Resonant Overvoltage Mechanism of Electromagnetic Voltage Transformer in 6kV Non-Direct Grounding System

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Abstract. This paper expounds the principle and conditions of ferromagnetic resonance generation, and analyzes the ferromagnetic resonance accident of Hetan substation. The article explains the concept of "illusive grounding" caused by ferromagnetic resonance, combined with the Peterson curve. The conditions for the generation of ferromagnetic resonance are analyzed, and the common measures to eliminate ferromagnetic resonance are given.

1. Introduction
There are many capacitors and inductive components in the power system. When the system operates or has some malfunctions, the parameters of these inductive and capacitive components may form various electrical loops. Under some certain circumstances, even resonance may occur, causing severe overvoltage in some components of the system, jeopardizing the safety of electrical equipment and affecting the reliability of protective equipment.

The Hetan Substation, the object studied in this paper is a neutral point ungrounded system in 6 kV voltage level. When the parameters of capacitance and the voltage transformer on the bus line are not properly matched, it is easy to cause a series of ferromagnetic resonance. The magnitude of the resonant overvoltage can be measured at the opening point of triangular on the second auxiliary winding side of the voltage transformer. This ferromagnetic resonance can cause illusory grounding, one phase or two-phase’s voltage rising greatly, affecting the normal operation of electrical equipment, jeopardizing the operation of measuring equipment and even causing accidents.

2. Ferromagnetic resonance accident
The power of Hetan Substation is introduced by the State Grid Changyi 220 kV Substation and Weifang 500 kV Substation to the two independent 6 kV power supplies (one main transformer and one standby) respectively. The substation is equipped with four voltage transformers with a capacity of 40000kVA. The group runs in “two groups work and two group standby” mode (the circuit diagram is showed in Figure 1). In the resonance accident, the fuse of 6 kV voltage transformer fuses, causing the malfunction of the low-voltage protection in important equipment, even constitutes a shutdown accident.
Figure 1. Circuit diagram of Yecheng Substation

The main performances of Hetan Substation resonance:

1. During the resonance, the relative ground voltage rises, the voltmeter swings at a low frequency and a system grounding signal appears. Then the fuse of voltage transformer fuses and resonance disappear automatically.

2. According to the analysis of voltage fault waveform, the resonant frequency is about $\frac{1}{2}$ times the frequency of power system. The amplitude of current in primary side is about 1.5A, resulting in the fusion of voltage transformer fuse.

3. If capacitor devices are put into operation at this time, which is equivalent to increase the capacitance in system, the resonance frequency would reduce to nearly $\frac{1}{3}$ time of the power frequency.

3. Ferromagnetic resonance related mechanism

In the system, electromagnetic voltage transformers are often connected to the busbars connected to the substation or generator to monitor the bus voltage. The voltage transformer acts to isolate the high voltage, and converts the primary side high voltage into a standard secondary voltage of 100V or 100/3V on the secondary side in proportion to the secondary circuit relay protection device, automatic device and measuring instrument. The device acquires the primary side voltage information. At the same time, the voltage transformer can isolate the high voltage from the electrical workers, ensuring the safety of the equipment and personal safety.

A potential transformer (PT) is a transformer with a core. It is mainly composed of a primary coil, a core and an insulating structure. When a voltage $U_1$ is applied to the primary winding, a magnetic flux $\phi$ is generated in the iron core. According to the law of electromagnetic induction, a secondary voltage $U_2$ is induced in the secondary winding, and $U_1$ and $U_2$ are proportional to each other. This realizes the transformation of the primary and secondary voltages.

In the neutral point not directly grounded system, the primary side of the voltage transformer adopts the star connection method (the wiring diagram is shown in Figure 1), and the neutral point of the primary side of the voltage transformer is directly grounded, so the relative excitation inductances $L_1$, $L_2$, $L_3$ and the A, B, and C three-phase bus ground-to-ground capacitors $C_0$ each form an independent loop. Here, the magnetizing inductance and the capacitance to ground can be regarded as the three-phase load to the ground. As shown in Figure 2.
In the figure, \( E_1 \), \( E_2 \), and \( E_3 \) are the three-phase power supply potential of the 6kV system A, B, and C respectively, and \( C_0 \) is the capacitance of each phase bus to ground. The distributed capacitance due to the long straight wire mainly depends on the cable geometry and parameters of cable, such as cable materials, so it can be approximated that the capacitance of each phase conductor to ground remains basically the same in the system operation, and the relative admittance can be approximately written as:

\[
Y_1 = j\omega C_0 + \frac{1}{j\omega L_1} \\
Y_2 = j\omega C_0 + \frac{1}{j\omega L_2} \\
Y_3 = j\omega C_0 + \frac{1}{j\omega L_3}
\]

During normal operation, the three-phase voltage is evenly distributed, and the magnetizing inductance \( L_1 = L_2 = L_3 = L_0 \), so there is \( Y_1 = Y_2 = Y_3 = Y_0 \), the loads of three-phase are balanced, the system is a symmetrical three-phase system, and the displacement voltage of neutral point is zero.

When the system is disturbed or malfunctions, it may cause the voltage of one or two phases to rise. Now assume that the fault type is A-phase metallic grounding, the grounding instant, the A-phase potential and the ground potential are equal, both are zero potential, and the neutral point potential (offset voltage) is no longer zero, and rises to the phase voltage. Correspondingly, the relative ground voltages of B and C rise to the line voltage. The A, B, and C three-phase voltage vector diagrams of the system before and after the fault are as follows:

![Figure 2. Schematic diagram of ferromagnetic resonance](image)

![Figure 3. Normal three-phase voltage vector](image)
As the voltages of the B and C phases rise instantaneously, the excitation current in the excitation windings of the B and C phases of the voltage transformer instantaneously increases, causing the corresponding excitation coil to be saturated, and the equivalent inductance values $L_B$ and $L_C$ of the excitation coil are reduced, so that $Y_B \neq Y_0$, $Y_C \neq Y_0$, and then the system is a three-phase asymmetric system, the system neutral point is displaced, and the displacement voltage $U_N$ is generated.

According to Kirchhoff’s first law:

$$U_N = \frac{E_1Y_1+E_2Y_2+E_3Y_3}{Y_1+Y_2+Y_3} \quad (4)$$

The size of $Y_i$ is related to the size of $L_i$ and $C_0$. Assuming that the system is normal, the admittance of the inductive reactance $\frac{1}{\omega L_A} = \frac{1}{\omega L_B} = \frac{1}{\omega L_C} = \frac{1}{\omega L_0} < \omega C_0$, then the system admittance $Y_A$, $Y_B$, $Y_C$ are all capacitive; When the disturbance is generated, the equivalent inductance $L_B$ and $L_C$ of the phase transformer BC phase excitation winding are reduced. When $L_B$ and $L_C$ are reduced to a certain extent, there may be $\frac{1}{\omega L_B} > \omega C_0$ and $\frac{1}{\omega L_C} > \omega C_0$. At this time, the BC phase admittance $Y_B$, $Y_C$ are inductive, the capacitive A-phase admittance $Y_A$ is offset by the inductive BC phase admittance $Y_B$, $Y_C$, and the total admittance $Y_A + Y_B + Y_C$ shows a decreasing trend, according to the formula (4), the neutral point offset voltage $U_N$ increases.

If the disturbance is such that the value of the total admittance $Y_A + Y_B + Y_C$ approaches zero, that is, the internal inductive part and the capacitive part of the three-phase system are self-compensated, and the power supply frequency is equal to the system frequency, that is, a severe series resonance is formed. It can be seen from the formula of the neutral point displacement voltage $U_N$ that the neutral point displacement voltage sharply rises at this time.

The three-phase wire-to-ground voltages $U_A$, $U_B$, and $U_C$ are equal to the vector sum of the three-phase power supply voltage $EEABEC$ and the neutral point displacement voltage $U_N$.

When the neutral point displacement voltage $U_N$ is small, the result of vector superposition may cause a relative ground voltage to rise, and the other two relatively lower ground voltages; or increase the relative ground voltages and a relative ground voltage decreases.

4. Three common measures for eliminating ferromagnetic resonance in neutral point ungrounded systems

(1) Select the electromagnetic voltage transformer with better excitation characteristic, or use the capacitive voltage transformer instead.

(2) In the electromagnetic voltage transformer, the secondary auxiliary winding with open delta
connection is installed with the resistor of \( R \leq 0.4X_m \) at the opening triangle \( (X_m \) is the line voltage, the voltage transformer single-phase primary winding excitation coil is converted to Auxiliary secondary reactance of secondary winding.

3. Use temporary operation, such as temporarily withdrawing some capacitive devices on the bus to reduce the system capacitance current, while reducing the system capacitance, according to the Peterson ferromagnetic resonance curve to make the system into the non-resonant region.

4. A nonlinear resistor (typically 50~100k\( \Omega \)) is connected to the neutral point of the voltage transformer.

5. For some special systems, the necessary calculations and analysis should be carried out in conjunction with the actual project, and corresponding measures should be taken to prevent accidents after putting into operation.

5. Ending

After analysis, the fundamental reason for the resonance of the 6kV system in Hetan substation is that the excitation characteristics of the busbar voltage transformer are poor, the excitation curve is prematurely saturated, the system inductance is too small, the system capacitive reactance is too large, and the ratio of \( \frac{X_C}{X_m} \) falls into the resonance region. When there is an excitation condition in the system, resonance occurs.

In the 6kV system of Hetan Substation, the voltage transformer is finally used to eliminate the resonance method by the neutral point-connected nonlinear resistor. At the same time, the harmonic elimination device is used in the triangular opening of the auxiliary secondary winding, and good results have been obtained through testing. After the actual operation analysis, when the neutral point of the voltage transformer is connected to the resistor \( R_0 = 40.8 \) k\( \Omega \), the harmonic elimination effect is better, and the harmonic elimination operation is simple.

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