Research on saturation model of ferromagnetic resonance voltage transformer

Qinghao Zheng¹, Yunge Li², Nana Zhang¹, Fan Gan¹ and Zhouxing Fu¹

¹College of electrical and control engineering of Xi’an University of Science And Technology, Xi’an, China
²State Grid Shaanxi Electric Power Research Institute, Xi’an, China

Corresponding author:18330215072@163.com

Abstract. The voltage transformer is a common nonlinear inductor in the power system. The core nonlinearity caused by saturation, hysteresis and eddy current makes it difficult to describe the dynamic magnetization of the core. At present, there are many different saturation models for nonlinear inductors. Different models are used to simulate ferromagnetic resonance, which will result in different results. In this paper, based on ATP-EMTP electromagnetic transient simulation software, the simulation of different voltage transformer saturation model is carried out, the calculation error is analyzed, and the results of different models are compared.

1.Introduction
In the power system, the voltage transformer is a core inductor component. If there is some kind of large disturbance or operation, the nonlinear core of the PT may be saturated, thus forming a resonance circuit. Ferromagnetic resonance occurs in both neutral grounded and ungrounded systems. Abnormal overvoltages during resonance cause insulation flashover and lightning tube explosion which seriously threaten the safe operation of the power grid [1]. However, the core nonlinearity makes it difficult to describe the dynamic magnetization characteristics of the core. Therefore, it is necessary to study the model of the voltage transformer.

The literature [1] uses a single-valued magnetization curve to describe the nonlinear characteristics of the voltage transformer, ignoring the loss, and there is no parallel resistance on the nonlinear inductance of the PT equivalent. In [2], starting from the magnetic flux waveform, based on the relationship between the magnetic flux and the excitation branch voltage and current, a method for calculating the magnetization curve is proposed. In [3], the piecewise linearization method is adopted. The processing of the saturated segment is approximated as a straight line segment. The loss is simulated by a linear resistor and paralleled with the nonlinear inductor. In [4], the curve fitting method is used to establish the saturation model of the voltage transformer by establishing an analytical expression to approximate the discrete data. It is divided into parameters and non-parametric fitting. The calculation of ferromagnetic resonance using different models will produce different results, so it is necessary to study the exact saturation model of the voltage transformer.

In this paper, based on the ferromagnetic resonance of a 110kV substation and ATP-EMTP simulation software, different voltage transformer saturation models are used for calculation. The calculation error is analyzed. The results of different models are compared.
2. Basic circuit

Figure 1 is a resonant circuit of a substation in which ferromagnetic resonance occurs. The isolating blades D0-1, D0-2, D1-1, D1-2 are in the closed position, the circuit breaker B0 or B1 is already open, and when the other is turned off, ferromagnetic resonance overvoltage that causes a sustained higher amplitude.

Applying the Thevenin's theorem, Figure 1 can be simplified to the basic resonant circuit shown in Figure 2, where $E$ is the equivalent power supply potential, $C$ is the equivalent capacitance, $L$ is the nonlinear inductance of PT, and $R$ is the PT core equivalent resistance. The parameter is:

- $E = 47951V$
- $C = 2.38 \times 10^{-9} F$
- $R = 80 M\Omega$
- The PT ratio is 1100.

![Figure 1](image1.png)

**Figure 1.** Typical configuration of substations prone to Ferroresonance

![Figure 2](image2.png)

**Figure 2.** Simplification of ferroresonant circuit

The current-flux characteristic reflects the excitation characteristics of the nonlinear inductor. However, the manufacturer does not provide an $i-\phi$ curve with the product and can be converted by a $U-I$ curve when needed. The subroutine supporting this function in ATP-EMTP is SATURA. The experimental data obtained from a set of secondary $U-I$ curves on the $U-I$ curve are shown in Table 1. The sub-program SATURA is used to obtain the nonlinear inductive excitation characteristic curve required for the simulation calculation.

**Table 1.** Voltage-current pairs on $U-I$ curve

| Voltage /V | Current /A |
|------------|------------|
| 55.0       | 1.22       |
| 70.7       | 3.95       |
| 85.6       | 9.83       |
| 111.0      | 37.10      |
| 152.0      | 89.80      |
| 212.0      | 177.00     |
This article will simulate the single-phase circuit shown in Figure 2, and simulate the case of a single open circuit breaker. Set the circuit breaker to open at 0.02s, the phase angle of the opening is set to 0°.

3. Matlab numerical simulation

3.1. Numerical solution of differential equation

In the neutral point direct grounding system, if the load of the line is not counted, the three-phase circuit can be simplified into three single-phase circuits due to the three-phase symmetry, as shown in Figure 2. Using the basic principles of circuit analysis, a set of equations of state (1) with \( \phi \) and \( u \) as state variables is obtained.

\[
\frac{d\phi}{dt} = u
\]
\[
\frac{du}{dt} = -\frac{1}{C} \left[ u + f(\phi) \right] + \frac{E}{L} \cos \omega t
\]

(1)

Where \( \phi \) is the magnetic flux in the nonlinear inductor; \( u \) is the voltage across the nonlinear inductor; \( E \) is the equivalent power supply potential; \( C \) is the equivalent capacitance; \( R \) is the PT core equivalent resistance.

In the analytical calculation, the excitation characteristics of the core inductor are as shown in equation (2).

\[
i_L = f(\phi) = a\phi + b\phi^2
\]

(2)

Where \( i_L \) is the current flowing through the PT, \( \phi \) is the magnetic flux of the PT core inductance, \( n=3, 5, 7 \) or 9, in the calculation of this example, \( n \) is 3. The excitation characteristics of the core inductor are obtained by polynomial fitting from the \( i-\phi \) curve in Table 1, wherein \( a=-3.04 \times 10^{-5} \), \( b=4.51 \times 10^{-9} \).

The simulation program is compiled by Matlab, mainly using the function ode23 (using the trapezoidal rule algorithm), which is suitable for solving moderately rigid differential equations. The results of the numerical analysis are shown in Figure 3. The analysis waveform can be found that the system fails to transition to the normal steady state, and a continuous, higher amplitude overvoltage occurs, and the steady-state voltage amplitude is 420 kV.
3.2. SIMULINK modeling simulation

The case of opening the circuit breaker was simulated, and the waveform results of the simulation are shown in Figure 4.

After opening the circuit breaker, the simulation results using Matlab are close to the numerical analysis. The system fails to transition to the normal steady state, and the transient process excites the resonance. The steady-state voltage amplitude is 471kV, which is about 12.14% higher than the numerical analysis. It can be seen that the ferromagnetic resonance simulation using Matlab's saturated transformer model produces errors.

4. ATP-EMTP simulation

4.1. Type98 type component nonlinear inductor

In the ATP, the modeling method of the literature [5] is used to establish a simulation model for the resonant circuit. The model of the nonlinear inductor Type98 type component shunt resistor is used instead of the PT. The Type98 inductor component is represented by the piecewise linearization method.

The case of opening the circuit breaker was simulated, and the waveform results of the simulation are shown in Figure 5. After opening the circuit breaker, the simulation results using ATP-EMTP are close to the numerical analysis. The system fails to transition to normal steady state, and a continuous, higher amplitude overvoltage occurs. The steady state voltage amplitude is 465kV. The results of the
analysis increased by approximately 10.71%. Since the Type98 inductor component adopts the piecewise linearization method, the simulation results also produce errors compared with the numerical analysis, but the accuracy of the Matlab simulation results is improved.

Figure 5. Waveform of ferroresonance voltage with the circuit breaker open (ATP)

4.2. Model using hysteresis eddy current loss

4.2.1. Type98 type component nonlinear inductor

In this paper, the EMTP simulation method is used to obtain the hysteresis loop of the nonlinear inductor. The transient process of the simple circuit shown in Figure 6 is simulated by EMTP, and the accurate hysteresis curve can be obtained. The direct result of the simulation is the discrete voltage and current values. In the figure, $E$ is the AC power supply potential, which varies over a wide range. In the ATP, $L$ is a nonlinear inductance expressed by a 98-type element. Given the $E$ value, the circuit response after the analog switch is closed, the simulation time should be long enough for the loop to reach steady state. The voltage is integrated by using the TACS integral component in ATP, and the appropriate initial value is selected to obtain the hysteresis curve. The specific data is shown in Table 2.

Table 2. Flux-current pairs on $i$-φ curve

| Current/A | Flux/Wb    |
|-----------|------------|
| 0.0086    | -272.35    |
| 0.0216    | 0          |
| 0.0434    | 490.22     |
| 0.0906    | 623.92     |
| 0.2117    | 938.88     |
| 0.6047    | 1912.16    |
| 0.8611    | 2747.72    |

Figure 6. Equivalent circuit with magnetic hysteresis and eddy current

The nonlinear inductor model is used to replace the PT. The Type 96 inductor is a nonlinear inductor model represented by the method of directly using the hysteresis loop. The excitation characteristic is
obtained by the EMTP simulation method described above. Arbitrarily set a group of moments to open the circuit breaker, perform a simulation, and obtain the resonance waveform as shown in Figure 7. It can be seen from the figure that the transient process excites the resonance, and as time goes by, the amplitude gradually decreases until it is stable. The steady-state voltage amplitude is 433kV, which is about 3.1% higher than that of the numerical analysis. It is very close to the numerical analysis. It can be seen that the model considering the hysteresis eddy current loss can improve the accuracy of the simulation. Therefore, when performing ferromagnetic resonance simulation calculations, a saturation model that accounts for hysteresis eddy current losses should be used.

![Figure 7. Waveform of ferroresonance voltage with the circuit breaker open (Type96)](image)

4.2.2. Using Hevia 98->96 type component nonlinear inductance. There is also a method in the ATP that directly converts the hysteresis loop into the hysteresis loop. The Hevia 98->96 model of the hysteresis loop nonlinear inductor is obtained. The excitation characteristic curve adopts the i-ϕ curve of the Type98 component in 3.1. Arbitrarily set a group of moments to open the circuit breaker, perform a simulation, and obtain the resonance waveform as shown in Figure 8. It can be seen from the figure that the transient process is numerically unstable. This may be due to the nonlinear inductive magnetization characteristics obtained by this conversion method, and a negative hysteresis loop occurs, resulting in amplification of the nonlinear inductor oscillation amplitude. And the result is an error. It shows that this model cannot be used to calculate the ferromagnetic resonance calculation model of the neutral point direct grounding system.
5. Model comparison
The polynomial fitting method is used for numerical calculation. When the circuit breaker is opened and the system does not reach the steady state, the maximum voltage appearing on the busbar is greater than the amplitude of the bus voltage at steady state, and the ferromagnetic resonance overvoltage occurs.

Using the saturation transformer model in Matlab and the Type98 model in ATP-EMTP, the system fails to transition to normal steady state, and the transient process excites resonance, but the amplitude of the resonant overvoltage produces a larger error than the numerical solution of the differential equation.

Using the Type96 model in ATP-EMTP, the transient process excites the resonance, which is very close to the numerical solution of the differential equation.

Using the Hevia 98->96 model in ATP-EMTP, the numerical process is unstable in the transient process. This model cannot be used to calculate the ferromagnetic resonance calculation model of the neutral point direct grounding system.

6. Conclusion
Aiming at the simulation calculation of ferromagnetic resonance in power system, the nonlinear inductance saturation model for ATP-EMTP simulation calculation is compared, and the influence of different models on ferromagnetic resonance is analyzed. When the fundamental resonance occurs in the system, by comparing the calculation results of different models, it can be known that the Type 96 saturation model considering the hysteresis eddy current loss, the fundamental frequency resonance amplitude is closer to the numerical calculation result, and is more accurate than the piecewise linearization model. Flexible and convenient to use, it helps to conduct a more comprehensive and in-depth study of ferromagnetic resonance from a system perspective.

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