Mechanism analysis of ferromagnetic resonance of electromagnetic voltage transformer in neutral ungrounded system

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Abstract. In the neutral point ungrounded power distribution system, due to the nonlinear characteristics of the electromagnetic voltage transformer (PT) excitation inductance, ferromagnetic resonance overvoltage is easily generated under certain conditions, which seriously affects the safe operation of the system. This paper takes the Yecheng substation 6 kV distribution network as the model, and uses ATP-EMPT electromagnetic transient calculation software to theoretically analyze the characteristics and mechanism of ferromagnetic resonance caused by electromagnetic voltage transformer, and points out the main problems of ferromagnetic resonance in PT operation. This article discussed the existing harmonic elimination measures, proposed some effective suppression schemes and demonstrated the effectiveness of some mainstream harmonic elimination methods. The author's work can provide a good reference for the prevention and control of ferromagnetic resonance overvoltage, and it also has high practical value for improving the power supply safety and reliability of the distribution network.

1. Introduction
In a neutral point ungrounded distribution system, there are three types of overvoltage effects that are most severe: lightning overvoltage, arc grounding overvoltage, and ferromagnetic resonance overvoltage. The first two types of overvoltage have relatively clear and effective measures for protection. For example, lightning surges are generally limited by lightning protection devices such as lightning arresters; arc grounding overvoltages are generally connected to arc suppression devices such as arc suppression coils to attenuate its effects and so on.

However, for the ferromagnetic resonance overvoltage caused by the matching of the system capacitance and inductance parameters, although there are many existing harmonic elimination measures, because the mechanism of resonance generation is not fully understood, and the actual operation of the power supply system is complicated and varied, the current suppression, the various measures to eliminate the influence of ferromagnetic resonance are evaluated differently. This paper studies this phenomenon.

2. Ferromagnetic resonance mechanism
In the neutral point ungrounded system, the equivalent circuit diagram of the power supply potential, the phase voltage transformers and the respective ground capacitors is shown in Figure.1. In Figure.1,
$L_A, L_B,$ and $L_C$ are the respective magnetizing inductances, $C_0$ is the relative capacitance, and $E_A, E_B,$ and $E_C$ are three-phase power sources. The relative admittances are:

$$Y_X = j \left( \omega C_0 - \frac{1}{\omega L_X} \right)$$

(1)

In the normal operation of the electromagnetic voltage transformer, the PT excitation inductance is much larger than the system capacitive reactance, namely:

$$\omega L \gg \frac{1}{\omega C}$$

(2)

The relative ground load is $Y_0$ and is capacitive, $U_N = 0 \text{kV}$, that is, the neutral point and zero potential of the power grid coincide, there is no neutral point voltage displacement phenomenon, and the sum of the total charge of the system line to ground capacitance is zero. Therefore, the system does not have a resonance condition during normal operation, and resonance does not occur.

However, when the grid breaker is grounded to the ground bus (especially the light loaded bus line), or a single-phase arcing grounding occurs due to lightning strikes, etc., the system is faulty or disturbed, and the non-fault is added to the electromagnetic voltage. The voltage on the transformer excitation coil is raised from the phase voltage to the line voltage. When the ground fault continues, under the action of the line voltage, the charge flows at the wire and the ground with the ground point as a path to form a capacitor current. When the ground fault is eliminated, the path is cut off, and the relative ground voltage is restored from the line voltage value to the original phase voltage value. The charge of the corresponding line voltage carried by the original non-faulty phase conductor needs to find the path to the ground. Because the original line ground path is cut off, the free charge has to flow to the ground through the grounded winding of the star-connected electromagnetic voltage transformer. If the line-to-ground capacitance is large, there will be a lot of accumulated free charges. In the process of venting to the earth, the excitation coil core will be saturated, and the excitation coil inductance $\omega L$ will decrease. When the excitation coil inductance continues to decrease, to $\omega L = 1/\omega C$, a linear resonance is formed between the PT excitation coil and the line-to-ground capacitance, thereby causing the electromagnetic voltage transformer to resonate.

The electromagnetic voltage transformer has an inductive reactance greater than the capacitive reactance ($\omega L > 1/\omega C$) under normal operating conditions, so the system does not have a resonant condition during normal operation and resonance does not occur.

However, in the event of a system failure or disturbance, the PT excitation coil voltage would increase from the phase voltage to the saturation of the excitation coil core, and the inductive reactance $\omega L$ would reduce. With the inductance of the excitation coil continues to decrease, even drop to $\omega L = 1/\omega C$, a linear resonance is formed between the PT excitation coil and the line-to-ground capacitance, resulting in an overvoltage. This phenomenon is called ferromagnetic resonance.

![Figure 1. Series resonant circuit diagram](image)

The research set Yecheng substation as the object. Yecheng substation is a neutral point ungrounded system. The grounding parameters of the system mainly include power equipment, cable-to-ground capacitance $C_0$ and voltage transformer's excitation inductance $L$, as shown in Figure 2.
In normal condition of operation, the magnetizing inductance is very strong, the system impedance is capacitive, and the three phases could basically keep balance. And the displacement voltage $U_0$ of the neutral point of the power grid is close to the value of zero. However, when the system has a phase-to-earth fault due to a wire breakage, a lightning strike or any other reasons, the relative ground voltage $U_A$ would reduce to near zero, and the non-fault relative ground voltage ($U_B$, $U_C$) would instantaneously increase, which would be three times the value of the original one. The excitation current of the $B$ Phase and $C$ Phase of the voltage transformer suddenly increases, the excitation coil is saturated, and the equivalent excitation inductance $L_0$ decreases, resulting in unbalanced three-phase impedance, thereby generating a neutral point displacement voltage $U_0$.

After the $B$ Phase is grounded, the system is disturbed, the $B$ Phase ground fault point flows through the 6kV system ground capacitance current, the sound phase $A$ Phase and $C$ Phase voltage rise to the line voltage, and the transformer $A/C$ Phase primary side field winding The excitation current suddenly increases, causing the excitation winding to become saturated. The saturation inductance of the transformer after saturation becomes smaller. When the system-to-ground inductance matches the parameter of capacitance to ground, that is, when $\omega L = 1/\omega C$, the system would lead to resonance and ferromagnetic resonance would take place.

### 3. Measures to suppress ferromagnetic resonance

Eliminating resonance generally takes measures from three aspects:

1. Change the inductance and capacitance parameters of the system by the Peterson curve so that it does not have the resonance matching condition. The measures attributed to this type of harmonic elimination method mainly include: installing a three-phase star capacitor group with neutral point grounding on the busbar, and selecting a voltage transformer with good excitation characteristics to reduce the number of parallel connections in the same network, and the neutral point of the PT high voltage side. String single-phase PT (4PT method), system neutral point would be grounded by arc suppression coil.

2. Increasing the system zero-sequence loop damping resistance, consuming the resonant energy of the zero-sequence loop after resonance. If the neutral point of the PT high voltage side is grounded via a non-linear resistor, the open delta winding of the voltage transformer is connected in series with a damping resistor or a harmonic elimination device.

3. Change the system wiring method. Change the system to ground via a small resistor, or operate at the moment of resonance, such as cutting off the voltage transformer, disconnecting the neutral point grounding wire of the high voltage side of the voltage transformer or switching the neutral point of the system side to temporary grounding.

A detailed study on several mainstream harmonic elimination methods would be listed as follows:

#### 3.1 System neutral point is grounded by arc suppression coil
The neutral point of the system power supply is grounded via the arc suppression coil. The wiring diagram is shown in Figure 3.

![Figure 3. Circuit diagram of system neutral point grounded by arc suppression coil](image)

Grounding the neutral point of the system through the arc suppression coil is equivalent to connecting the arc suppression coil on each phase excitation inductance of the main voltage transformer, because the value of the inductance of the arc suppression coil is much smaller than the inductance of the excitation winding, and the resonance condition would be broken after the parallel connection, the system capacitance. The inductance parameters cannot meet the requirements of resonance, making the resonance difficult to occur. The harmonic elimination of the neutral point of the system through the arc suppression coil preserves all the advantages of the neutral point ungrounded system, and could prevent the occurrence of ferromagnetic resonance as well.

### 3.2 Voltage transformer high-voltage side neutral point is grounded by single-phase PT

The neutral point of the high voltage side of the voltage transformer is grounded through a single-phase PT. The wiring diagram is shown in Figure 4.

![Figure 4. Circuit diagram of voltage transformer high-voltage side neutral point is grounded by single-phase PT](image)

The high-voltage winding side of the main voltage transformer adopts the star connection method; the neutral point of the high-voltage side is grounded to earth by a single-phase voltage transformer (4 PT); the secondary auxiliary winding side of the main voltage transformer adopts the delta connection method, of which the triangular opening is short-circuited; the single-phase voltage transformer’s secondarily the winding is on the secondary winding coil of the main voltage transformer.

With this type of wiring, when a single-phase ground fault occurs in the system or other causes cause asymmetrical distribution of the three-phase voltage of the system, the zero-sequence voltage in the system will be proportionally distributed according to the magnitude of the zero-sequence impedance. Since the secondary auxiliary winding of the main voltage transformer is short-circuited by the triangle, the zero-sequence impedance of the main voltage transformer is extremely small, and the zero-sequence voltage is almost entirely borne by the single-phase voltage transformer on the
ground line, which means that three phases’ voltages of the main voltage transformer could stay basically around the phase voltage, instead of rising to the line voltage. This phenomenon ensures the system cannot meet the requirements of resonant excitation condition. And, also, the impedance of the single-phased voltage transformer itself has the effect of expanding the energy of resonance.

3.3 Voltage transformer high-voltage side neutral point string nonlinear resistance
The neutral point of the high voltage side of the voltage transformer is grounded via a non-linear resistor. The circuit diagram is shown in Figure 5.

![Circuit diagram of system neutral point grounded by nonlinear resistance](image)

Figure 5. Circuit diagram of system neutral point grounded by nonlinear resistance

The high-voltage winding coil of the main voltage transformer adopts the star connection method; the neutral point of the high-voltage side is grounded to earth through the nonlinear resistor, and the secondary auxiliary winding of the main voltage transformer adopts the delta connection method.

In the high voltage side of the voltage transformer, the neutral point grounding wire is connected to the resistor, which is equivalent to connecting a non-linear resistor in each phase of the three-phased voltage transformer. When the grid is in normal operation, the voltage on the nonlinear resistor is not high. The nonlinear resistor is high in value of resistance, which means resonance is not easy to occur in the initial stage. When a single-phased grounded to earth accident occurs in the system, a high voltage appears on the nonlinear resistor, then the resistance would exhibit a low resistance value. The resistor can share the voltage applied to the voltage transformer, thereby limiting the current in the voltage transformer. The nonlinear resistor could also limit the high-amplitude current, which flows through the voltage transformer when the arc is grounded. Making the current in the high voltage winding coil to a small level, the nonlinear resistor is equivalent to improving the volt-ampere characteristics of the voltage transformer.

4. Conclusion
At present, when relating about the ferromagnetic resonance phenomena in the power system, we tend to pay attention to the governance after the accident while ignoring the process of prevention. In view of the importance of substation power reliability for the safe and stable operation of the system, the ferromagnetic resonance overvoltage threatens the normal operation of the substation, and measures should be done before the accident happens. We should focus on the beginning of the design of the power supply system, and considering about various operating conditions of the substation, and make the substation reliably predicted before it is put into operation, making the equipment of substation as far from the resonance region as possible to avoid resonances; even if it is unavoidable, it can be based on the predicted resonant resonance type as much as possible. Considering about other factors, such as communication systems, the requirements on protection of the personal and electrical equipment, etc., we should take appropriate harmonic elimination measures to ensure reliable operation of the substation.

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