

Research on Capacitance Voltage Transformer Harmonic Measurement

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According to the issue of transmission characteristics of a capacitor voltage transformer (CVT), which leads to the inaccuracy of power grid voltage harmonics values, a new test system and a method of measuring the capacitive current of a CVT were proposed. A comparison of the results of the conventional test method and actual power grid harmonics verified the validity and accuracy of the proposed test method, and a test of the voltage harmonics in the actual power grid showed that the test system can completely satisfy the requirements of testing the voltage harmonics.

1. Introduction

Currently, 110 kV measurement systems are widely used to monitor the grid voltage on the secondary side of a transformer. Owing to disadvantages such as the ferromagnetic resonance with line distributed capacitance, large size, and high cost, electromagnetic voltage transformers (VTs) cannot meet the needs of a power system. Compared with electromagnetic VTs, a capacitor voltage transformer (CVT) has a large electric field strength margin and a reliable insulation. A voltage-dividing capacitor also serves as a coupling capacitor in a high-frequency carrier channel and does not form a ferromagnetic resonance with the switch port capacitance. In addition, the advantages of small size, light weight, less maintenance work, and low cost result in the wide use of the CVT. In foreign countries, CVTs are mostly used at voltages above 72.5 kV. In China, CVTs are widely used at 110 kV and above.⁽¹⁾

Although CVTs meet the requirements of the system used in the fundamental voltage measurement, system protection, and fundamental signal conversion of automatic devices, owing to the characteristics of CVT transmission, CVTs cannot correctly reflect the actual situation in the system with harmonic components. In measuring the voltage harmonics of the system, the secondary side voltage signal obtained by a CVT transformation device has a large error and the harmonic measurement data cannot be adopted. Therefore, the national standard GB/T 14549-1993 “grid harmonic” appendix D7⁽²⁾ states that “a CVT cannot be used for harmonic measurement,” and IEC standards and other related technical reports are also

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provided. Therefore, how to test and grasp accurate grid harmonic levels and exact voltage distortion data through CVTs, what measurement method to adopt, and what test equipment to use for harmonic voltage testing have become the focus of power quality supervision of the power grids, and this is the primary problem that should necessarily be solved.⁽³⁾

2. Analysis of the Harmonic Characteristics of CVT

The CVT composed of voltage dividing capacitors, compensation reactors, intermediate transformers, dampers, and loads is shown in Figs. 1 and 2.⁽⁴⁻⁶⁾ In essence, it is mainly a capacitive voltage divider; in Fig. 1, C_1 is a high-voltage capacitor and C_2 is a medium-voltage capacitor. The partial pressure ratio of the CVT is

$$n = \frac{u_1}{u_2} = \frac{C_1 + C_2}{C_1} + \frac{1}{\omega^2 C_1 L}. \quad (1)$$

Compared with the partial pressure of the capacitive divider, the partial pressure ratio of the CVT is higher by Δn , that is, $\Delta n = 1/(\omega^2 C_1 L)$, as shown in Eq. (1). Δn is equal to the ratio of the capacitive reactance of the CVT low-voltage arm to the inductive reactance of the TV and is related to the frequency, i.e., when the frequency is different, the ratio of Δn is also different. The TV equivalent inductor L is a nonlinear element whose size varies with the operating voltage and frequency. Therefore, the CVT variable ratio differs at different frequencies. From Eq. (1), the amplitude- and phase-frequency characteristics of the transfer functions of a multiple 220 kV CVT are obtained and shown in Fig. 3.

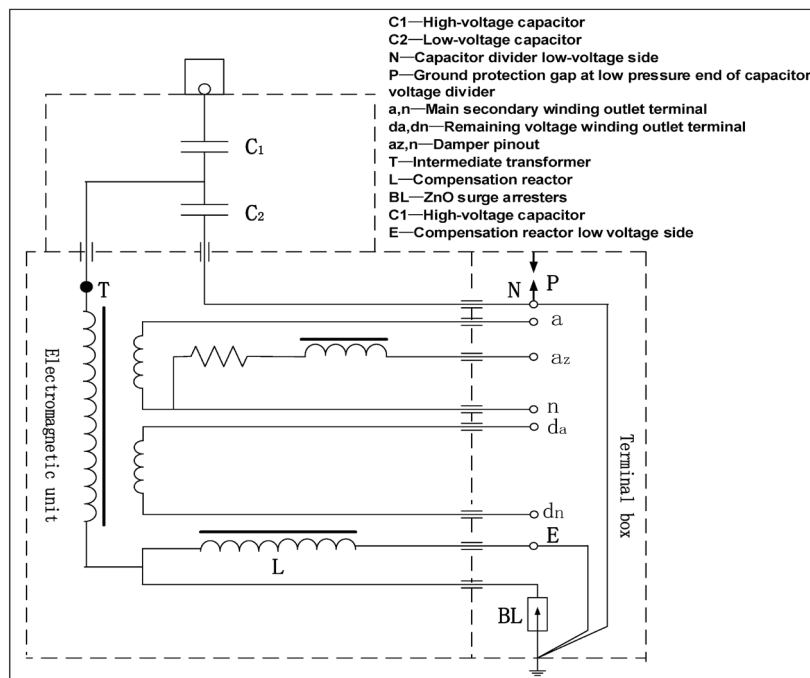


Fig. 1. Structure of CVT.

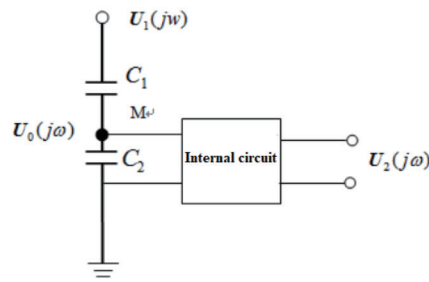


Fig. 2. Equivalent circuit diagram.

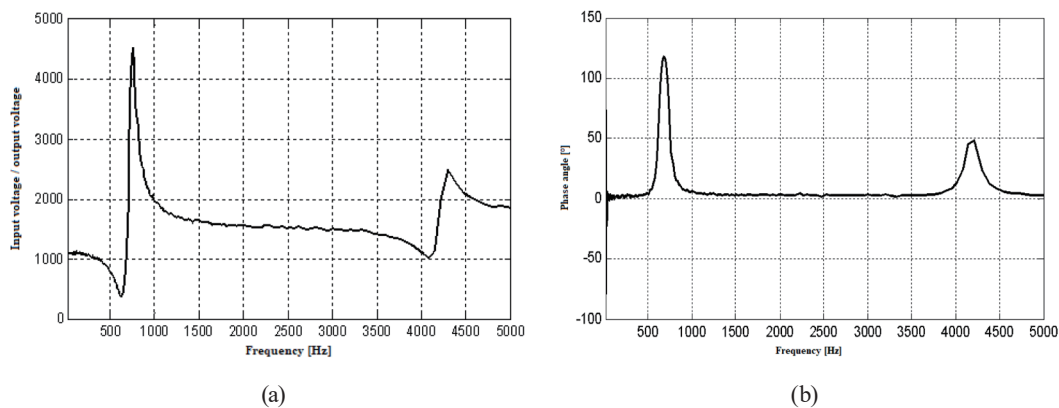


Fig. 3. (a) Amplitude- and (b) phase-frequency characteristics of transfer functions of multiple 220 kV CVT.

According to the amplitude- and phase-frequency characteristics of the CVT, it can be seen that the CVT has different transformation ratios at different frequencies. Therefore, both low- and high-order harmonics have a certain filtering effect, which is essentially a band-pass filter system, and for different CVTs, owing to the different components of the parameter values, the initial and cut-off frequencies are different. Therefore, it is inevitable that distortion occurs in the harmonic measurement when the voltage signal is collected from the secondary side of the CVT.⁽⁷⁻⁹⁾

3. CVT Harmonic Measurement Based on Capacitive Current

At present, the method of measuring grid voltage harmonics based on the CVT is to obtain the voltage signal from the secondary side of the CVT and combine the harmonic measurement and analysis instrument for harmonic analysis.⁽¹⁰⁻¹²⁾ To prevent the distortion of the harmonic components caused by the CVT transmission characteristics, some scholars have proposed a method of obtaining the CVT transfer function and then correcting the harmonic measurement offline. Commonly used methods of obtaining the CVT transfer function are the network analyzer method, high-voltage harmonic injection method, and the like. Owing to the different transmission characteristics of different CVTs, this method should test the transfer function of each CVT, which is theoretically feasible, but the project is actually not suitable for generalization.

To solve the technical problem that a CVT cannot be used in harmonic measurement, a method of calculating the grid voltage by measuring high- and medium-voltage capacitive currents flowing through a CVT is proposed according to the principle of a CVT and the analysis of the characteristics of capacitive reactance that changes with frequency. The feasibility and limitation of this method are verified. Finally, a CVT harmonic measurement system based on the capacitive current method is designed.

3.1 Measuring principle

The method of testing CVT harmonics based on capacitive current follows Kirchoff's voltage principle, a high-precision current sensor is loaded on the CVT capacitor branch to test the high- and medium-voltage capacitive currents flowing through the CVT,^(13–16) and the grid voltage is calculated by combining the CVT high- and medium-voltage capacitive reactances for further analysis. The equivalent circuit is shown in Fig. 4.

In Fig. 3, the high-precision current sensors A and B respectively measure the currents flowing in the high-voltage capacitor C_1 and medium-voltage capacitor C_2 , and the voltage $U_1(j\omega)$ on the primary side is calculated as

$$U_1(j\omega) = I_1(j\omega)jX_{c1} + I_2(j\omega)jX_{c2}. \tag{2}$$

Here, $U_1(j\omega)$ is the primary-side voltage; $I_1(j\omega)$ is the total current flowing through the high- and medium-voltage capacitors and the internal circuit at the frequency point, which can be measured by the current coil B; I_2 is the in-ground current flowing through the medium-voltage capacitor C_2 at the frequency point, which can be measured by the current coil A. $X_{c1}(j\omega)$ is the

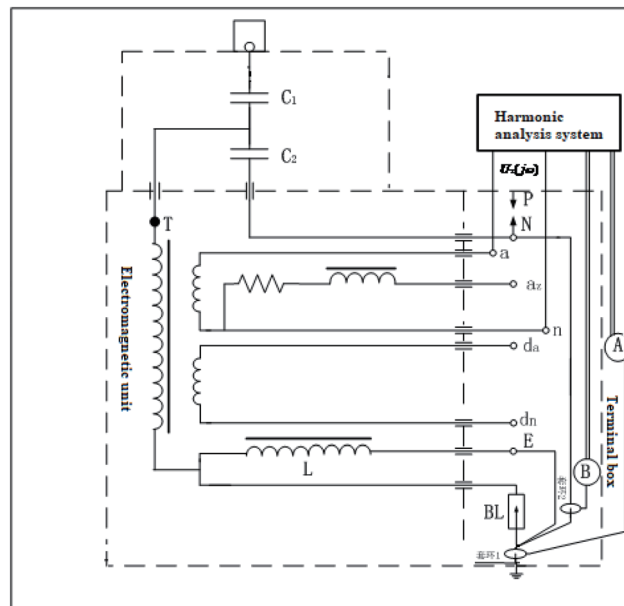


Fig. 4. Equivalent circuit diagram of capacitive current method.

reactance of the high-voltage capacitor C_1 at the frequency point, and $X_{c2}(j\omega)$ is the reactance of the medium-voltage capacitor C_2 at this frequency point.

3.2 Test of CVT high- and medium-voltage capacitors C_1 and C_2

The realization of the CVT harmonic testing method based on capacitive current requires that the capacitive reactance has a linear relationship with the reciprocal of the frequency in the concerned harmonics test frequency band (up to 5 kHz).

To verify this requirement, the impedance of the 110 kV CVT (TYD110/ $\sqrt{3}$ -0.02H) used for testing was measured using an impedance analyzer, Agilent 4294A (working frequency: 40–110 MHz and resolution: 1 mHz).

The test method is described as follows. During the test, disconnect the connection line between the electromagnetic unit and the midpoint of the capacitor, and connect the impedance analyzer to the CVT high-voltage capacitor C_1 and middle-voltage capacitor C_2 . As shown in Fig. 5, the capacitances of the test high-voltage capacitor C_1 and medium-voltage capacitor C_2 vary with frequency.

Impedance parameters of TYD110/ $\sqrt{3}$ -0.02H were tested using Agilent 4294A. The test frequency range is 40–5 kHz.

The impedance test results of the high- and medium-voltage capacitors C_1 and C_2 are shown in Fig. 6. By using these test results, the changes in C_1 and C_2 capacitances with the frequency are obtained and shown in Fig. 7.

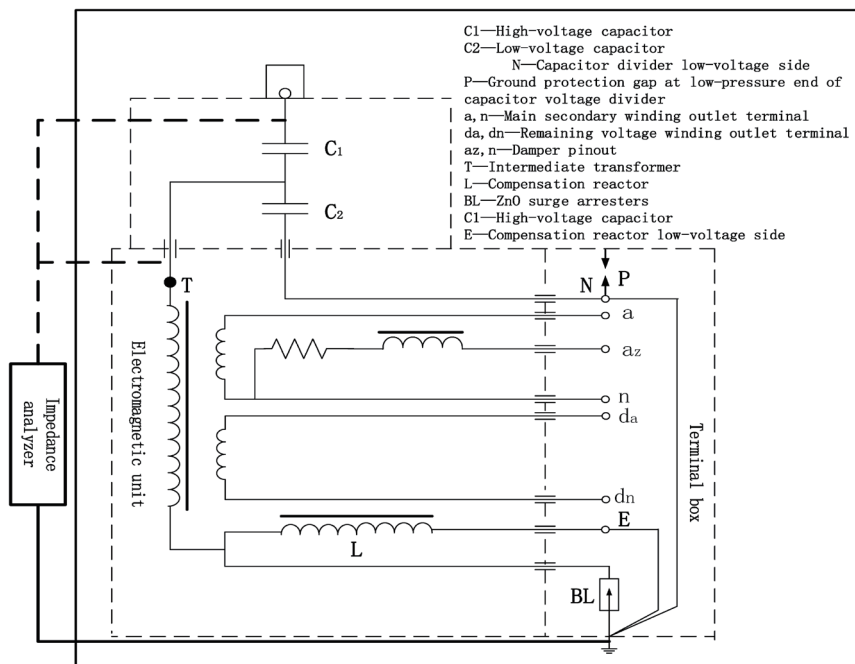


Fig. 5. Principle diagram of the CVT capacitive reactance measurement.

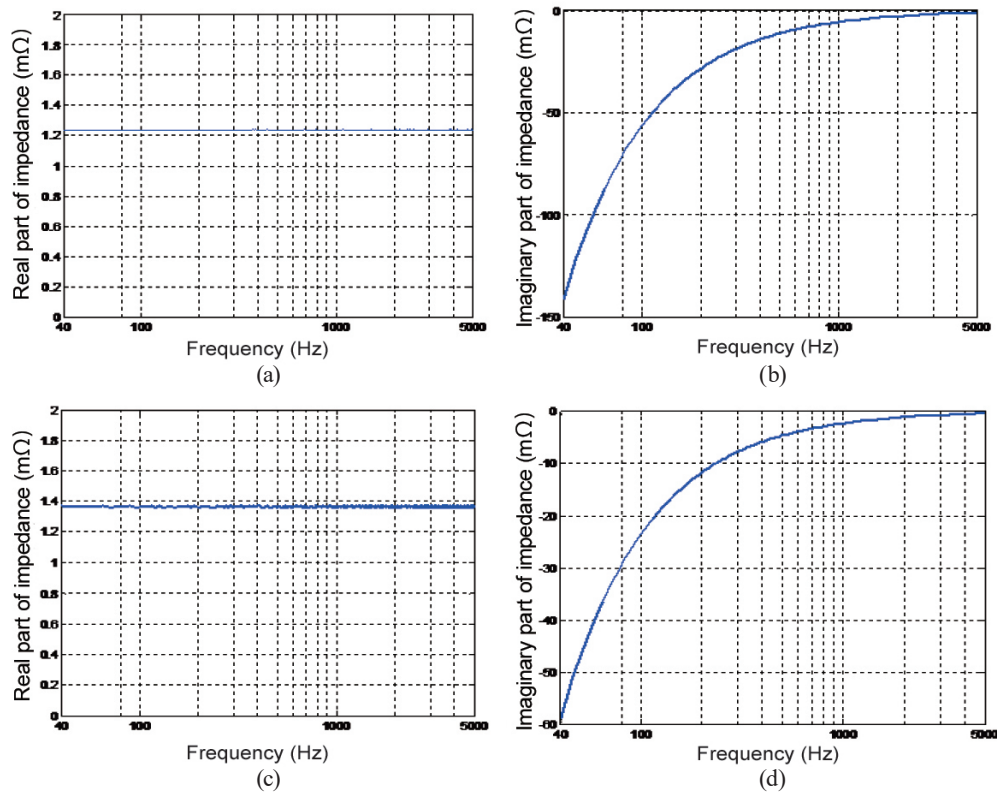


Fig. 6. (Color online) Test results of CVT high- and medium-voltage capacitor C_1 and C_2 impedances.

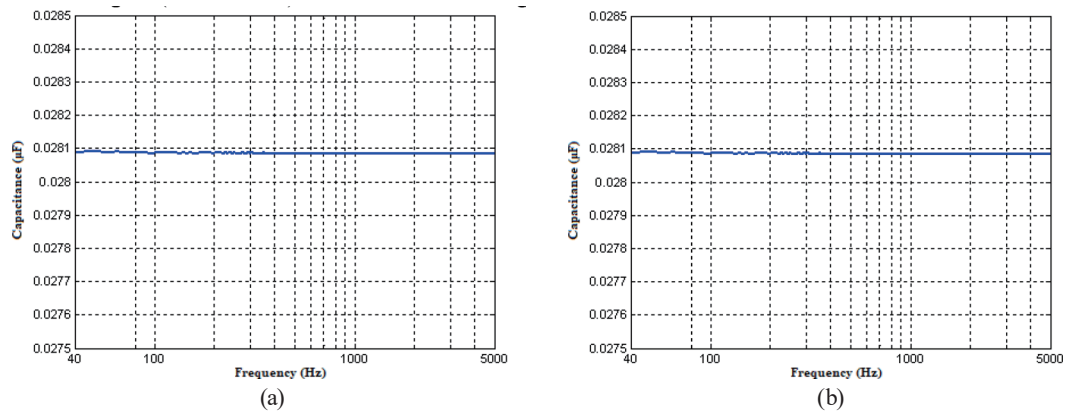


Fig. 7. (Color online) Changes in frequency capacitances of CVT high- and medium-voltage capacitors C_1 and C_2 : (a) high-pressure side of C_1 and (b) high-pressure side of C_2 .

The test results show that the capacitance of the CVT high-voltage capacitor C_1 is 0.028 087 μF , which is in accordance with the value of the given parameter C_1 (0.028095 μF). The capacitance of the CVT medium voltage capacitor C_2 is 0.067 485 μF , which is consistent with the value of the given parameter C_2 (0.06755 μF).

Note that there is a resistive component in the measurement due to the existence of the lead during the test, but the maximum resistance does not exceed $1.4 \text{ m}\Omega$, and the test result is not affected compared with the capacitive reactance exceeding $1 \text{ k}\Omega$ at 5 kHz . In the frequency band below 5 kHz , the capacitance is not affected by stray parameters, lead resistance and inductance, but only the capacitance characteristics. Therefore, the currents flowing through CVT high- and medium-voltage capacitors are tested; moreover, it is feasible to measure the grid voltage by calculating the capacitive reactances of CVT high- and medium-voltage capacitors.

3.3 Design of CVT harmonic testing system based on capacitive current

According to the test principle of CVT harmonics based on the capacitive current method, the harmonic test system designed in this study is shown in Fig. 8. Because the currents of CVT high- and medium-voltage capacitors are at the microlevel, the current sensor used is an Agilent N2820A probe. The Agilent N2820A probe offers a high sensitivity that is 200 times higher than the sensitivity of a clamp-on current probe that can only measure sub-milliamps current. The probe bandwidth ranges from DC to 500 kHz and the minimum measurable current is $250 \mu\text{A}$, which will be wound on the wire under test for many turns to amplify the measured current in the test, simultaneously reducing the space circuit area, to prevent external interference. A data acquisition card is used for each channel 250 kHz sampling rate, 12-bit resolution, with the simultaneous sampling of the 4-channel data acquisition card.

The CVT equivalent circuit is simplified, and the secondary load is equivalent to the primary side, the simplified equivalent circuit shown in Fig. 9. Here, U_1 is the primary-side line voltage, U_2 is the primary voltage of the electromagnetic unit, C_1 and C_2 are partial pressure capacitors, L is the compensation reactor, L_M is the intermediate transformer excitation reactance, and R_x is the equivalent load impedance. According to the simplified equivalent circuit, U_1 is calculated from U_2 and the current I_L of the compensation reactor L is obtained as

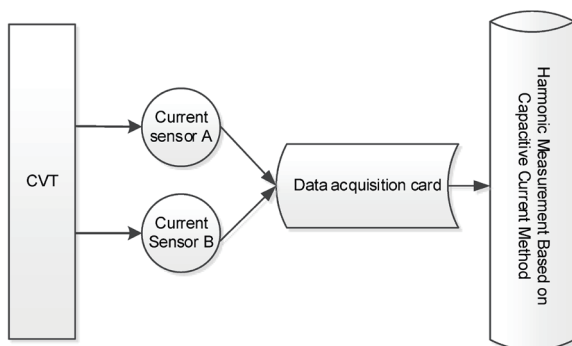


Fig. 8. Structure diagram of CVT harmonic test system based on capacitive current method.

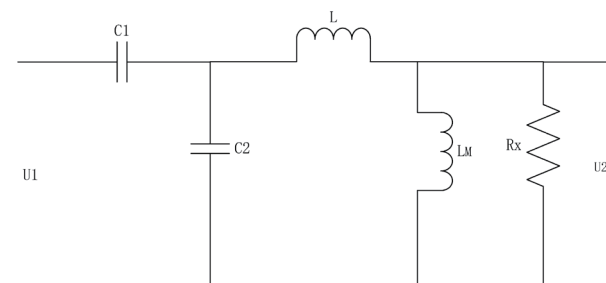


Fig. 9. CVT simplified equivalent circuit diagram.

$$I_L = \frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j}. \quad (3)$$

The voltage U_{c2} of the capacitor C_2 is

$$U_{c2} = U_2 + \left(\frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times 2\pi f L j. \quad (4)$$

The current I_{c2} of the capacitor C_2 is

$$I_{c2} = \frac{U_{c2}}{-\frac{1}{2\pi f C_2} j} = \frac{U_2 + \left(\frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times 2\pi f L j}{-\frac{1}{2\pi f C_2} j}. \quad (5)$$

The current I_{c1} of the capacitor C_1 is

$$I_{c1} = I_{c2} + I_L = \frac{U_2 + \left(\frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times 2\pi f L j}{-\frac{1}{2\pi f C_2} j} + \frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j}. \quad (6)$$

The primary-side voltage U_1 is

$$U_1 = U_{c1} + U_{c2} = \left(\frac{U_2 + \left(\frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times 2\pi f L j}{-\frac{1}{2\pi f C_2} j} + \frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times \left(-\frac{1}{2\pi f C_1} j \right) + U_2 + \left(\frac{U_2}{R_x} + \frac{U_2}{2\pi f L_M j} \right) \times 2\pi f L j. \quad (7)$$

Assuming that the transformation ratio of the electromagnetic unit is the $P_{electromagnetic\ unit}$, the overall transformation ratio of the CVT is

$$\begin{aligned}
 P_{CVT} &= P_{electromagnetic\ unit} \times \frac{U_1}{U_2} \\
 &= P_{electromagnetic\ unit} \times \left\{ \frac{1 + \left(\frac{1}{R_x} + \frac{1}{2\pi f L_M j} \right) \times 2\pi f L j}{-\frac{1}{2\pi f C_2} j} + \frac{1}{R_x} + \frac{1}{2\pi f L_M j} \right\} \\
 &\quad \times \left\{ -\frac{1}{2\pi f C_1} j \right\} + 1 + \left(\frac{1}{R_x} + \frac{1}{2\pi f L_M j} \right) \times 2\pi f L j \quad (8)
 \end{aligned}$$

By using this equation, the variation characteristics of the overall transformation ratio P_{CVT} of the CVT with the frequency are experimentally studied under saturation and nonsaturation conditions.

4. Experiment and Test

Several 110 and 220 kV CVTs were tested with the CVT harmonic current measurement system based on capacitive current. The principle of the test is shown in Fig. 10.^(17–22)

The test method is described as follows. The high-voltage harmonic source is used to inject the harmonic with a ratio of 10% into the CVT. The order of the harmonic is 2–50. Owing to

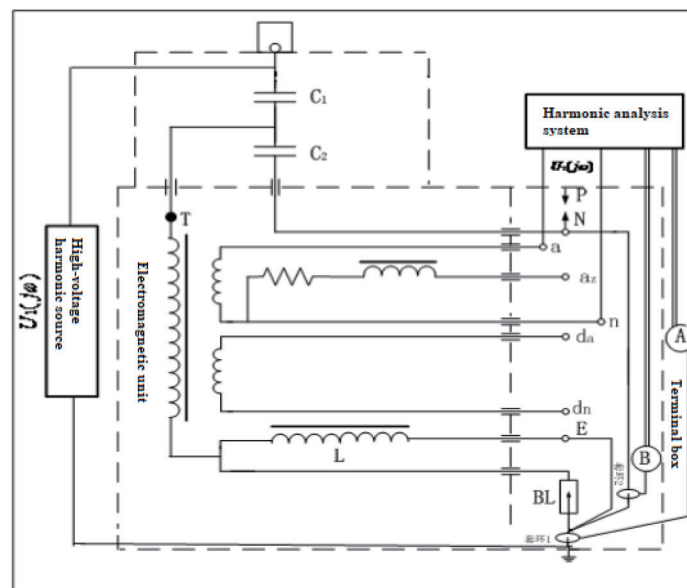


Fig. 10. Testing connection diagram.

space limitation, the article lists only one 220 kV CVT test result. The test result of the CVT through the high- and medium-voltage capacitor currents is shown in Fig. 11.

The CVT primary voltage after injection and the CVT primary voltage calculated using Eq. (2) are shown in Fig. 12.

The frequency spectrum of the voltage shown in Fig. 12 is analyzed, and the obtained results are shown in Fig. 13.

It can be concluded that, when the percentage of primary harmonic voltage is 10%, the calculated percentage of primary voltage harmonic is close to 10% with a small error. Table 1 gives the numerical results of the harmonic test. The harmonic percentage measured by the capacitive current method is close to the harmonic level of the primary side of the CVT injected at the time of testing. The maximum deviation of the harmonic percentage is 1.89%.

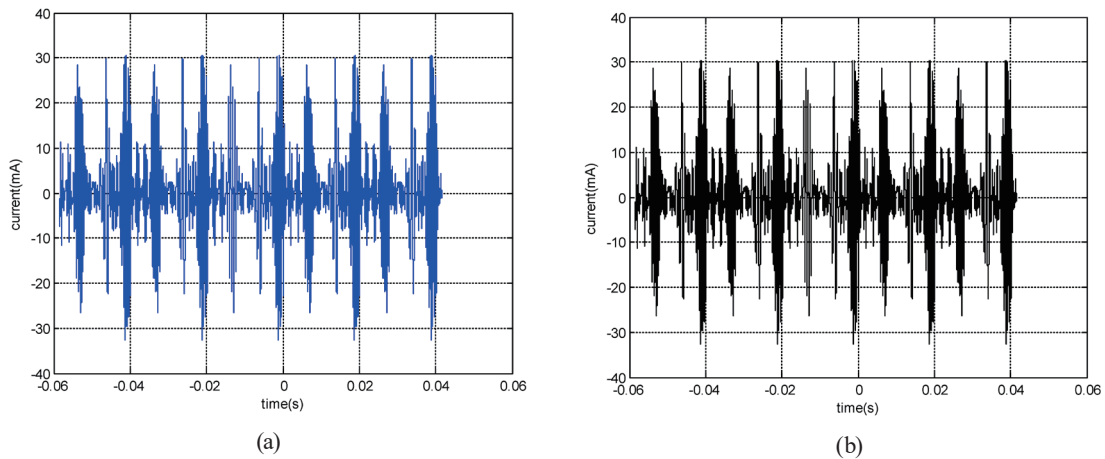


Fig. 11. (Color online) Curve diagram of current flowing through (a) high- and (b) medium-voltage capacitors.

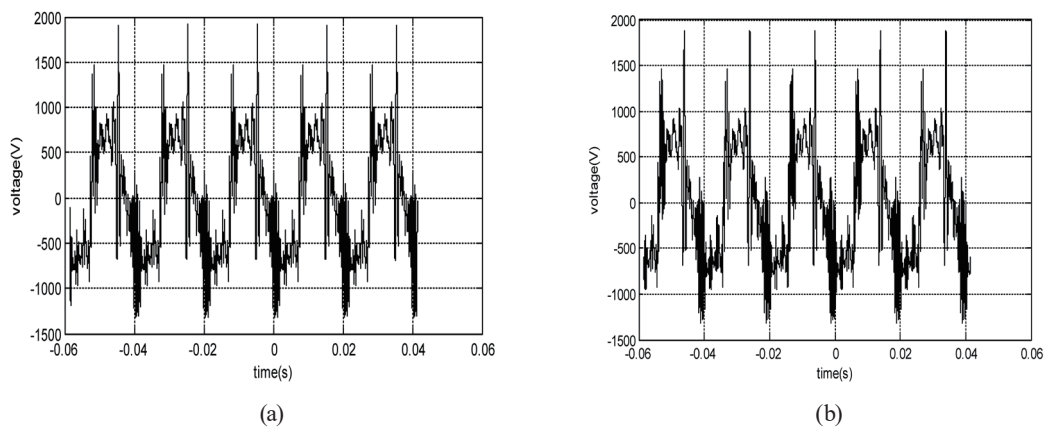


Fig. 12. Comparison of CVT high voltages (time domain). (a) CVT primary voltage after injection. (b) CVT primary voltage calculated using Eq. (2).

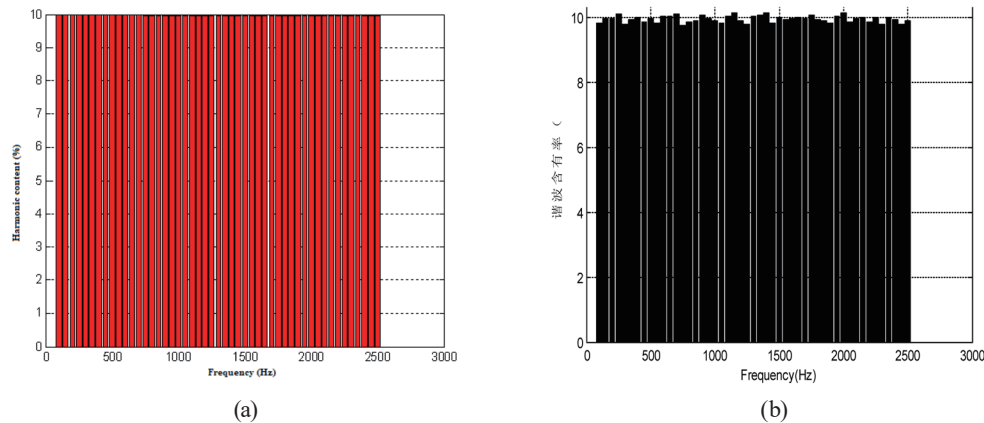


Fig. 13. (Color online) Comparison of CVT high voltages (frequency domain). (a) CVT primary voltage after injection. (b) CVT primary voltage calculated using Eq. (2).

Table 1
Harmonic errors.

Harmonic (order)	$U_1(j\omega)$ (V)	$U_2(j\omega)$ (V)	δ (%)	Harmonic (order)	$U_1(j\omega)$ (V)	$U_2(j\omega)$ (V)	δ (%)
1	220.00	220.00	—	27	22.07	22.21	0.62
3	21.99	22.41	1.89	29	21.99	22.13	0.63
5	21.99	22.24	1.12	31	22.02	22.33	1.43
7	21.99	22.21	0.99	33	22.03	22.08	0.24
9	21.98	22.30	1.46	35	22.00	22.07	0.34
11	21.98	22.01	0.12	37	22.05	22.37	1.43
13	21.96	22.18	0.98	39	22.04	22.21	0.77
15	22.03	22.37	1.56	41	22.00	22.32	1.44
17	22.03	22.20	0.76	43	22.01	22.03	0.08
19	22.02	22.22	0.91	45	21.93	22.05	0.56
21	22.02	22.04	0.1	47	21.97	22.12	0.67
23	22.02	22.31	1.31	49	21.93	22.05	0.54
25	22.01	22.04	0.13				

Note: $U_1(j\omega)$ is the primary-side injection voltage of the CVT during the test, $U_2(j\omega)$ is the calculated CVT primary-side voltage, and δ is the relative deviation of the harmonic ratio.

4.1 Comparison with traditional harmonic testing methods

To further analyze the validity of the CVT harmonic detection method based on capacitive current, the harmonic test of the above 220 kV CVT is carried out by using the conventional test method, that is, the same high-voltage harmonic is injected into the primary side of the CVT as the CVT harmonic testing method based on capacitive current. The CVT secondary voltage signal is derived for harmonic analysis. Finally, the test results of the two methods are compared. The results of such a comparison are shown in Figs. 14 and 15.

From Figs. 14 and 15, it can be seen that the results obtained by the traditional test methods have larger deviations than those obtained by the method of injecting the voltage with a harmonic content of 10% into the primary side of the CVT during the test. However, the results

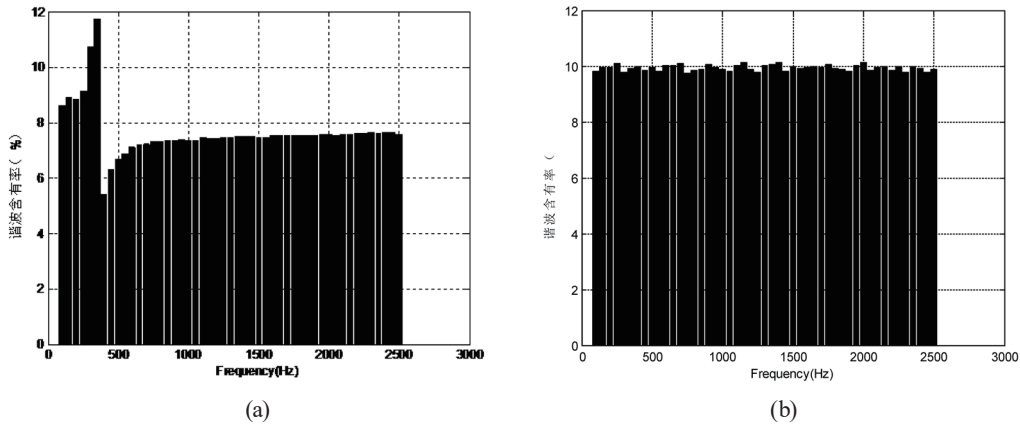


Fig. 14. Comparison of CVT high voltages (frequency domain). (a) Test results of traditional test method. (b) Capacitive current test results.

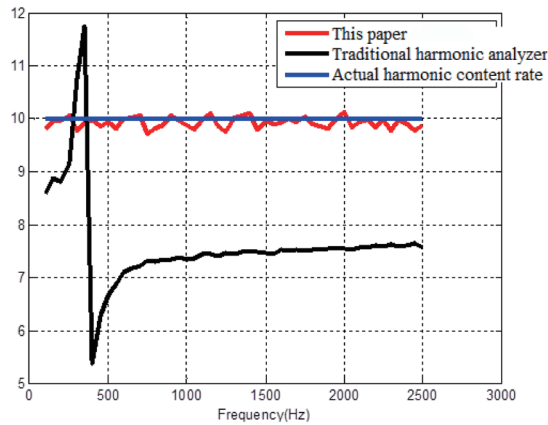


Fig. 15. (Color online) Comparison of conventional harmonic test data.

Table 2

Comparison of test results of two methods.

Harmonic (order)	1	3	5	7	9
Error of traditional method (%)	—	23.45	35.98	24.58	36.70
Error of capacitive current method (%)	—	1.89	1.12	0.99	1.46
Harmonic (order)	11	13	15	17	19
Error of traditional method (%)	21.23	21.56	27.67	18.34	16.21
Error of capacitive current method (%)	0.12	0.98	1.56	0.76	0.91
Harmonic (order)	21	23	25	27	29
Error of traditional method (%)	2.94	3.41	1.92	3.15	2.29
Error of capacitive current method (%)	0.10	1.31	0.13	0.62	0.63
Harmonic (order)	31	33	35	37	39
Error of traditional method (%)	12.56	19.67	18.33	11.25	17.68
Error of capacitive current method (%)	1.43	0.24	0.34	1.43	0.77
Harmonic (order)	41	43	45	47	49
Error of traditional method (%)	17.32	13.13	16.43	17.85	15.53
Error of capacitive current method (%)	1.44	0.08	0.56	0.67	0.54

of the CVT harmonic test based on capacitive current have a very small deviation from those obtained by the method of injecting the harmonic into the primary side of the CVT during the test. Table 2 shows the numerical results of the comparison of the two test methods. The maximum deviation of the harmonic content obtained by the traditional method is 35.98%. The harmonic content measured based on the capacitive current method is close to the harmonic level of the primary side of the CVT injected during the test, with a maximum deviation of 1.89%.

5. Conclusions

We focus on solving the problem that a traditional high-voltage system voltage harmonic measurement method does not consider the wide-band characteristics of a CVT and leads to inaccurate measurement results. On the basis of the principle of a CVT and the characteristic of capacitive reactance that changes with frequency, a capacitive current method for accurately measuring the voltage harmonics of the power grid by a CVT is proposed. By comparing the test results of the traditional harmonic test method and the actual harmonics of the power grid, the correctness and accuracy of the capacitive current method are verified. Finally, a test system based on the capacitive current method to accurately test the voltage harmonics of the power grid is designed. The harmonic test method based on capacitive current is safe and reliable, shows an anti-interference ability, accurately measures the harmonic level of the power system by a CVT, and eliminates the distortion and drift caused by a CVT in harmonic measurements, providing reliable data for harmonic control. The maximum deviation of the harmonic content obtained by the traditional method is 35.98%. The harmonic content based on the capacitive current method is close to that of the primary side of the CVT injected under test, with a maximum deviation of 1.89%. The method can be applied to the random testing and on-line monitoring of the harmonics of EHV, HV, and MV grids. The testing method is simple, reliable, and safe, and has solved the problem that a CVT cannot be applied to harmonic measurements, as specified in the GB/T14549-1993 “Power Quality Utility Harmonic”.

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