The Simulation Analysis on the Transient Process of Transformer

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Abstract. Power transformer is one of the important equipment in the power grid, we must ensure its reliable operation. To achieve that goal, the insulation property of power transformer must be fine, for its breakdown mainly caused by the insulation damage. When the power transformer suffered from the lightning surges, the windings insulation is damaged easily, so we should optimize and design on the power transformers windings insulation structure. Firstly, the computational methods of the inductance, capacitance and the resistance parameter were introduced in this paper, then the inductance, capacitance and the resistance parameters of a SFP-180000/220 three-phase transformer were calculated. Based on the equivalent circuit of transformer, the circuit model in the Matlab was established and simulated when the neutral is grounded or insulated respectively. The relevant initial potential distribution, the oscillating potential distribution, and the final potential distribution were gotten by the simulation. Finally, the characteristics of each potential distribution were analysed, which could provide some references to the insulation structure design for transformers.

1. Parameters calculation of Transformer
The parameters calculation of transformer windings is of great significance to the reasonable determination of transformer longitudinal insulation structure and lightning protection measures [1].

The wave process analysis of transformer windings is based on circuit calculation, which is composed of equivalent inductance, equivalent capacitance and equivalent resistance in series and parallel [2]. The calculation method of transformer capacitance is simple, the direct formula can be used [3] [4]. The calculation method of inductance parameters is varying [5]. In recent years, there are two mature methods available, foreign scholars P.I.Fergested and A.Г.БыHHH raised two models to calculate the inductance, which is proved that it can get satisfactory results [6]. This chapter introduces the calculation method of the equivalent capacitance, equivalent inductance parameters and resistance parameters, with carrying out the calculation of a SFP-180000/220 three-phase power transformer.

1.1. Parameters calculation of equivalent capacitance
The calculation of equivalent capacitance is based on geometric capacitance. To transformer coils, in the radial direction, there are capacitance between coils and iron core, capacitance between coils and
coils, and capacitance between coils and oil tank; in the axial direction, there are inter-turn capacitance between wire turns, the inter-cake capacitance between wire cakes, etc.

It is necessary to realize not only the parameters such as coils size, cross section area, radius, but also the dielectric constant when calculating the capacitance. This is because that transformer has combined insulation rather than a single medium. For example, oil paper and oil barrier are combined insulation, and their equivalent dielectric constant needs to be calculated. Therefore, the formula of equivalent dielectric constant of combined insulation should be discussed first.

1.1.1. Equivalent dielectric constant of inter-cake medium $\varepsilon_{de}$. The insulation between the wire cakes is formed by the series connection between the turn insulation and the oil channel. The oil channel is formed by the parallel connection between the insulation pad and the oil gap. The oil channel is connected by the parallel connection between the insulation pad and the oil gap.

$$\varepsilon_{de}S_{de} = \varepsilon_0S_0 + \varepsilon_cS_c$$

$$\varepsilon_{de} = \varepsilon_cBnBn + \varepsilon_0(\pi d_b B - bBn) = (\varepsilon_c - \varepsilon_0)K + \varepsilon_0$$

$\varepsilon_{de}, S_{de}$: equivalent dielectric constant and oil channel area; $\varepsilon_0, S_0$: dielectric constant and area of oil gap; $\varepsilon_c, S_c$: dielectric constant and area of pad after oil immersion; $d$: the average diameter of the coils; $B$: the radial width of the coils; $b$: block width; $n$: block number.

$$\varepsilon_{de} = a_d^\prime (a_0 \varepsilon_{de} + a_0^\prime \varepsilon_p)$$

$\varepsilon_{de}, a_d^\prime$: equivalent dielectric constant and insulation thickness of inter-cake insulation; $\varepsilon_p, a_0^\prime$: the dielectric constant of the turn insulation and the thickness of both sides; $a_0^\prime$: the oil channel height.

1.1.2. Equivalent dielectric constant of the dielectric between coils $\varepsilon_{we}$. $\varepsilon_{we}$ is the equivalent dielectric constant between coils, coils and cores, or coils and tanks. The insulation between them is composed of several media such as turn insulation, oil gap and insulated paper tube in series. There is an equivalent dielectric constant of brace oil gap.

$$\varepsilon_{we} = \frac{a_s}{d_s(\frac{a_p}{\varepsilon_p d_p} + \frac{a_o}{\varepsilon_o d_o} + \frac{a_{pc}}{\varepsilon_{pc} d_{pc}} + \ldots)}$$

$a_s = a_p + a_o + a_{pc} + \ldots$: the insulation thickness between the coils; $a_p, a_o, a_{pc}$: the average diameters of turn insulation, oil gap and insulated paper tube; $d_s$: the average diameter of the insulation between the coils, which is equal to the sum of the outer diameter of the inner coils and $a_s$.

1.1.3. Calculation of geometric capacitance of coils. The geometric capacitance of the transformer coils has the capacitance between the coils in the radial direction, the capacitance of the coils to the iron core, and the capacitance of the coils to the oil tank; the capacitance between the axial wire turns and the capacitance between the wire cakes. The radial geometric capacitance can be calculated by the coaxial cylindrical capacitance formula or by the plate capacitance formula. The axial geometric capacitance is calculated by the plate capacitance formula.

There are two kinds of axial geometric capacitance: inter-turn geometric capacitance and inter-cake geometric capacitance, which are respectively represented by $C_w$ and $C_s$. The calculation formula of plate capacitance is:
\[ C_w = \varepsilon_p \varepsilon_0 \frac{\pi d_a a_p}{4 a_p^2} = \varepsilon_p \frac{\pi d_a a_p}{4 a_p^2} \times 0.11 \] (5)

\[ C_s = \varepsilon_d \frac{d_s B}{4 a_d} \times 0.11 \] (6)

\( d_a \): average diameter of thread cake, mm; \( a_p \): thickness of bare conductor, mm; \( \varepsilon_p \): insulation thickness of turns, mm; \( \varepsilon_{de} \): inter-cake equivalent dielectric constant; \( B \): radial width of thread cake, mm; \( a_d \): cake insulation thickness, mm.

Radial geometric capacitance can also be calculated by plate capacitance formula,

\[ C_{sw} = \frac{\pi d_a \varepsilon_w \varepsilon_0 h}{a_{sw}} = \frac{d_a \varepsilon_w h}{4 a_{sw}} \times 0.11 \] (7)

\( d_w \): average diameter between coils, mm; \( \varepsilon_{we} \): inter-coils equivalent dielectric constant; \( h \): average coils height, mm; \( a_{we} \): equal distance between coils, mm.

### 1.1.4. Calculation of equivalent longitudinal capacitance.

The formula for calculating the equivalent capacitance between the turns and wire cakes is derived according to the principle of energy equality regardless of the structure of the windings. In the derivation, it is assumed that the distribution of the line turns of impingement rolling is linear. Under the action of impulse voltage, the voltage applied on a pair of double cakes is \( U_{ds} \). The energy of a capacitance between turns is \( E_w \), the total energy \( E_w \) of the inter-turn capacitance of the double cakes is:

\[ E_w = (N - 2)E'_w = C_w U_{ds}^2 \frac{N - 2}{2N^2} \] (8)

The total energy \( E_D \) of the distributed capacitance between the cakes is:

\[ E_D = \frac{1}{3} C_D U_{ds}^2 \] (9)

\( C_D \): geometric capacitance between line cakes, pF; \( B \): Radial width of line cake, mm. \( C_{De} \) is the equivalent capacitance of the double cake:

\[ C_{De} = \frac{2(E_w + E_D)}{U_{ds}} = \frac{N \cdot 2}{N^2} C_w + \frac{2}{3} C_D \] (10)

### 1.2. Parameters Calculation of inductance

The inductance of the transformer winding is 1/15 of the no-load inductance of the transformer when the impulse voltage is applied. The inductance of the power transformer winding can be calculated by the following formula:

\[ L_{sl} = \mu, \mu_0 \frac{A}{l_c} N^2 \] (11)

\( \mu_0 \): the relative permeability of the iron core; \( \mu_0 \): the permeability of the vacuum; \( A \): the cross-sectional area of the iron core; \( l_c \): the length of the iron core.

The inductance when calculating the impulse voltage distribution is:
\[ L = \frac{1}{15} L_{el} \quad (12) \]

\[ L_1 = \frac{L}{n} \left[ 1 + 2 \sum q^k (n-k)/n \right] \quad (13) \]

\( L_1 \): self-perception of a unit; \( q \): the coefficient of the degree of mutual inductance coupling, \( q=0.97-0.99 \). \( L \): the total inductance of the whole coils, \( n \): the number of cells.

1.3. Parameters calculation of resistance

The resistance per unit length is expressed as:

\[ R = \frac{1}{2(d_1 + d_2)} \sqrt{\frac{\pi \mu}{\sigma}} \quad (14) \]

\( d_1, d_2 \): the width and length of the cross section of the rectangular conductor; \( \mu \): The permeability of a conductor; \( \sigma \): the conductivity of a conductor; \( f \): the corresponding frequency.

1.4. The calculation example

The high-voltage winding of a SFP-180000/220 three-phase power transformer is calculated. The calculation results of equivalent capacitance are shown in table 1.

| Cakes number | Equivalent capacitance | Cakes number | Equivalent capacitance |
|--------------|------------------------|--------------|------------------------|
| 1-2 cakes    | 1954.43                | 25-26 cakes  | 1399.99                |
| 2-3 cakes    | 1954.43                | 26-27 cakes  | 1398.67                |
| 3-4 cakes    | 2138.06                | 27-28 cakes  | 1399.99                |
| 4-5 cakes    | 1954.43                | 28-29 cakes  | 1398.67                |
| 5-6 cakes    | 2138.06                | 29-30 cakes  | 1399.99                |
| 6-7 cakes    | 1954.43                | 30-31 cakes  | 1399.99                |
| 7-8 cakes    | 1954.43                | 31-32 cakes  | 1399.99                |
| 8-9 cakes    | 1954.43                | 32-33 cakes  | 1399.99                |
| 9-10 cakes   | 2138.06                | 33-34 cakes  | 1399.99                |
| 10-11 cakes  | 1465.53                | 34-35 cakes  | 1399.99                |
| 11-12 cakes  | 1649.16                | 35-36 cakes  | 1399.99                |
| 12-13 cakes  | 1465.53                | 36-37 cakes  | 1399.99                |
| 13-14 cakes  | 1465.53                | 37-38 cakes  | 1399.99                |
| 14-15 cakes  | 1649.16                | 38-39 cakes  | 1399.99                |
| 15-16 cakes  | 1170.36                | 39-40 cakes  | 1399.99                |
| 16-17 cakes  | 1170.36                | 40-41 cakes  | 1399.99                |
| 17-18 cakes  | 1170.36                | 41-42 cakes  | 1399.99                |
| 18-19 cakes  | 1170.36                | 42-43 cakes  | 1399.99                |
| 19-20 cakes  | 986.73                 | 43-44 cakes  | 1399.99                |
| 20-21 cakes  | 1277.21                | 44-45 cakes  | 1399.99                |
| 21-22 cakes  | 1399.99                | 45-46 cakes  | 1402.23                |
| 22-23 cakes  | 1399.99                | 46-47 cakes  | 1402.23                |
| 23-24 cakes  | 1399.99                | 47-48 cakes  | 1402.23                |
| 24-25 cakes  | 1399.99                | 48-49 cakes  | 1400.28                |
|              |                        | 49-50 cakes  | 1399.7                 |

Unit of inductance:
\[ L_i = 0.067/50 \left[ 1 + \sum 0.97^k(50-k)/25 \right] = 4.2 \times 10^{-5} \text{H} \]  

(15)

The resistance per unit length:

\[ R = \frac{1}{2(5 + 9) \times 10^{-7}} \sqrt{\frac{3.14 \times 0.48 \times 10^6 \times 4 \pi \times 10^{-7}}{5.977 \times 10^7}} = 0.0064 \Omega \]  

(16)

2. Simulation Analysis

2.1. Power selection

This paper mainly studies the simulation results of rated high voltage winding under standard shock wave. The rated voltage of the selected transformer is 220kV, with this voltage as the reference value, and the expression of the impulse voltage \( u_t \) established by taking its per-unit value is as follow:

\[ u_t = \begin{cases} 
1.03725 \times e^{-14658.9t} - 1.03725 \times e^{-246087.8t}, & t < 2.0829 \mu s \\
1 & , \quad t \geq 2.0829 \mu s 
\end{cases} \]  

(17)

2.1.1. Initial potential distribution of windings in grounded neutral condition.

Figure 1 a) shows the equivalent circuit simulation model of the initial potential distribution of the transformer winding when it is grounded at the neutral point. \( C_1, C_2, \ldots, C_{50} \) and \( C_{k1}, C_{k2}, \ldots, C_{k49} \) respectively calculated by the equivalent capacitance. Figure 1 b) shows the initial potential waveform obtained by simulation, Figure 1 c) shows the winding gradient potential waveform.

![Figure 1](image)

Figure 1. Initial potential distribution

It can be seen that the initial potential distribution curve of the winding is smooth and monotonically decreasing when the neutral point is grounded, the maximum gradient occurs at the position of gradient No.1, its value reaches 7.97% of the incoming wave voltage. For this transformer, the descending voltage is 1050×7.97% = 83.69kV. The potential gradient of other oil channels is small, margins are greater than 1.28, which can meet the design needs.

2.1.2. Initial potential distribution of windings in insulated neutral condition.

Figure 2 a) is a simulation model of the equivalent circuit simulation of the initial potential distribution of the transformer winding when it is insulated at the neutral point. Figure 2 b) shows the initial voltage waveform and Figure 2 c) shows the gradient voltage waveform.
It can be seen that the initial potential distribution curve of the winding is smooth and monotonically decreasing when the neutral point is insulated, the maximum gradient occurs at the position of gradient No.1, whose value reaches 8.5% of the incoming wave voltage. For this transformer, the descending voltage is \(1050 \times 8.5\% = 89.25 \text{kv}\). The potential gradient of other oil channels is small, margin are greater than 1.19, which can meet the design needs.

2.1.3. The oscillation potential distribution of the winding in grounded neutral condition. Figure 3 a) shows the potential distribution waveform of each node when the neutral point is grounded. Figure 3 b) c) shows the potential distribution waveform of each node at \(t_1\) and \(t_2\).

It can be seen the maximum potential reached during the oscillation is 0.98p.u., which does not exceed the amplitude of the incoming wave. The value is mainly determined by the difference between the initial potential distribution and the final distribution. The resistance in the simulation model continuously consumes energy during the oscillation process, so the peak value of the voltage waveform of each node shows a decreasing trend with the passage of time, and gradually approaches the final distribution value of the node.

2.1.4. The oscillation potential distribution of the winding in insulated neutral condition. Figure 4 a) shows the distribution of oscillation potential. Figure 4 b) c) shows the potential distribution waveform of each node at \(t_1\) and \(t_2\).

It can be seen that the maximum potential of the oscillation reaches 1.2 times of the incoming voltage and appears at 7.5s, which is noteworthy. The resistance in the simulation model continuously consumes energy during the oscillation process, so the peak value of the voltage waveform of each
node shows a decreasing trend with the passage of time, and gradually approaches the final distribution value of the node.

2.1.5. The final potential distribution in grounded neutral condition. The final potential distribution simulation model of the winding when the neutral point is grounded is the same as that of the oscillation simulation model, and its waveform is shown in Figure 5 a). The waveform of the difference between the final distribution and the initial potential distribution is shown in Figure 5 b).

![Figure 5](image)

**Figure 5.** Final potential distribution (grounded)

It can be seen that when the neutral point is grounded, the voltage of the transformer under impulse reaches a steady state and the potential decreases linearly from the first end to the end of the coils. The larger the difference between the final distribution and the initial distribution is, the more violent the oscillation will be. The No.15 node of this transformer oscillates more violently, which should be taken into account in the design.

2.1.6. The final potential distribution in insulated neutral condition. The final potential distribution simulation model of the winding in neutral insulation is the same as that of the oscillation simulation model, and its waveform is shown in Figure 5 a). The waveform of the difference between the final distribution and the initial potential distribution is shown in Figure 5 b).

![Figure 6](image)

**Figure 6.** Final potential distribution (grounded)

It can be seen that when the neutral point is insulated, the voltage of the transformer under impulse reaches a steady state and the potential is almost equal from the first end to the end of the coils. The larger the difference between the final distribution and the initial distribution is, the more violent the oscillation will be. The transformer will oscillate violently after about the No.25 node, which is worth noting.

3. Conclusion

In this paper, the high-voltage winding of a SFP-180000/220 three-phase transformer is calculated, the simulation is done to recognize the difference of potential distribution of different treatment modes of the neutral point, which is convenient for us to have a discussion that how to separate or combine two cases in different circumstances, with providing a theoretical basis for different transformers to choose which treatment mode of the neutral point is more reasonable. It is of great significance for insulation design to transformer.
Acknowledgments
This work was supported by Science and Technology Project of SGCC (Research on Low-temperature Resistance Characteristics and Evaluation Technology of New Sensors for Power Transmission and Transformation).

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