Electromagnetic modeling of 35kV distribution transformer lightning overvoltage and its prevention method

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Abstract. Distribution transformers are important power conversion equipment, whose safe and reliable operations affect the power supply quality of the distribution network. In order to analyze the lightning strike fault of distribution transformers, some more reasonable protection measures of transformers could be put forward. In this paper, a 35kV distribution transformer under the lightning strike is taken as the research object. Firstly, the lightning overvoltage model of the distribution transformer was established with the method of the double exponential model. Secondly, through the simulation of the distribution transformer, it was found that the electromagnetic transient distribution change dramatically, which will quickly cause the winding current flickering and form the winding overvoltage. Finally, through the voltage distribution law and the magnetic flux distortion of the transformer, it can be seen that the lightning overvoltage has a serious effect on the electromagnetic parameters of the transformer. The protection scheme is briefly analyzed, which has a guiding significance for the lightning protection design of distribution transformers.

1. Introduction

Distribution transformers are the electrical energy conversion equipment that connect the power grid and users. They are the very important part of the distribution network, and their stable operation plays a vital role in the operation of the distribution network. In actual operation, the insulation configuration of the distribution network is low, and the lightning overvoltage has a great threat to the distribution transformer[1]. Therefore, improving the lightning protection measures of distribution transformers and improving the lightning overvoltage tolerance of distribution transformers have
become an urgent problem to be solved in the distribution network. At present, SIMULINK modeling method and the numerical analysis method are commonly used to analyze the lightning overvoltage\textsuperscript{[2, 3]}. Although there are many studies on the overvoltage of the neutral point of transformer under the impact of the lightning wave, there is no accurate theoretical description for the lightning wave due to its complexity and randomness.

It is known that 35kV and 10kV transmission lines are close to the users in the power system. Due to the low insulation level of the system, there are few studies on lightning protection measures in these distribution networks \textsuperscript{[4]}. Compared with the high-voltage lines above 110kV, the distribution network lines are more vulnerable to the lightning strike, which would have a significant impact on the power supply reliability and the security of the power system. According to relevant statistics, the line tripping accidents caused by the lightning strike on transmission lines account for 70\%~80\% of the total tripping times \textsuperscript{[5-7]}. In these statistics, the insulation of the distribution network is weak, and the lightning accidents are extremely easy to happen.

![Transformer windings damage](image)

**Figure 1** Transformer windings damage

Lightning strikes can generate extremely high voltage, which is an important factor causing power system failure. After the lightning wave, it is easy to cause the insulation damage between turns and even make the windings of transformers burn out. Figure 1 shows the transformer windings damage. The phenomenon of these accidents is obvious, but what the specific effect of the lightning strike on transformer electromagnetic transient is unknown. The voltage distribution of transformer windings, the excitation current distortion and the magnetic flux of transformer core change have been rarely described in the scientific literature. If the electromagnetic transient parameter of the distribution transformer under the lightning wave invasion can be got, it is of great significance to analyze the extremely uneven voltage and current caused by the lightning strike\textsuperscript{[8, 9]}.  

2. **Mathematical model of the lightning voltage**

The standard lightning wave pattern specified by the international electrotechnical commission is shown in figure 2. In the actual test, the lightning voltage model is built based on the mode of double-exponential model superposition the frequency power supply. The output waveform of the power of the double-exponential model can be adjusted according to the standard lightning voltage waveform.
Figure 2 Standard lightning wave pattern

The peak time $t_1$ and the half peak time $t_2$ of the lightning wave are specified as follows. The point E is connected with the F point as a straight line, and the E-F extension line intersects the current peak horizontal line at P point and intersects with the x-coordinate at $t_0$ shown in figure 2. The time interval $t = t_F - t_0$ in the figure is called as the lightning wave head time. The time interval $t_2 = t_M - t_0$ between $t_0$ and $t_M$, the half peak of the current wave, is the half peak time of the lightning wave. The lightning wave shape is usually represented by $t_1$ / $t_2$ ($\mu$s). After the values of $t_1$ and $t_2$ of the standard waveform are determined, the following equation can be obtained according to the definition of parameters and the thunder waves.

$$k(e^{-\alpha t_F} - e^{-\beta t_F}) = 0.1$$

$$k(e^{-\alpha t_E} - e^{-\beta t_E}) = 0.9$$

$$k(e^{-\alpha t_M} - e^{-\beta t_M}) = 0.5$$

$$t_F = 0.1 t_1 - t_0$$

$$t_E = 0.9 t_1 - t_0$$

$$t_M = t_2 - t_0$$

In the equation, $t_0$ is positive. Let it is on the left of the origin of the axis. The time of the peak lightning current is $t_1$, and then the equation can be got.

$$k(e^{-\alpha t_1} - e^{-\beta t_1}) = 1.0$$

And the slope of the highest point of the current is 0, the equation can be obtained.

$$e^{-\alpha t_1} - e^{-\beta t_1} = 0$$

By substituting equations (4), (5), and (6) into equations (1), (2), and (3) and connecting them with vertical equations (7) and (8), parameters $\alpha$, $\beta$ and $k$ according to different waveforms $t_1$/$t_2$ can be obtained. The following table is the corresponding parameter values of different waveforms.

| Lightning current waveform | $\alpha$ | $\beta$ | $k$  | $t$  |
|----------------------------|---------|---------|-----|-----|
| 8/20$\mu$s                 | $7.713 \times 10^4$ | $7.713 \times 10^7$ | 2.32 | 0.679 |
| 10/200$\mu$s               | $3.913 \times 10^3$ | $7.713 \times 10^5$ | 1.09 | 1.792 |
| 10/350$\mu$s               | $2.125 \times 10^3$ | $7.713 \times 10^5$ | 1.05 | 1.943 |
| 1.2/50$\mu$s               | $1.471 \times 10^4$ | $7.713 \times 10^6$ | 1.04 | 0.241 |
| 0.25/100$\mu$s             | $6.984 \times 10^3$ | $7.713 \times 10^7$ | 1.01 | 0.068 |
3. Lightning strike process and establishment of simulation model

3.1. Lightning strike process of distribution transformer

When the lightning strikes the transmission line, because of the high amplitude of the lightning current, a high voltage surge would be generated on the transmission line. The arrester located on the high-voltage side of the distribution transformer starts to conduct, and leads the lightning current to the earth. However, this process is not instantaneous, so there is a high voltage strike on the high voltage side of the distribution transformer.

\[ U_p = U_r + L \frac{di}{dt} + iR \]  \( (9) \)

\( U_p \) is the voltage of the high voltage side of the distribution transformer. \( U_r \) is the residual voltage of the high voltage side arrester. \( L \) is the arrester lead inductance of the high voltage side. \( i \) is the current passing through the high voltage side arrester. \( R \) is the grounding resistance in the high voltage side arrester. If the transformer ratio is \( k \), the voltage on the low voltage side of the distribution transformer is \( U_s \), then \( U_s = U_p / k \). Since the voltage on the high voltage side \( U_p \) is high, \( U_s \) will also be high.

3.2. Lightning action design of transformer

According to the characteristics of the lightning strike behavior, the lightning voltage waveform rises to a peak value in the exponential form approximately with time, and then decreases in the exponential form to a minimum value. The mathematical expression of the lightning voltage can be formulated with the double exponential model. It mainly contains the lightning voltage amplitude \( U_m \), the wave head time factor \( \alpha \) and wave tail time factor \( \beta \), which can be illustrated by formula (10).

\[ u = kU_m(e^{-\alpha t} - e^{-\beta t}), \quad 0 \leq t < \infty \]  \( (10) \)

Among them, \( \alpha \) and \( \beta \) are determined by three characteristics of the lightning strike. \( k \) is the waveform correction factor. In this paper model, \( \alpha \) and \( \beta \) are set as \( 1.46 \times 10^3 \) and \( 2.5 \times 10^6 \). \( k \) is 1.1. Figure 3 shows the standard lightning voltage waveform simulated by the double exponential model.

![Figure 3 Distribution of lightning voltage waveform](image)

3.3. Co-Simulations of transformer lightning strike

In this paper, the double exponential model combined with ANSOFT and MATLAB software is used to construct the lightning strike behavior. The intrusion lightning strike model is superimposed with
the power frequency voltage source excitation through MATLAB SIMULINK. The lightning voltage invasion operation was introduced into the A-phase of transformer winding at 1s.

![Figure 4](image)

**Figure 4** Distortion of transformer voltage and excitation current

When the distribution transformer is in stable operation, the voltage and current waveforms at each node are stable. The established distribution transformer model can operate normally. But after 1s, it can be seen from Figure 4 that when the high voltage side is struck by the lightning, the amplitude of the voltage and current was obviously raised. The current of the distribution transformer winding is nearly 280A after the lightning strike, which exceed the insulation withstand voltage seriously. Then, from the local amplification figure in Figure 4, it can clearly see how the excitation current distortion process, and the excitation current gradually enters a stable state after 10s.

3.4. Calculation of magnetic density distribution

At the same time, the magnetic density distribution of the transformer core is also seriously distorted. The positive and negative half-period of the excitation current is symmetric with respect to the X-axis under the normal working condition. The maximum and minimum magnetic density values are around 1.0T during the normal operation shown in figure 5. In the process of the lightning strike, the magnetic density distribution change dramatically. The positive and negative half-period of the transformer core flux density field no longer is symmetrical. The positive half-period maximum value is about 2.0 T shown in figure 6, the negative half-period flux density minimum value dropped to 0.5 T, which poses a huge threat to normal operation of transformer.

![Figure 5](image)

**Figure 5** Core flux distribution under the normal operation (a) The negative half cycle, (b) The positive half cycle.
Figure 6 Core flux distribution after the lightning strike (a) The negative half cycle. (b) The positive half cycle.

By simulating the lightning strike behavior of the transformer and monitoring the electromagnetic parameters of the transformer caused by the lightning strike, the obtained results can visibly show the amplitude, steepness, duration and other information of the overvoltage waveform that cannot be seen before. This information can provide scientific basis for the fault analysis of the power system, comprehensive analysis of the types and reasons of the overvoltage combined with other records means power system.

4. Lightning protection scheme for distribution transformers
Improving the lightning protection ability of distribution transformers can effectively reduce the lightning fault of distribution network and improve the reliability of power supply. Through simulation, this paper shows that increasing protective measures can improve the protection ability of transformers against the lightning overvoltage, but it is necessary to develop a reasonable lightning protection scheme for distribution transformers according to the local actual situation, such as the lightning frequency, the cost requirements, etc.

5. Conclusion
In this paper, the lightning-stroke overvoltage of the distribution transformer was introduced on the basis of the double exponential model. Under the action of lightning shock wave, firstly, the excitation current had experienced a serious distortion process, which may damage the insulation of transformer windings. The neutral point of its high-voltage winding is the most vulnerable to breakdown. Secondly, the magnetic flux of the transformer core was also seriously distorted and not symmetrical any more, which would pose a serious threat to the normal operation of the transformer. Finally, some suggestions for improving the lightning protection ability of distribution transformers are put forward. Based on the research of electromagnetic simulation under the lightning strike behavior of the transformer, it can effective to prevent the lightning damage to distribution transformers, better guarantee the safe and stable operation of distribution transformers.

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