operation.

In this paper, the accuracy and effectiveness of the proposed method are verified by the experimental
results of 1000kV CVT. In the next step of work, the harmonic measurement error correction method
will be used in online harmonic monitoring data correction.

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