Analysis and Simulation of Ferroresonance Mechanism of Potential Transformer Based on Harmonic Balance Method

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Abstract. In power systems with voltage levels of 66kV and below, the bus potential transformer (PT) burnout accidents frequently occur. Based on the harmonic balance method, this paper analyzes the ferromagnetic resonance mechanism, and analyzes the fault waveform recorded by the fault recording system in the 66kV substation, and obtains the possible cause of the accident. The PSCAD/EMTDC software was used to build the electromagnetic transient model, and the PT burnout process was restored. It is concluded that the main cause of the accident is the ferromagnetic resonance overvoltage caused by the saturation of the PT iron core. Three solutions are also proposed, the PT primary side neutral point ground by nonlinear resistance, open triangle of PT short-time access a little resistance, and PT with better excitation characteristics are selected. The feasibility of the solutions is verified by simulation.

1. Introduction

In the 66kV and below neutral point ungrounded system, the low-voltage side of the electromagnetic voltage transformer has a small load and is close to no-load. The high-voltage side has a high excitation impedance, and the system voltage is greatly disturbed (such as lightning striking, single-phase grounding fault disappearing and switching operation, etc) [1-3], the high-voltage side magnetizing inductance is likely to cause saturation. After saturation, the inductance value decreases rapidly. It forms a special three-phase or single-phase resonance circuit with the wire-to-ground capacitance or the stray capacitance of other equipment, and can excite various harmonic ferromagnetic resonance overvoltage, which seriously affects the safe operation of the system [4].

Literature [5] proposed a subharmonic resonance detection method based on wavelet packet transform analysis, which used the characteristics of wavelet multi-resolution analysis to analyze the ferromagnetic resonance signal, and applied this method to successfully detect that the system has 1/3 times frequency resonance. Literature [6] first applied the Atomic Decomposition Method to the field of ferromagnetic resonance detection, selected a damped sine atom library for the ferromagnetic resonance signal, and introduced the improved particle swarm algorithm into the matching pursuit algorithm as an algorithm for solving the best atom, design the process of atomic decomposition.
method to analyze the ferromagnetic resonance, and propose an effective ferromagnetic resonance
detection method. Literature [7] based on the time series analysis method, taking the time series of
ferromagnetic resonance overvoltage as the object, and through theoretical derivation, proposed a
method for extracting the nonlinear characteristic quantities of the ferroresonance overvoltage, which
provides a comprehensive analysis of the ferroresonance overvoltage in the power system.

This paper analyzes the mechanism of ferroresonance by the harmonic balance method [8-9], and
analyzes the cause of a 10kV bus voltage transformer burnt out in a 66kV substation based on the fault
record. The simulation analysis result is consistent with the recording result, which proves the
rationality of the analysis. It is verified by simulation and a reasonable Improvement measures in order
to reduce the incidence of such failures.

2. Principle analysis of ferroresonance in harmonic balance method

The simplified equivalent circuit of the ferromagnetic resonance system is shown in the figure 1. In
figure 1, L is the magnetizing inductance of PT, and C is the equivalent capacitance of the system to
ground.

![Figure 1. Simplified equivalent circuit diagram of ferroresonance system](image)

Since the capacitance and inductance value of ferromagnetic resonant circuit are not constant, it is
possible to produce fundamental frequency resonance with a resonant frequency equal to the power
supply frequency [10-11], as well as higher frequency harmonics and subharmonic resonance. The
resonant frequency of ferromagnetic resonance is

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

(1)

The harmonic balance method is used to analyze the fundamental frequency ferromagnetic
resonance characteristics of the ferromagnetic resonance circuit shown in Figure 1. The magnetization
characteristic of the PT primary side equivalent nonlinear inductance is

\[ i = a_1\varphi + a_3\varphi^3 (a_1, a_3 > 0) \]  

(2)

A third-order polynomial is used to equivalent the nonlinear excitation characteristics of the
excitation inductance L, and it can also be expressed by a higher-order polynomial. According to
Kirchhoff’s voltage law (KVL), the loop voltage equation is

\[ L\frac{di}{dt} + Ri + \frac{i}{C}dt = \sqrt{2}E \sin(\omega t) \]  

(3)

Substituting equation 3 into equation (2) and seeking the derivation, the loop differential equation
can be obtained as

\[ \frac{d^2\varphi}{dt^2} + R(a_1 + 3a_3\varphi^2) \frac{d\varphi}{dt} + \frac{a_1 + a_3\varphi^3}{C} = \sqrt{2}\omega E \cos(\omega t) \]  

(4)
Using the harmonic balance method to solve above differential equation, the magnetic flux flowing through the inductance can be expressed as the sum of the sine components of the fundamental frequency flux and a series of high frequency and subharmonic frequency flux:

\[ \varphi(t) = \Phi_1 \sin(\omega t + \theta_1) \]

\[ + \sum_{n=1}^{\infty} \Phi_{2n+1} \sin[(2n+1)\omega t + \theta_{2n+1}] \]

\[ + \sum_{n=1}^{\infty} \Phi_{1/2n+1} \sin[\omega t / (2n+1) + \theta_{1/2n+1}] \]  

If only the fundamental ferromagnetic resonance is considered, other harmonic components are ignored, bring equation 5 into equation 4, and the influence of resistance R is ignored, let R=0, can obtain

\[ 9a_1\Phi_1^6 + 24a_1(a_1 - \omega^2 C)\Phi_1^4 \]

\[ + 16(a_1 - \omega^2 C)^2 \Phi_1^2 - 32\omega^2 C^2 E^2 = 0 \]  

Assume

\[ x = \Phi_1^2 \]  

Bring equation (7) into equation (6), and obtain the derivative

\[ f'(x) = 27a_1x^2 + 48a_1(a_1 - \omega^2 C)x \]

\[ + 16(a_1 - \omega^2 C)^2 \]  

The discriminant is

\[ \Delta = 576a_1^2(a_1 - \omega^2 C)^2 \]  

(1) When \( a_1 = \omega^2 C \) or \( a_1 > \omega^2 C \), equation \( f(x) = 0 \) has a unique non-negative real root, this root increases with the increase of the power supply potential E, so no resonance occurs.

(2) When \( a_1 < \omega^2 C \), the discriminant is greater than zero.

When the power supply potential \( E = 0 \), \( f'(x) = 0 \) have \( x = 0 \) and \( x = \frac{4(\omega^2 C - a_1)}{3a_3} \) two real roots,there are two working points.

When the power supply potential \( E > 0 \), \( f'(x) = 0 \) have \( x_m = \frac{4(\omega^2 C - a_1)}{9a_3} \) and \( x_n = \frac{4(\omega^2 C - a_1)}{3a_3} \) two positive real roots, \( x_m > x_n \), bring into equation (8),

\[ f(x_m) = \frac{256(\omega^2 C - a_1)^3}{81a_3} - 32\omega^2 C^2 E^2 = 0 \]  

\[ f(x_n) = -32\omega^2 C^2 E^2 < 0 \]  

When \( f(x_m) > 0 \) which is \( E < \sqrt{\frac{8(\omega^2 C - a_1)^3}{9a_3\omega^2 C^2}} \), equation \( f(x) = 0 \) have \( x_1, x_2 \) and \( x_3 \) three roots,as shown in figure 2, Where \( x_1 \) is the unstable working point, \( x_2 \) increases as the power supply potential E decreases, and will finally move to the \( x_1 \) and \( x_3 \) working points after being disturbed,
the smaller value of $x_1$ is the normal operating point of the loop, and the larger value of $x_3$ is the resonance point.

When $E = \sqrt[3]{\frac{8(\omega^2C-a_i)^3}{9a_i\omega^2C^2}}$, equation $f(x) = 0$ have $x_1$ and $x_3$ two positive real roots, at this time, $x_1$ corresponds to an unstable working state, and ferromagnetic resonance is prone to occur.

When $E > \sqrt[3]{\frac{8(\omega^2C-a_i)^3}{9a_i\omega^2C^2}}$, equation $f(x) = 0$ has $x_3$ one positive real root, at this time, the loop self-oscillates.

Therefore, it can be concluded that the necessary conditions for the occurrence of fundamental frequency ferromagnetic resonance are $a_i < \omega^2C$, which is

$$\frac{1}{a_i} = \left. \frac{d\varphi}{dl} \right|_{a_i} = L_0$$

In equation (12), $L_0$ is the initial value of the nonlinear inductance, so we can get the necessary conditions for ferromagnetic resonance as

$$\omega L_0 > \frac{1}{\omega C}$$

![Graph of function f(x)](image)

**Figure 2.** Graph of function $f(x)$

Therefore, the ferromagnetic resonance can be excited only when the equivalent inductance in the system is greater than the capacitive reactance, that is, when the system is inductive and excited by large disturbances, the iron core of the voltage transformer will be saturated, and the ferromagnetic resonance may occur.

When the line of power system is very short, the equivalent capacitance $C$ will be small. When the excitation of PT is bad, the probability of iron core saturation is very high, or there are more PTs in the power grid, and the equivalent inductance of the system is small, the risk of high-frequency resonance is greater. When the capacitance $C$ of the system to the ground is large, the subharmonic resonance of the system is more likely to occur [12]. Subharmonic and high frequency harmonic ferromagnetic resonance can be maintained because there are a large number of harmonic sources in the system [13].

GE engineer Peterson has confirmed through a lot of experiments that no matter what kind of ferromagnetic resonance, it will only appear within a certain range of power system parameters. According to Peterson's experiment [14], ferromagnetic resonance is divided into four resonance ranges.
3. Analysis of typical accidents

The main wiring of a 66kV substation is shown in Figure 3. The #1 main transformer of the substation is made by Y/Δ, the transformation ratio is 66kV/10kV, the neutral point of the Y connection is not grounded, there are 6 lines of 10kV side of #1 transformer, and a PT is installed on the 10kV bus. At 12:10 on August 3, the substation #1 transformer overcurrent protection actioned, #1 transformer low-voltage side 901 breaker tripped, and the fault was removed. The fault is that the 10kV bus PT interval trolley isolation insulation breakdown leads to discharge and burns the trolley isolation. According to the system fault recorder, the 10kV Xingfu line first experienced a B-phase short-circuit grounding fault, and then evolved into an AB two-phase short-circuit grounding fault. Finally, the relay protection device actioned to trip the line-side breaker to remove the fault. After the line breaker tripped, the recording waveform of the PT is distorted, and then the PT is burned. The recording waveform is shown in figure 4. It is preliminarily judged that the accident of the 10kV bus PT was caused by the system ferroresonance overvoltage, after the transformer protection actioned, the fault of the voltage transformer interval was removed, but the harmonics of the system still existed. Through the analysis of the voltage waveform during the fault It can be seen that when the accident occurs, there are a large number of second harmonics and a small amount of higher harmonics in the system, which may cause saturation of the iron core, or ferromagnetic resonance in PT, which may cause PT to be damaged. According to some information, in addition to the residential electricity loads, this 10kV substation also has many factories loads that can generate a large number of harmonics. The existence of these harmonic sources also provides conditions for the occurrence and continuation of ferromagnetic resonance.

![Figure 3. Main wiring diagram of 66kV substation](image-url)
4. Simulation analysis

According to the main wiring diagram of the 66kV substation and the existing information, a simulation model is built in the PSCAD environment. The frequency-dependent model is used for modeling transmission line. The 10kV PT uses the unified magnetic equivalent circuit model (UMEC). The UMEC model considers the magnetic coupling between windings of different phases and the magnetic coupling between windings of the same phase in the simulation, and can reflect saturation, the simulation model is shown in figure 5.

The three-phase voltage waveform in the simulation result is similar to the three-phase voltage waveform in the fault recorder. After the fault is removed, the PT voltage waveform of both are distorted, and at the moment the fault is removed, a larger voltage overshoot appears in the three-phase voltage. The voltage overshoot may damage the interphase and inter-turn insulation of the PT, and then burn the PT. With the three-phase voltage waveform distorts, the PT’s three-phase magnetic flux waveform is also distorted, and the PT core is saturated. Using FFT to analyze the frequency spectrum of the PT voltage waveform in the ferromagnetic resonance process, it is found that there are a large number of high-order harmonics in the waveform.
The simulation output waveform is shown in figure 6 and figure 7:

**Figure 5.** Simulation model diagram

The simulation output waveform is shown in figure 6 and figure 7:

**Figure 6.** Three-phase voltage waveform of PT
The cause of ferromagnetic resonance overvoltage is that the excitation in the process of fault occurrence or fault removal leads to PT saturation, which causes the excitation inductance to match the resonance parameters of the system zero-sequence loop capacitance. Therefore, there are two main methods to prevent ferromagnetic resonance in the neutral point ungrounded system. The first method is to change the capacitance and inductance parameters to destroy the resonance excitation condition; the second method is to consume the energy generated by the ferromagnetic resonance and eliminate the occurrence of the ferromagnetic resonance. The following is a simulation analysis of three commonly used solutions in engineering.

1) Choose PT with better excitation characteristic

Using PT with good excitation characteristic in the system, the PT core will not easily saturate with sudden changes in voltage, which will reduce the range of capacitance parameters for resonance in the power system, and the probability of resonance when the PT and system capacitance parameters match greatly reduced. The saturation degree of PT is related to the linearity of the iron core, the higher the linearity of the iron core of the PT, the less likely the PT is to saturate, and the lower the risk of ferromagnetic resonance. Therefore, the iron core made of high-permeability materials will reduce the risk of PT saturation, but it will also increase the manufacturing cost of PT. According to statistics, most of the PTs that have failed have a small capacity. Therefore, considering the cost, the capacity of the PT can be increased, and its excitation characteristic can be optimized to avoid over-saturation of the PT and cause the equipment to resonate.

Choose PT with better excitation characteristic, and its excitation characteristic curve and original PT excitation characteristic curve are shown in figure 8. After selecting a PT with better excitation characteristic, the accident process was simulated. The simulation result is shown in figure 9. It can be seen from the simulation results that no ferroresonance occurred under the same fault.

2) Insert resistance to the open triangle on the PT secondary side short-term

Put a damping resistor in the open triangle of the secondary side of the PT, the voltage applied to this resistor is the zero-sequence voltage. During normal operation, the zero-sequence voltage is zero, and the damping resistor does not consume energy. When resonance occurs, the energy can be consumed by the damping resistor, which can effectively suppress the ferromagnetic resonance overvoltage. So under ideal circumstances, it is better if the resistance is smaller. However, when a continuous single-phase ground fault occurs in the power grid, a zero-sequence voltage of about 100V
will be generated at the TV open triangle. If the damping resistor with a small value is connected to the system for a long time, it will cause the damping resistor to overheat and burn. In order to solve this problem, many manufacturers have improved the introduced damping resistance, using power electronic switch to realize the inserting and removing of the damping resistance. Once ferromagnetic resonance occurs, the power electronic switch is turned on, and the damping resistance is put in the open triangle to eliminate the resonance. Then remove the damping resistor and restore the normal wiring of the system.

A 0.5 ohm resistor is connected to the PT open triangle for a short time. The resistor is inserted through the switch before the fault is removed, and the resistor is removed after the fault is removed. The simulation results are shown in figure 10. The voltage waveform shows that the fault is removed after a small disturbance, the voltage returns to normal.

Because the resistance value connected in the PT open triangle is very small, it can dampen the three resonances of high frequency, fundamental frequency and subharmonic frequency, and it is effective for the entire power grid, only one PT needs to install in a system. The main disadvantage is that it is difficult to correctly distinguish between fundamental resonance and single-phase grounding. In order to prevent the PT from being overloaded for a long time due to the device's misoperation when single-phase grounding, the criterion voltage of the device's fundamental frequency resonance is usually set higher. In this way, when the fundamental frequency drift voltage is not very high, the device will not be able to operate, which may cause some PTs with poor excitation characteristic burnout and iron core saturation. Moreover, when the power grid has a large capacitance to the ground, this device is powerless to prevent the accident caused by the instantaneous saturation due to the inrush current of the transformer.

**Figure 8.** Excitation characteristic curve of original PT and new PT
(3) The neutral point of PT is grounded via a non-linear resistance

Installing a non-linear resistor R at the neutral point of the primary side of the PT is equivalent to connecting a resistance to ground in series with each phase PT, sharing the voltage applied to each phase of PT, limiting the current flowing through the primary side of the PT, which can prevent the PT from entering saturation occurs in the ferromagnetic resonance zone, even if resonance occurs, resonance energy can be consumed by resistor. In terms of the harmonic elimination effect, the resistance value cannot be too small, otherwise the suppression effect will not be achieved, but the resistance value is not the bigger the better. When the resistance value is infinite, it is equivalent to the neutral point insulation of the PT primary side and there is no PT saturation. But the resistance value is too large, when a single-phase grounding fault occurs, the zero sequence voltage is mainly shared by the harmonic elimination resistor according to the resistance value distribution, which causes the voltage of open triangle to be too low, which affects the correct operation of the relay protection device.

A non-linear resistance is connected to the neutral point of the primary side of the PT, and the
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Simulation results are shown in figure 11. After the non-linear resistance is connected, the ferromagnetic resonance of the PT is eliminated.

Figure 11. Three-phase voltage simulation waveform of PT

6. Conclusions
This paper analyzes the ferroresonance mechanism of PT by harmonic balance method, and through the fault recording of a 10kV PT burn-out accident, conclude that the main cause of the transformer damage is ferroresonance overvoltage which is made by the disappearance of the ground fault on the line side. The ferroresonance overvoltage is verified by PSCAD simulation.

(1) Through the simulation of the accident process, the occurrence of the ferroresonance overvoltage was proved. A large ferroresonance overvoltage appeared in the simulation waveform, and both the voltage waveform and the magnetic flux waveform were distorted.

(2) The three harmonic elimination solutions were selected, choosing PT with better excitation characteristic and installing a nonlinear resistor to the PT neutral point and inserting a resistor in the open triangle for a short time when resonance occur. The simulation results showed that the voltage overshoot was suppressed, and the voltage waveform and flux waveform has not been distorted, and the three harmonic elimination solutions can effectively suppress the occurrence of ferroresonance.

(3) No matter which kind of harmonic elimination solutions. The next research direction should focus on improving the discrimination of the type of ferroresonance. Before resonance occurs, put in corresponding resonance elimination devices according to the characteristics of ferromagnetic resonance in the area, or put in corresponding elimination measures quickly according to different resonance types at the initial stage of the occurrence of ferromagnetic resonance to avoid resonance expanding or reduce destructive effect of resonance.

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