Calculation and Analysis of Transient E-Field Distribution of 110kV Dry Type Transformer Under Lightning Impulse

Junfeng Zhou1*, Shuo Wang1, Chong Peng1, Ning Wang1, Kang Wang1, Tiantong Zhu1

1Economic Research Institute of State Grid Hebei Electric Power Company, Shijiazhuang, Hebei, 050021, China

*Corresponding author’s e-mail: wsxjtustu@163.com

Abstract: The 110kV dry type epoxy casting transformer had the characteristics of high voltage grade, great difficulty and uncertainty in research. Especially in the field strength control under lightning impulse, higher requirements were put forward for its insulation structure design. In this paper, an equivalent circuit model was built based on the heap winding structure, and the voltage distribution of winding nodes under lightning impulse was calculated. According to the actual drawing, a two-dimensional transformer model was established, and the E-field distribution of transformer under lightning impulse was obtained by simulation. The results showed that the maximum field strength at sampling point 1 was 4.1kV/mm, appearing around 65μs and 157μs. From the simulation results, the insulation performance of the pile winding did not meet the safety requirements. The research results in this paper could provide an important basis for the design of 110kV dry type transformer and technical support for the product development and safe operation of large capacity dry type transformer.

1. Introduction

Dry type transformers could withstand various overvoltage effects during actual operation, including operating overvoltage and atmospheric overvoltage. Among them, the most common and the most serious was the atmospheric overvoltage. The transmission line may suffer from lightning strike or lightning cloud discharge during running. The overvoltage caused by the violent change of electromagnetic field was called atmospheric overvoltage. Under such overvoltage external impact, the dry type transformer would generate complex electromagnetic transient wave process due to free oscillation in the coil [1-3]. Transient voltage was very short, but voltage distribution in the winding was uneven. There would be oscillating overvoltage between turns, layers, segments and ground parts of the coil, which would increase the local field strength and exceed the insulation level of electrical equipment in the dry type transformer, leading to insulation weakening or even breakdown. Although the dry type transformer could be protected by the arrester during operation, the lightning impulse would still have a great impact on it [4-5].

Therefore, studying the lightning shock response wave process of dry type transformer, calculating the voltage distribution of each winding under lightning impulse, calculating the field strength distribution in the transformer (including the field strength of the main port, the field strength of the high-pressure port and the field strength of the epoxy resin), determining whether air breakdown would occur in the transformer had great significance for optimizing winding structure of dry type transformer, determining economical and reasonable insulation structure, improving product reliability and ensuring safe and stable operation of dry type transformer.
Since the 1950s, the voltage distribution of transformer windings under transient impulse had been studied extensively by experts at home and abroad. Dianchun Zheng and Dingguo Cai [6-7] introduced the mathematical expression of the lightning impulse wave, the physical model and mathematical formula for calculating the winding equivalent capacitance and inductance parameters, and built the equivalent circuit model of the winding to study the transient wave process of the dry type transformer. Smajic, Trkulja and Vahdi [8-10] successfully used the finite element method to simulate and calculate the overvoltage waveform in the windings of dry type transformer under lightning impulse, analyzed the change of winding wave process, and the error was within the reasonable range through measurement comparison, which provided guidance and reference for the author to simulate and calculate the lightning impulse response of 110kV dry type transformer.

In the paper, the equivalent circuit model was build based on actual structure of the transformer winding, and the overvoltage distribution of winding under the lightning impulse was calculated. Transformer two-dimensional model was established. The transient electric field of 110kV dry type transformer was calculated and analysed by the method of field-circuit combination. This paper could provide reference for electrical insulation design of 110kV dry type transformer.

2. Material and Methods

2.1. Transformer two-dimensional calculation model

110kV dry type transformer was single-phase two-column type, and the core structure was mouth type. Only one column winding was tested during the lightning impulse test. In view of the high symmetry of core and winding, in order to simplify calculation and save calculation time, a two-dimensional model of 110kV dry transformer was established, as shown in Figure 1.

The size of the low-voltage winding wire was 2.5×8.0mm2, two wires were wound in parallel with a total of 4 layers and 86 turns in each layer, and the width of the winding airway was 20mm. The high-voltage winding of the pile structure was divided into three layers, with 16 segments, 20 segments and 20 segments in each layer from the inside to the outside. The segment winding had 9 different wire winding structures, 3 of which were shown in the local winding diagram. The wire size of the high-voltage winding was 2.0×4.05mm2, with a total of 2,136 turns. There were two air passages in the high-voltage winding, with a width of 20mm. The epoxy resin insulated cylinder is 1780mm high and 154mm wide. When the equivalent circuit of high voltage winding was built, each segment in the local diagram of winding was a unit with a total of 56 units.

The wire connection of the high-voltage winding was shown in Figure 2. It could be seen from the figure that the inlet and outlet lines of 110kV dry type transformer were on the same side of the trans-
former high-voltage winding, and the thunder waves entered from port A and flowed into the earth from port X. Although the high-voltage winding was divided into 56 units, the actual windings was not wound with divided units, but more refined into 20 segments and 15 layers of winding structure, with at least 6 turns and at most 10 turns of wire for each small unit. The windings of small units of the same axial height were connected sequentially, changing wires at specified places.

![Figure 2. Schematic diagram of high-voltage winding wire connection mode](image)

2.2. Calculation of winding equivalent inductance

Inductance had the characteristic of resisting high frequency and passing low frequency. In engineering calculation, the lightning impulse frequency was large, and the influence of frequency on winding inductance could be ignored when dry type transformer was affected by lightning impulse wave. According to the relevant research and the comparative analysis of experimental and computational results, the inductance of transformer winding under the action of lightning impulse was 1/15 times of the inductance of transformer winding without load \(^{[11]}\). The inductance calculation formula of transformer winding without load was shown as follow:

\[
L = \mu_r \mu_0 \frac{A}{l_c} w^2
\]

(1)

Where:
- \(L\) —— no-load inductance of winding /H;
- \(\mu_r\) —— the relative permeability of the core;
- \(\mu_0 = 4\pi \times 10^{-7}\) —— vacuum permeability /H·m\(^{-1}\);
- \(A\) —— cross-sectional area of iron core /mm\(^2\);
- \(l_c\) —— iron core length /m;
- \(w\) —— turns of high-voltage winding.

The calculation formula of total inductance of transformer winding under lightning impulse was shown in Equation (2):

\[
L_{n1} = \frac{1}{15} L
\]

(2)

Where: \(L_{n1}\) —— total equivalent inductance of high voltage winding under lightning impulse/H.

In the construction of high-voltage winding equivalent circuit, each winding segment could be regarded as a calculation unit. The inductance calculation formula of transformer winding element was shown in Equation (3):

\[
L_i = \frac{L_{n1}}{n(1 + \sum_{k=1}^{n-1} \frac{2(n-k)}{n} q^k)}
\]

(3)

Where:
- \(L_i\) —— unit inductance /H;
- \(n\) —— total number of units in the high voltage winding;
- \(q = 0.97~0.99\) —— coupling coefficient of each winding element.
The calculation formula of mutual inductance between different units in the high-voltage winding was shown in Equation (4):
\[ M_{i,j} = L_{ij}{q^{i-j}}, i \neq j \]  
(4)
Where: \( M_{i,j} \) — mutual inductance of units/H; \( i, j \) — high voltage winding unit number.

2.3. Calculation of winding equivalent capacitance
In the process of lightning impulse response of 110kV dry type transformer, the calculation accuracy of winding equivalent capacitance had important influence on the initial voltage distribution. In the transformer, capacitance existed wherever two stages were formed. The equivalent capacitance of high voltage winding included longitudinal capacitance and ground capacitance. The longitudinal capacitance included the inter-turn capacitance, inter-layer capacitance and inter-segment capacitance of the coil. The ground capacitance was mainly the capacitance of the winding to the ground or the core. Where, the longitudinal capacitance was the distribution parameter. When the wave front voltage of the lightning impulse entered the winding, the longitudinal capacitance had a great influence on the voltage distribution in the coil.

Depending on the physical model and mathematical formula to solve the equivalent capacitance of the winding, the error was large and the calculation accuracy was low. The winding of 110kV dry type transformer had many coil layers, complex winding mode, and the calculation amount was huge. With comprehensive consideration, the paper used a numerical simulation method to calculate the geometric capacitance of the winding.

2.4. Equivalent circuit model of high voltage winding
According to the connection mode of the wire, the equivalent capacitance, inductance and resistance parameters of the winding were calculated and the equivalent circuit of the high-voltage winding was built, as shown in Figure 3. According to the figure, the winding unit under the pile structure was relatively orderly and the layout of equivalent circuit was relatively neat. In the figure, the first was listed as the equivalent structure of the outermost layer of the winding, the second was listed as the equivalent structure of the winding in the middle of the airway, and the third was listed as the equivalent structure of the innermost layer of the winding.

![Figure 3. High voltage winding equivalent circuit diagram](image-url)
3. Results and Discussion

3.1. Calculation and analysis of voltage distribution in transformer under lightning impulse

After the winding equivalent circuit was built, the voltage distribution of each unit node under the impact of full lightning impulse wave was simulated. The voltage variation curves of the second node, the 26th node and the 55th node of the winding as well as the lightning impulse voltage waveform curve were shown in Figure 4. According to figure, when the lightning impulse wave was injected from the winding inlet, due to the existence of inductance and distributed capacitance, the voltage of each winding would oscillate to different degrees.

The change trend of node 2 voltage was similar to the injection voltage, but the voltage oscillates rapidly, and the peak voltage reached 486kV, exceeding the peak voltage of lightning impulse. The voltage waveform of node 26 was completely different from the lightning impulse. The waveform showed a certain periodicity. Although the oscillation frequency slowed down, the oscillation amplitude was more severe, and the negative voltage was obviously intensified. Although the peak voltage in each oscillation period decreased slightly, the trend of decrease was slow. In the second half of the impulse, the voltage oscillation peak of node 26 greatly exceeded node 2. The voltage waveform of node 55 basically fluctuated around 0 potential, and the voltage waveform decreased periodically. Although the attenuation of thunder wave in each winding unit was small, the voltage attenuation was large due to the large number of winding units, and the potential at the end node was still very low, with a peak value of only 45kV.

![Figure 4. Voltage distribution of internal node in high voltage winding under full lightning shock](image)

The voltage distribution in the winding at different moments of lightning impulse was shown in Figure 5. It could be seen from the figure that, in the early stage of lightning impulse, the first section windings vibrated and the voltage rose. the maximum voltage reached 509kV and appeared at node 4. Then the voltage dropped, and the voltage between node 4 and 56 presented a nearly linear distribution. In 50μs, winding waveform fluctuation was not big. Because of the voltage oscillation, the middle winding potential did not fall up, even more than the first section of the winding, which indicated that the middle winding voltage oscillation was far greater than the voltage attenuation. In 100μs, the winding voltage decreased significantly. The voltage of node 1 was only 121.7kV. At node 44, the voltage started to oscillate and rise, and the overall winding presented negative voltage. By observing the envelope of the high-voltage winding potential, the maximum voltage value in the whole lightning impulse was 517kV, which appeared at node 8.
3.2. Calculation and analysis of E-field distribution in transformer under lightning impulse

When calculating the transient electric field, the low-voltage winding and core were grounded. With the transient voltage of each winding unit under the lightning impulse as the initial condition, the transient electric field inside the 110kV dry type transformer was simulated and calculated.

The transient voltage distribution of dry type transformer under lightning impulse was shown in Figure 6. According to the figure, at 1.2µs moment, the lightning impulse just entered the winding, at this time the first 2 segments of the winding bear most of the voltage, the voltage of the final segment of the winding was basically 0. At 10µs moment, with the transmission of lightning impulse, high voltage shifted down, the voltage of the middle winding rose up, and because of the voltage oscillation, the middle winding voltage value was more than the first section winding. At 50µs time, the lightning wave voltage was attenuation, winding overall voltage was reduction, and voltage distribution tended to be uniform.

![Figure 5. Voltage distribution and envelope of each node in high voltage winding](image)

Figure 5. Voltage distribution and envelope of each node in high voltage winding

![Figure 6. Transient voltage distribution of 110kV dry type transformer under lightning impulse](image)

Figure 6. Transient voltage distribution of 110kV dry type transformer under lightning impulse

The transient electric field distribution of 110kV dry type transformer with pile winding structure under lightning impulse was obtained by numerical calculation, as shown in Figure 7. According to the figure, the electric field variation trend and voltage were not exactly the same. At the time of 1.2µs, the electric field intensity was mainly concentrated in the first 4 segments of the winding. The electric field intensity in the upper part of the high-voltage winding airway was all greater than 3kV/mm, and the air broke down. At 10µs, the breakdown position in the high-pressure airway moved slightly...
downward. At this time, although the voltage of the winding in the middle part became high, the pressure drop was small and the field strength of the airway included was low. At 50µs, the field strength of the high-pressure airway and the main airway was lower than the air breakdown field strength, and the high field strength position of the main airway moved to the upper part of the winding.

![Figure 7](image1.png)

Figure 7. Transient electric field distribution of 110kV dry type transformer under lightning impulse

According to the electric field distribution cloud map, two sampling points were selected in the high pressure airway of 110kV dry transformer and one sampling point in the main airway. The position of the sampling point was shown in Figure 8.

![Figure 8](image2.png)

Figure 8. Sampling point position in transformer airway

The variation curve of electric field intensity at the sampling point with time was extracted, as shown in Figure 9. It could be seen from the figure that the maximum electric field intensity at sampling point 1 was 4.1kV/mm, which occurred in the initial stage of lightning impulse, and then the electric field intensity decreased rapidly. The electric field intensity produced irregular oscillation, and the oscillation intensity was relatively severe. During the whole oscillation process, a total of 10 oscillation peaks occurred. The electric field intensity was close to or slightly more than 3kV/mm around 65µs and 157µs. In summary, 110kV dry type transformer would have serious gas discharge phenomenon in the high-pressure airway and main airway under the lightning impulse, which could not meet the insulation requirements. It was necessary to design a new 110kV dry type transformer winding structure to reduce voltage oscillation and electric field distortion.
4. Conclusions
In this paper, the transient voltage and electric field distribution of each element node in the 110kV dry transformer windings under lightning impulse were calculated by using field-circuit coupling method, the test platform was built, and the lightning impulse test was carried out. The simulation results and test results were compared and analyzed, and the following conclusions were obtained:

1) Under the lightning impulse, the voltage of each node in the high voltage winding would produce oscillation and hysteresis. The head end of the winding oscillated most violently. During the whole lightning impulse time, the maximum oscillation voltage was 517kV and appeared at node 8.

2) The electric field in winding airway was distorted. The maximum field strength at sampling point 1 was 4.1kV/mm, appearing around 65µs and 157µs. The maximum field strength at the sampling point 3 was 3.8kV/mm, appearing at the moment of 13µs. The transient field intensity in both high pressure airway and main airway would exceed the air breakdown field intensity.

References
[1] Guo X. (2017) Attention problems should be paid in distribution design. J. Scientific and Technological Innovation, 25: 126-127.
[2] Han W.M. (2012) Problems that should be paid attention to in transformer operation and maintenance. J. Journal of Electrical Engineering, 9: 76-77.
[3] Wang W.H. (2009) Application status and future development of dry type transformer. J. Journal of Baotou Vocational and Technical College, 10: 11-13.
[4] Wang W.M. (2008) Summary of dry type transformer and its future development. J. Science and Technology Information, 5: 301-302.
[5] Liao H.W. (2015) Analysis and improvement of shock overvoltage in coil of dry type transformer. J. Electromechanical Engineering Technology, 7: 164-166.
[6] Zhen D.C, Dou Y.L, Wang X.Y, et al. (2010) Transient voltage distribution characteristics of the winding of a segmental layer dry transformer. J. Transformer, 47: 13-16.
[7] Cai D.G, Liang H.B, Qian J. (2002) Calculation of impulse voltage wave process of dry type transformer. J. Electromechanical Engineering Technology, 31: 48-50.
[8] Smajic J, Steinmetz T, Ruegg M, et al. (2014) Simulation and Measurement of Lightning- Impulse Voltage Distributions Over Transformer Windings. J. IEEE Transactions on Magnetics, 50: 553-556.
[9] Trkulja B, Drandić A, Milardić V, et al. (2017) Lightning impulse voltage distribution over voltage transformer windings — Simulation and measurement. J. Electric Power Systems Research, 147: 185-191.

[10] Vahdi B, Eslamian M, Hosseinian S.H. (2013) Transient simulation of cast-resin dry-type transformers using FEM. J. European Transactions on Electrical Power, 21: 363-369.

[11] Zheng D.C, Dou Y.L, Wang X.Y. (2010) Calculation of inductance parameter of transformer coil under transient voltage. J. Journal of Harbin University of Science and Technology, 15: 31-34.