Postprint: Fault Handling and Root Cause Analysis of a 500kV Capacitive Voltage Transformer

Authors: Employment Land Use, Li Xianpeng, Dong Xinfeng, PENG Chenguang

Date: 2018-12-25T00:00:00+00:00

Abstract

For a case of secondary voltage abnormality fault in a 500 kV line Capacitor Voltage Transformer (CVT), field tests and disassembly inspection identified that the cause was a failed protective arrester connected in parallel with the compensation reactor within the CVT, due to insulation degradation. A qualitative phasor analysis was conducted to elucidate the reasons for the reduced magnitude and leading phase of the CVT secondary output voltage following the protective arrester failure. Furthermore, based on equipment test data, a quantitative analysis of the variation in secondary output voltage with load was performed.

Full Text

Preamble

Vol. 13 No. 12
DOI: 10.11985/2018.12.005
JOURNAL OF ELECTRICAL ENGINEERING

Treatment and Analysis of a 500kV Capacitor Voltage Transformer Fault

Gu Yongdi, Li Xianpeng, Dong Xinfeng, Peng Chenguang
(Maintenance Company of State Grid Zhejiang Electric Power Corporation, Hangzhou 310000, China)

Abstract

This paper investigates a secondary voltage abnormality fault in a 500kV line capacitor voltage transformer (CVT). Through field testing and disassembly inspection, the cause of the abnormal secondary voltage was identified as a failure of the protective arrester connected in parallel with the compensation reactor in the CVT, resulting in insulation degradation. A qualitative phasor analysis explains why the CVT secondary output voltage exhibited reduced magnitude and phase lead after the protective arrester failure. Combined with equipment test data, the variation of secondary output voltage with load is quantitatively analyzed.

Keywords: Capacitor voltage transformer, protective arrester, qualitative phasor analysis, secondary output voltage

1 Introduction

In high-voltage power systems of 110kV and above, capacitor voltage transformers (CVTs) are commonly used for voltage and power measurement, relay protection, and carrier communication applications [1]. Compared with electromagnetic voltage transformers, CVTs offer advantages including reasonable insulation structure, lower cost, and higher operational reliability, leading to their widespread adoption in ultra-high voltage and extra-high voltage systems.

A CVT consists primarily of a capacitive voltage divider and an electromagnetic unit. The electromagnetic unit comprises an intermediate transformer, compensation reactor, protective devices (typically zinc oxide arresters), and a damper. Operational experience indicates that common CVT failures include damage to capacitive or electromagnetic units, protective arrester failures at compensation reactor terminals, improper parameters in the damper’ s saturable reactor, poor grounding of the capacitive divider’ s last screen, and loose secondary wiring. These faults cause abnormal secondary voltage output, severely impacting protection and measurement functions and threatening grid safety [2-4]. During grid operation, cases of arrester failure in electromagnetic units due to resonant overvoltage or prolonged moisture aging, leading to secondary voltage abnormalities, have occurred frequently [3-5]. This paper presents a detailed analysis of a secondary voltage abnormality in a 500kV line CVT.

Case Overview

At 21:16 on December 26, 2017, a substation returned a 500kV line to service after maintenance. Following energization, monitoring systems indicated alarm signals from both line protection devices. Inspection revealed that the B-phase voltage in the three-phase line voltage was significantly low, with its phase angle leading the normal state by approximately 67°. The three-phase line voltages displayed by monitoring and protection equipment are shown in Table 1 .

Table 1. Three-phase line voltages

Equipment	Voltage
Monitoring Device	59.00 0° kV, 59.00 120° kV
Protection Device	19.13 -53° V

Equipment	Voltage

Infrared temperature measurement of the CVT body revealed that the B-phase electromagnetic unit reached 53°C, while the same location on A and C phases measured only 5°C. The B-phase temperature was significantly higher than the other phases, as shown in the infrared thermogram [Figure 1: see original paper].

3.1 Primary and Secondary Inspection

A detailed inspection of the line CVT B-phase was conducted, including the secondary terminal box. The inspection covered the intermediate transformer' s low-voltage side grounding, last screen grounding, secondary winding protection arresters, secondary terminal tightness, CVT test switch position, and oil level, with no obvious abnormalities found.

Secondary maintenance personnel inspected the line CVT terminal box. No moisture or condensation was present inside the box. All CVT secondary windings were properly grounded, secondary wiring was in good condition, pressure tests showed no abnormalities, and insulation resistance measurements of each secondary winding were normal, as shown in Table 2 .

Table 2. Insulation resistance of CVT secondary windings

CVT Secondary Winding	Insulation Resistance (MΩ)
First winding	2,000
Second winding	2,000
Third winding	2,000
Open-delta winding	2,000

Note: The CVT second winding is not connected to the CVT terminal box.

3.2 Diagnostic Tests

The faulty CVT is model WVB500-5H with a rated voltage ratio of $500/\sqrt{3} : 0.1/\sqrt{3} : 0.1/\sqrt{3} : 0.1/\sqrt{3} : 0.1$ and commissioning date of June 1, 2012. To further identify the fault cause, field testing personnel conducted diagnostic tests on the abnormal B-phase CVT after outage. The oil test data are shown in Table 3 .

Table 3. CVT oil test data

Parameter	Value (L/L)
Acetylene	0
Total hydrocarbons	6.83

Parameter	Value (L/L)
H	28.92

The oil test data show zero acetylene content, total hydrocarbons of only 6.83 L/L, and H of 28.92 L/L, all within the limits specified in DL/T 722-2004 "Guide for Analysis and Judgment of Dissolved Gases in Transformer Oil" [6]. Using the "three-ratio" method from DL/T 722-2004 to analyze characteristic gases, the results are shown in Table 4 .

Table 4. Three-ratio method results

Ratio	Value	Interpretation
C H /C H	-	Low-temperature overheating (<150°C)
CH /H	-	
C H /C H	-	

The three-ratio method indicates low-temperature overheating (<150°C) in the CVT electromagnetic unit, consistent with the field infrared temperature measurements.

Tests on the capacitive divider of the abnormal B-phase CVT included insulation resistance, dielectric loss, and capacitance measurements, with results shown in Table 5 .

Table 5. CVT component test data

Parameter	Value
Main insulation resistance	Normal
C (measured)	Normal
C (initial)	Normal
tan (%)	Normal
ΔCx (%)	Normal

Table 5 shows that all main insulation components are normal, capacitance values show no significant deviation from initial values, and dielectric loss values are within power equipment preventive test 规程 limits, indicating the capacitive divider is in good condition.

DC resistance tests were performed on the intermediate transformer electromagnetic unit, with secondary winding test results shown in Table 6 .

Table 6. DC resistance of CVT secondary windings

Winding	DC Resistance (mΩ)
1a-1n	Normal
2a-2n	Normal
3a-3n	Normal
da-dn	Normal

Table 6 shows normal DC resistance values for the intermediate transformer secondary windings, with no broken wires.

Insulation resistance and AC withstand voltage tests were conducted on the intermediate transformer electromagnetic unit, with results shown in Table 7 .

Table 7. Intermediate transformer test data

Test Item	Result
Secondary winding insulation resistance	Normal
AC withstand test (2kV/1min)	Normal
Protective arrester insulation resistance	0.1 MΩ (abnormal)

Table 7 shows normal secondary winding insulation resistance and AC withstand test results. However, the zinc oxide arrester parallel to the compensation reactor showed an insulation resistance of only 0.1 MΩ, which does not meet technical requirements.

Based on the above investigation and test results, the preliminary conclusion was that the line CVT B-phase voltage abnormality was likely caused by failure of the protective arrester parallel to the compensation reactor. To confirm the exact cause, the faulty CVT was replaced on-site and returned to the factory for disassembly inspection. After replacement, the line was returned to service and three-phase secondary voltages displayed normally.

4 Disassembly Inspection

To definitively determine the CVT fault cause, the unit was disassembled at the manufacturer (Rixin Electric, Wuxi). The internal structure of the electromagnetic unit is shown in Figure 3 [Figure 3: see original paper]. An induced overvoltage test was performed on the intermediate transformer at 12.5 kV with 150 Hz, with normal results. After removing the electromagnetic unit cover plate, inspection revealed transparent, clear insulating oil with no suspended impurities. After oil drainage, internal wiring was found intact with no discharge or heating traces. The compensation reactor DC resistance measured 298 Ω, meeting manufacturer design requirements.

The protective arrester parallel to the compensation reactor terminals is located externally in the secondary terminal box, as shown in Figure 4a [Figure 4: see original paper]. It is model HYW-2.0/4.5 manufactured by Xi' an High Voltage Porcelain Factory, with rated voltage 2 kV and continuous operating voltage 1.6 kV.

Insulation resistance measurement of the arrester using 1000 V yielded 0 MΩ. Multimeter measurement showed 1461 Ω. Disassembly inspection revealed a misaligned valve plate compression spring, a discharge mark at the center of the arrester resistor valve plate, and surface discharge with burn marks on the valve plate side and the arrester' s epoxy insulating tube inner wall, as shown in Figures 4b-4d [Figure 4: see original paper].

Based on the fault investigation and factory disassembly inspection, the cause of the line CVT secondary voltage abnormality was definitively identified as internal valve plate damage and insulation degradation in the protective arrester parallel to the compensation reactor terminals in the CVT electromagnetic unit.

5 Fault Cause Analysis

The CVT circuit contains capacitance and nonlinear inductance (the intermediate transformer' s excitation inductance Lm). During primary side energization, the transient process may produce ferroresonance. The resulting overvoltage can exceed the protective arrester' s operating voltage across the compensation reactor terminals, causing the arrester to operate and cut out the reactor, thereby destroying the resonant circuit parameters and eliminating internal ferroresonance [7-9]. The following sections use this line CVT secondary voltage abnormality case to qualitatively and quantitatively analyze why arrester failure leads to reduced secondary voltage magnitude and phase lead.

5.1 CVT Operating Principle

The CVT utilizes impedance division principle. The capacitive voltage divider circuit is shown in Figure 5 [Figure 5: see original paper]. Let the impedances of capacitors C1, C2 and compensation reactor L be:

$$Z_{C1} = r_{C1} + \frac{1}{j\omega C_1}$$

$$Z_{C2} = r_{C2} + \frac{1}{j\omega C_2}$$

$$Z_L = r_L + j\omega L$$

where r_{C1} and r_{C2} are equivalent resistances representing active losses in capacitors C1 and C2; C_1 and C_2 are capacitances of the high-voltage and intermediate-voltage capacitors; r_L is the resistance of the compensation reactor coil; and L is the inductance of the compensation reactor.

From circuit laws:

$$\dot{U}_1 = \dot{U}_2 + Z_{C1}(\dot{I} + \dot{I}_{C2}) + Z_L \dot{I}$$

$$\dot{U}_2 = Z_{C2}\dot{I}_{C2}$$

From equation (2):

$$\dot{U}_2 = \frac{Z_{C2}}{Z_{C1} + Z_{C2}}\dot{U}_1 - \frac{Z_{C1}Z_{C2}}{Z_{C1} + Z_{C2}}\dot{I}$$

where $Z_{C2}/(Z_{C1} + Z_{C2}) \approx C_1/(C_1 + C_2) = K$ is the CVT step-down ratio, and $Z_{C1}Z_{C2}/(Z_{C1} + Z_{C2}) = Z_C = r_C + \frac{1}{j\omega C}$ is the equivalent impedance of the capacitive voltage divider, with r_C and C being the equivalent resistance and capacitance, and $C = C_1 + C_2$.

Equation (3) can be further written as:

$$\dot{U}_2 = K\dot{U}_1 - (Z_C + Z_L)\dot{I} \quad (4)$$

From equation (4), the CVT equivalent circuit and phasor diagram are shown in Figure 6 [Figure 6: see original paper]. When C1 and C2 are fixed (i.e., step-down ratio K is constant), $\dot{U}_2$ varies with $\dot{I}$, making the voltage ratio error unable to meet accuracy requirements. Therefore, a compensation reactor is configured. With proper parameter matching where $\omega L_T = 1/\omega C$, $\dot{U}_2$ is only affected by the small voltage drop across resistances $r_C + r_L$, where L_T is the sum of compensation reactor inductance L and intermediate transformer leakage inductance L_k. From equation (4), the equivalent circuit is shown in Figure 6a, where Z is the equivalent load impedance referred to the primary side.

The capacitive divider output connects to the intermediate transformer, with its equivalent circuit shown in Figure 6b. The intermediate transformer's excitation current is very small and can be considered negligible, meaning the excitation impedance is nearly infinite. The simplified equivalent circuit is shown in Figure 6c, where $X_C = 1/(j\omega C)$, $X_k = j\omega(L + L_{kT})$, $r_k = r_C + r_L + r_{kT}$, and L_{kT} and r_{kT} are the short-circuit inductance and resistance of the intermediate transformer. The corresponding voltage balance equation is:

$$\dot{U}_2 = K\dot{U}_1 - [r_k + j(X_k + X_C)]\dot{I} \quad (5)$$

The corresponding phasor diagram is shown in Figure 6d. In compensation reactor engineering design, typically $X_k = X_C$ is used to minimize voltage ratio error. Phase error mainly originates from the power factor of voltage transformer load impedance Z. When $\cos\phi = 1$, $\dot{U}_2$ is in phase with $\dot{U}_1$. Additionally, since resistance r_k is very small, under normal operation it can be considered that $\dot{U}_2 \approx K\dot{U}_1$.

5.2 Post-Fault Phasor Analysis

After the protective arrester parallel to the compensation reactor terminals failed, its insulation resistance became 0 and it lost protective function. Multimeter measurement showed arrester resistance of 1461 Ω, far smaller than the compensation reactor impedance of 21.5 kΩ. The parallel combination approximates an equivalent resistance $r_M = 1461\,\Omega$. Capacitor equivalent resistance (approximately 27 Ω) and intermediate transformer short-circuit resistance are small enough to be neglected. The equivalent circuit is shown in Figure 7a, where $X_{kT} = j\omega L_{kT}$ is much smaller than X_C. The corresponding voltage balance equation becomes:

$$\dot{U}_2 = K\dot{U}_1 - [r_L + r_M - j(X_C - X_{kT})]\dot{I} \quad (6)$$

From equation (6), the post-fault CVT equivalent circuit exhibits capacitive characteristics, with current $\dot{I}$ leading voltage $\dot{U}_1$. The lead angle depends on the magnitude and power factor of the equivalent load. The corresponding phasor diagram is shown in Figure 7b [Figure 7: see original paper]. Clearly, the load voltage drop magnitude U_2 will also be smaller than KU_1, producing the observed abnormal condition of reduced secondary voltage magnitude and phase lead.

5.3 Quantitative Post-Fault Analysis

Based on the post-fault CVT equivalent circuit and test data from this case, quantitative calculation and analysis were performed. Table 8 provides the parameters used in this calculation.

Table 8. Calculation parameters

Parameter	Value
C1 (pF)	-
C2 (pF)	-
XkT (Ω)	-
U1 (kV)	295 -120°

Let the intermediate transformer secondary output voltage be $\dot{u}_2$. From Figure 7a:

$$\dot{u}_2 = \frac{\dot{U}_2}{k_T} = \frac{K\dot{U}_1}{k_T} \quad (7)$$

where k_T in equation (7) is the intermediate transformer voltage ratio, taken as 218. Using parameters from Table 8 and combining equations (6) and (7):

$$\dot{u}_2 = \frac{1757 - j20501 + Z}{59\text{"}} \angle -120\text{"} \quad (8)$$

Numerical simulation calculations were performed using MATLAB software for different equivalent load impedances. The results are shown in Figure 8 [Figure 8: see original paper].

Figure 8. Secondary voltage calculation results

Figure 8 shows that secondary output voltage magnitude u_2 increases with increasing equivalent load impedance Z, and the phase of secondary output voltage u_2 leads the normal angle (-120°). The smaller the equivalent load impedance, the greater the phase lead angle of u_2. The larger the power factor of the equivalent load impedance, the smaller the secondary output voltage magnitude u_2 and the smaller its phase lead angle (compared to the normal -120° angle).

Substituting the field-measured secondary voltage of $19.13\angle -53°$ into equation (8) yields $Z = 7229\angle 0.77°\,\Omega$. This means when the equivalent load Z is $7229\angle 0.77°\,\Omega$, the secondary voltage abnormality observed in this case will occur.

6 Conclusions

Based on the fault handling and cause analysis of a 500kV CVT arrester failure, this paper studied the causes of abnormal secondary output voltage due to protective arrester failure at CVT compensation reactor terminals, reaching the following conclusions:

1. The cause of the CVT secondary output voltage abnormality was internal valve plate damage and insulation degradation in the protective arrester parallel to the compensation reactor terminals in the CVT electromagnetic unit.
2. Maintenance measures for CVT protective arresters should be strengthened, including enhanced monitoring of CVT secondary voltage during operation and timely action when abnormalities are detected.
3. With the development of AC-DC hybrid grids, harmonic components in the power system have become significantly more complex, presenting new challenges for CVT parameter coordination. Professional technical personnel should be organized to optimize CVT parameter configuration to suppress potential ferroresonance.
4. A qualitative phasor analysis was performed on the protective arrester failure in CVT, explaining why the secondary output voltage exhibits reduced

magnitude and phase lead.

5. Combined with test data from this case, quantitative analysis was conducted on the variation of CVT secondary output voltage with load after protective arrester failure. Calculations determined that when the equivalent load Z is $7229\angle 0.77^\circ\,\Omega$, secondary voltage abnormalities will occur.

References

[1] Liu Shengjun. Safe operation discussion of capacitor voltage transformer[J]. Transformer, 2012, 49(1): 73-75.

[2] Hong Lezhou, Wu Yizhi, Li Jingxiang. Analysis and treatment on abnormal secondary voltage of capacitor voltage transformers[J]. Power Capacitor & Reactive Power Compensation, 2012, 33(3): 73-76.

[3] Zhang Guangdong, Wen Dingjun, Hu Chunjiang, et al. Treatment and analysis of one CVT fault[J]. Power Capacitor & Reactive Power Compensation, 2015, 36(1): 64-66.

[4] Yi Ran, Liang Yuxiong, Huang Qitai, et al. Fault analysis and test on secondary voltage loss of 220kV capacitor voltage transformer[J]. Power Capacitor & Reactive Power Compensation, 2014, 35(5): 86-90.

[5] Zhou Yue, Zhu Jianjun. Fault analysis on surge arrester of CVT[J]. Hebei Electric Power, 2007, 26(2): 50-51.

[6] People' s Republic of China Electric Power Industry Standard. DL/T 722-2014 Guide for analysis and judgment of dissolved gases in transformer oil[S]. Beijing: National Energy Administration, 2015.

[7] Gao Hongliang, Li Qionglin, Yu Xiaopeng, et al. Harmonic transfer characteristic of capacitor voltage transformer[J]. Power System Technology, 2013, 37(11): 3126-3129.

[8] Wang Liming, Fang Bin. Simulations on transient characteristic of 500kV capacitor voltage transformer[J]. High Voltage Engineering, 2012, 38(9): 2389-2396.

[9] Du Yongping, Cao Xinyi, Li Yizhong, et al. The theoretical analysis and disposal of CVT in the ferroresonance[J]. Journal of Anhui Electrical Engineering Professional Technique College, 2008, 13(3): 2-5.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.