Study on the Influence of Harmonics on Load Loss of Transformer

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Abstract. Under harmonic condition, transformer loss is significantly higher than that of traditional calculation method. It is necessary to re analyze the resistance model of transformer winding in harmonic environment. In this article, the harmonic loss model of transformer winding considering skin effect and proximity effect is established, and the characteristics of the conductor resistance of transformer winding are obtained by electromagnetic field principle analysis; the conductor resistance of typical harmonic current is measured by experiment, and the effectiveness of the model in reflecting the winding loss under harmonic condition is verified, which makes the load loss of transformer The calculation is more accurate.

Keywords. Skin effect; proximity effect; load loss; harmonic condition.

1. Introduction

With the increase of non-linear load, the harmonic content in power grid gradually increases [1-3], which makes the harmonic problem of power system. It is becoming more and more serious [4], various faults and accidents caused by harmonic also happen constantly, and the severity of harmonic harm has aroused people’s general concern [5]. Transformer is an indispensable electrical equipment in the power system, which links different voltage level networks. When it flows through the transformer, not only the insulation of the transformer will be damaged, but also the load capacity of the transformer will be reduced, affecting its safe and stable operation. Because of the huge total capacity of the transformer running at the same time, the effective use time is long, even if the loss is very small, the annual power consumption is also very large. According to the existing statistics, the total loss of the transformer is not small, it accounts for about 8% of the total power generation. Therefore, in-depth study of the harmonic loss of the transformer is not only of great significance to the economic operation of the transformer, energy saving and loss reduction, but also provides theoretical and data support for the optimal design of the transformer [6-8].

In our country, transformer harmonic loss model is rarely mentioned in the research of power system related fields [9-12], mainly using IEEE conventional transformer model [13-14]. In a harmonic environment, these models are not perfect enough, which will cause errors in the resistance parameters of the transformer windings, it often uses \( \sqrt{n} \) times the DC resistance to calculate by replacing the AC resistance. In the case of harmonic wave, the DC resistance is much smaller than the equivalent resistance of the transformer winding at different frequencies due to the skin effect and the proximity effect [15-16], which will cause errors in the calculation model. In addition, the improved parameter method [17] is widely used in transformer harmonic loss calculation because it is easy to...
implement. The calculation of the improved parameter method is relatively simple, because its loss is only related to the current. But the improved parameter method does not do well enough to reflect the changes in the phase angle of voltage and current. In the field of practical engineering, the improved parameter method can be used as a fast estimation method.

In order to calculate the harmonic loss more accurately, based on Maxwell’s equations and Poynting’s theorem, we consider the distortion characteristics of the winding parameters under the harmonic current under the skin effect and proximity effect, and then introduce the AC winding coefficient, consume and establish calculation model of winding loss. The experiment platform is built to measure the resistance of transformer winding under the background of each harmonic current, observe the change rule of harmonic resistance with frequency, and compare the calculation model of this paper with the existing research. It can be seen that the harmonic loss calculation model in this paper is more accurate, and according to the experimental data to fit the harmonic resistance of each winding, to establish a practical engineering model, to show its applicability, the calculation error is within the allowable range, the model has a certain guiding value for engineering calculation.

2. Calculation of Transformer Winding Loss Under Harmonic Condition

2.1. Harmonic Loss Model of Conventional Transformer

The font format of the title should be set to 17 point Times Bold, flush left, unjustified. There should be 28 mm and 10 mm of space above and behind the title, respectively. The title should not be indented, its first letter should be capitalized, and the remaining letters lowercase. At present, the mainstream power system simulation software mainly uses the following two kinds of transformer harmonic models.

(a) Conventional transformer model.

Both PSASP and IEEE use conventional transformer model. The calculation formula of this model is:

\[ Z_h = \sqrt{h}R_1 + jhX_1 \]  \hspace{1cm} (1)

There, \( h \) is the order of harmonics; \( R_1 \) is the fundamental resistance value of transformer winding; \( X_1 \) is the corresponding fundamental sequence reactance of transformer; \( Z_h \) is the fundamental impedance of transformer winding.

(b) CIGRE transformer model.

The equivalent circuit of the transformer is shown in figure 1, and its calculation formula is as follows:

\[ X_h = hX_1 \]  \hspace{1cm} (2)

\[ R_S = \frac{U_N^2}{S_N F_{RS}} \quad 90 \leq F_{RS} \leq 110 \]  \hspace{1cm} (3)

\[ R_P = \frac{F_{RP}U_N^2}{S_N} \quad 13 \leq F_{RP} \leq 30 \]  \hspace{1cm} (4)

where, \( U_N, S_N \) is the rated voltage and rated capacity of transformer; \( F_{RS}, F_{RP} \) is the correlation coefficient of CIGRE model.

![Figure 1. Equivalent circuit of transformer.](image)
2.2. Improved Parameter Method

According to standard IEEE/ANSI C57.110 [18-19], the total load loss of the transformer can be divided into three parts, which are DC loss, winding eddy current loss and other stray losses. The total load loss of transformer under rated condition is obtained by calculating the superposition of three kinds of losses respectively.

\[
P_{LL-R} = I_R^2 R_{dc} + P_{EC-R} + P_{OSL-R}
\]

(5)

where, \(P_{LL-R}\) is the loss of the load; \(I_R\) is the rated current; \(R_{dc}\) is the DC resistance; \(P_{EC-R}\) is the Rated eddy current loss of winding; \(P_{OSL-R}\) is the rated other stray loss.

When the transformer is loaded with non-linear load, the influence of harmonic on eddy current loss and other stray loss of winding shall be considered, which is defined as follows:

\[
F_{HL} = \frac{P_{EC}}{P_{EC-O}}
\]

(6)

\[
F_{HL-STR} = \frac{\sum_{h=1}^{h_{max}} (\frac{I_h}{I_1})^2 h^{0.8}}{\sum_{h=1}^{h_{max}} (\frac{I_h}{I_1})^2}
\]

(7)

where, \(F_{HL}\) is the harmonic loss factor of eddy current loss of transformer winding; \(F_{HL-STR}\) is the harmonic loss factor of other stray losses of transformer winding; \(P_{EC}\) is the winding harmonic eddy current loss; \(P_{EC-O}\) is the measure eddy current loss of winding under current and frequency conditions; \(h\) is the order of harmonics; \(h_{max}\) is the highest frequency of the main harmonic; \(I_h\) is the effective value of current with harmonic; \(I_1\) is the effective value of load fundamental current. \(F_{HL}\) and \(F_{HL-STR}\) are not consider the nonlinear frequency variation of the model parameters, but the corresponding loss of each harmonic is calculated by superposition. The load loss of transformer calculated by \(F_{HL}\) is economical.

\[
P_{LL-R} = I_R^2 R_{dc} + F_{HL} P_{EC-R} + F_{HL-STR} P_{OSL-R}
\]

(8)

Generally, the calculation of \(P_{EC-R}\) and \(P_{OSL-R}\) contains the test resistance of the transformer in the operation state, but it can not meet the test conditions in the actual operation state. Therefore, generally only the loss of DC resistance in formula (8) is taken. Generally, eddy current loss and stray loss are about 20% - 30% of load loss. \(K\) may be 1.25.

It is improved to form a relatively simple improved parameter method for calculation. The calculation method is as follows [20-21]:

\[
P = K \sum_{h=2}^{h_{max}} I_h^2 R_{dc}
\]

(9)

The parameters of DC resistance of transformer winding are improved and calculated. The parameters of DC resistance, AC fundamental resistance and harmonic frequency are obtained as follows:

\[
R_{dc} = R_1 (c_0 + c_1 h^b + c_2 h^2)
\]

(10)
where, $P$ is the harmonic winding loss of the transformer; $I_h$ is the harmonic current of the winding; $R_{DC}$ is the DC resistance; $R_1$ is the AC fundamental resistance; $K$ can be taken as 1.25; the values of coefficients $C_0$, $C_1$, $C_2$ and $b$ can be obtained by looking up the table, and the values of coefficient $C_0+C_1+C_2=1$. are shown in table 1.

Table 1. Improve the DC resistance method parameter values.

| Type          | $C_0$    | $C_1$    | $C_2$    | $b$     |
|---------------|----------|----------|----------|---------|
| Distribution Tr | 0.85-0.90 | 0.05-0.08 | 0.05-0.08 | 0.9-1.4 |
| Distribution Tr | 0.75-0.80 | 0.10-0.13 | 0.10-0.13 | 0.9-1.4 |
| Power Tr       | 0.85-0.90 | 0.05-0.08 | 0.05-0.08 | 0.9-1.4 |

When the transformer is a three-phase transformer, the above formula can be rewritten as:

$$P = 3K \sum_{h=2}^{n} I_h^2 R_i (c_0 + c_1 h^b + c_2 h^2)$$

This method has the characteristics of low accuracy, especially in the calculation of DC resistance, the undetermined coefficient is selected in a specific range, which increases the random error.

3. Analysis of Harmonic Loss of Transformer Winding

When the transformer winding passes through the AC current, if the transformer loss needs to be calculated accurately, the conductor on the first layer of the winding can be analyzed as a whole, and the skin effect and proximity effect can be considered.

Set the radius direction of transformer winding as $r$, axis direction as $z$, current flow direction as $\phi$, and establish the coordinate system. As figure 2 is shown. For example, the currents in the k, $\phi$, and $r$ directions are represented by $i_k$, $i_\phi$, and $i_r$, respectively, and the magnetic field strengths parallel to the inner and outer surfaces of the transformer winding layer are represented by $H_-$ and $H_+$, respectively. Assuming that the electric field strength $E$ ($\phi$-axis direction) and magnetic field strength $H$ ($z$-axis direction) of the circular conductor in the winding satisfy the column coordinate relationship when the current passes:

$$-\frac{\partial H_z}{\partial r} = \sigma E_\phi$$

$$\frac{1}{r \frac{\partial}{\partial r}} (r E_\phi) = -j \omega \mu H_z$$

Figure 2. Hollow cylindrical conductor.
where the magnetic field strength in the $z$-axis direction is expressed in $H_z$; The electric field intensity in the $z$-axis direction is expressed by $E_{\phi}$; $r$ is the radius of the winding layer; $\sigma$ is the conductivity of the copper conductor; $\mu$ is the permeability of the copper conductor; $\omega$ is the angular frequency.

Because the function of the distance $r$ between any point on the winding and the winding axis can represent the magnetic field strength and electric field strength, the Bessel function equation can be understood as:

$$H(r) = c_1 J_0(mr) + c_2 K_0(mr)$$

$$E(r) = -m / \gamma \times \left[ c_1 J_1(mr) - c_2 K_1(mr) \right]$$

In the formula, $J_0$ and $J_1$ are the first type of Bessel functions, $K_0$ and $K_1$ are the second type of Bessel functions; $c_1$ and $c_2$ are determined by boundary conditions.

For the winding layer, the electric field strength $E$ and the magnetic field strength $H$ are orthogonal, so Poynting vector is used to represent the energy flux through a unit area per unit time. From the perspective of energy loss, the energy injected into the unit length of the $n$th layer winding is:

$$P_n = \frac{N^2 I^2}{\gamma W} \left[ \frac{2(n^2 - 2n + 1) \coth(md_n)}{\sinh(md_n)} \left( \frac{1}{\sqrt{1 + d_n/r_n}} - \frac{1}{\sqrt{1 + d_n/r_n}^2} \right) \right]$$

where, $P_n$ is the power loss of the $n$th layer of winding; The width of the winding is represented by $W$; The number of coil turns contained in the winding layer is denoted by $N$; $I$ is the current flowing through the winding layer; $d_n$ is the thickness of the $n$th layer of winding; The distance between the winding axis and the $n$th winding layer is denoted by $r_n$. By simplifying formula (16) with Taylor expansion, the loss of the $n$th layer winding can be obtained as follows:

$$P_n = \text{Re} \left\{ \frac{N^2 I^2}{W \gamma} \left( \frac{\coth(md_n) - 2(n^2 - n) \tanh(md_n/2)}{2} \right) \right\}$$

Under the condition that the DC current in the winding is $I$, the DC power loss per unit length of the $n$th layer winding is:

$$P_{\text{dc}} = I^2 R_{\text{dc}} = \frac{N^2 I^2}{\gamma W d}$$

where, $P_{\text{dc}}$ is the power loss of winding layer $n$; $d$ is the thickness of each layer of winding; $R_{\text{dc}}$ is the DC resistance of winding layer.

The ratio of AC resistance to DC resistance of the same winding is defined as AC resistance coefficient when the same winding is respectively connected with h-harmonic AC current and DC current with the same effective value.

$$K_{rh} = \frac{R_{rh}}{R_{dc}}$$

$$K_{rh} = \text{Re} \left\{ F_h(1+j) \left[ \frac{\coth(F_h(1+j)) + 2(n^2 - 1) \tanh(F_h(1+j))}{3} \right] \right\}$$
where the ratio of the thickness of the winding layer \( d \) to the skin depth \( \delta \) of the \( h \)th harmonic is represented by \( F_h \); \( \delta_h \) is the skin depth of the \( h \)th harmonic, \( n \) is the number of winding layers.

By simplifying the expansion of formula (20), the AC resistance coefficient under the \( h \)th harmonic can be obtained.

\[
K_{rh} = 1 + \frac{5n^2 - 1}{45} F_h^4
\]

(21)

Then the total loss of transformer winding caused by each harmonic is:

\[
P_{cu} = I_{dc}^2 R_{dc} + R_{dc} \sum_{h=1}^{\infty} K_{rh} I_h^2
\]

(22)

where \( P_{cu} \) is the total winding loss of the transformer under the background of composite harmonic current; The harmonic current of each order is represented by \( I_h \); the number of harmonics is represented by \( h \); \( R_{dc} \) is the DC resistance of the winding; The DC current flowing through the winding is represented by \( I_{dc} \); \( K_{rh} \) is the AC resistance coefficient.

4. Experimental Study on Harmonic Resistance of Transformer Winding

4.1. Winding Harmonic Resistance Measurement Test

In order to enable the harmonic loss test of the transformer to be carried out effectively. This article is based on the comprehensive test and research platform of power quality in the laboratory. The harmonics of the output voltage can be simulated with the platform grid simulator. Sg-150/0.38 dry-type isolation transformer is used in this experiment. The experimental platform is shown in figure 3.

![Test Platform](image)

Figure 3. Experiment platform.

During the short circuit test, connect the primary side of the transformer with a grid simulator, and short-circuit the secondary side, and the harmonic voltage is generated by the grid simulator. The copper loss of the transformer is measured under different harmonic times and different harmonic voltage. In order to observe the harmonic current frequency variation of the transformer harmonic resistance change, apply 1, 3, 5, 7 49th harmonic voltage. The power loss on the transformer is calculated according to the effective value of the current flowing through the transformer and the active power on the primary side of the transformer.

It is convenient to carry out experiments and avoid errors as much as possible. In this experiment, the transformer winding resistance under harmonics is calculated by taking the active power passing through both ends of the transformer and dividing the square of the current. The measurements in this paper are obtained at room temperature of 20 ℃, and the experimental results are shown in table 2.
Table 2. Winding harmonic resistance measurement results.

| n   | Voltage rms (V) | Current rms (A) | Power (W) | R (Ω) |
|-----|----------------|-----------------|-----------|-------|
| 1   | 7.380          | 4.892           | 32.984    | 1.379 |
| 3   | 10.35          | 4.521           | 30.56     | 1.489 |
| 5   | 12.266         | 4.410           | 28.756    | 1.479 |
| 7   | 17.3           | 4.741           | 40.404    | 1.794 |
| 9   | 15.67          | 3.86            | 33.44     | 2.3115|
| 11  | 14.014         | 3.944           | 42.61     | 2.7393|
| 13  | 9.150          | 4.305           | 62.021    | 3.3465|
| 15  | 13.46          | 4.25            | 72.7      | 4.025 |
| 17  | 11.632         | 4.974           | 124.05    | 5.014 |
| 19  | 13.270         | 5.406           | 169.01    | 5.796 |
| 21  | 13.262         | 4.352           | 131.65    | 6.958 |
| 23  | 14.50          | 4.560           | 169.78    | 8.165 |
| 25  | 15.052         | 4.962           | 232.18    | 9.43  |
| 27  | 14.79          | 4.05            | 173.54    | 10.58 |
| 29  | 14.712         | 4.044           | 189.52    | 11.845|
| 31  | 17.652         | 4.713           | 314.2     | 14.145|
| 33  | 20.345         | 4.832           | 351.741   | 15.065|
| 35  | 23.044         | 4.935           | 408.9074  | 16.79 |
| 37  | 18.780         | 4.166           | 323.334   | 18.63 |
| 39  | 18.5           | 4.0             | 314.824   | 19.6765|
| 41  | 16.938         | 3.375           | 233.8211  | 20.5275|
| 43  | 22.878         | 4.183           | 398.4178  | 22.77 |
| 45  | 23.502         | 3.994           | 391.112   | 24.518|
| 47  | 24.051         | 3.904           | 410.3164  | 26.9215|
| 49  | 24.444         | 3.886           | 443.184   | 29.348|

Figure 4 shows the relationship between the number of harmonics and the equivalent resistance of the winding harmonics. We can see from the picture that as the number of harmonics increases, the equivalent resistance of winding increases significantly, which is approximately positive correlation, indicating that its resistance is gradually increased under the influence of skin effect and proximity effect.

Figure 4. The relationship between harmonic equivalent resistance and frequency.
Table 3 deals with the experimental measured values partially, calculates the AC group coefficient, that is, the ratio of each harmonic resistance value to the DC resistance, and calculates and compares the AC group coefficient of each harmonic using equation (2) in this paper.

| n  | R /Ω | Experiment resistance coefficient | Skin depth/mm | Calculated resistance system $1/\sqrt{n}$ |
|----|------|-----------------------------------|---------------|------------------------------------------|
| 1  | 1.379| 1.02                              | 14.2          | 1.011                                    | 1                           |
| 3  | 1.489| 1.22                              | 8.2           | 1.2                                      | 1.73205                     |
| 5  | 1.479| 1.286                             | 6.35          | 1.276                                    | 2.2361                     |
| 7  | 1.794| 1.56                              | 5.37          | 1.54                                     | 2.6847                     |
| 9  | 2.3115| 2.01                               | 4.73          | 1.9                                      | 3                           |
| 11 | 2.7393| 2.382                              | 4.28          | 2.34                                     | 3.3166                     |
| 13 | 3.3465| 2.91                               | 3.94          | 2.865                                    | 3.6056                     |
| 15 | 4.025| 3.5                               | 3.67          | 3.4774                                   | 3.873                      |
| 17 | 5.014| 4.36                               | 3.444         | 4.2                                      | 4.123                      |
| 19 | 5.796| 5.04                               | 3.26          | 4.98                                     | 4.359                      |
| 21 | 6.958| 6.05                               | 3.1           | 5.8664                                   | 4.582576                   |
| 23 | 8.165| 7.1                                | 2.96          | 6.8545                                   | 4.795832                   |
| 25 | 9.43 | 8.2                                | 2.84          | 7.91                                     | 5                           |
| 27 | 10.58| 9.2                                | 2.733         | 9.056                                    | 5.196152                   |
| 29 | 11.845| 10.3                               | 2.64          | 10.252                                   | 5.385165                   |
| 31 | 14.145| 12.3                               | 2.55          | 11.63                                    | 5.567764                   |
| 33 | 15.065| 13.1                               | 2.472         | 13.035                                   | 5.744563                   |
| 35 | 16.79| 14.6                               | 2.4           | 14.546                                   | 5.91608                    |
| 37 | 18.63| 16.2                               | 2.334         | 16.144                                   | 6.082763                   |
| 39 | 19.6765| 17.11                              | 2.3           | 17.06                                    | 6.244998                   |
| 41 | 20.5275| 17.85                              | 2.274         | 17.807                                   | 6.403124                   |
| 43 | 22.77| 19.80                              | 2.22          | 19.503                                   | 6.557439                   |
| 45 | 24.518| 21.32                              | 2.17          | 21.268                                   | 6.708204                   |
| 47 | 26.9215| 23.41                              | 2.12          | 23.25                                    | 6.855655                   |
| 49 | 29.348| 25.52                              | 2.07          | 25.478                                   | 7                           |

Figure 5 shows the comparison curve between the AC resistance coefficient measured by experiment and the AC resistance coefficient in the theoretical formula proposed in this paper. With the increase of harmonic current times passing through the transformer winding, the increase of harmonic resistance is more obvious. From the figure, we can see that the theoretical formula in this paper does not work well at low frequencies, but its general trend is more consistent with the fact. And at high frequency, when the skin effect and proximity effect are more and more obvious, the theoretical calculation value proposed in this paper is more accurate.

Due to the difference between the theoretical value and the test sample, and the calculation formula does not take into account the small proportion of stray loss, in addition to the accuracy of the experimental equipment and other factors, there is still a certain error between the theoretical value and the experimental value. However, compared with the traditional calculation method, the accuracy of the harmonic loss calculation of transformer winding proposed in this paper is improved.

Figure 6 shows the comparison between the coefficient of AC group calculated by theoretical formula and the equivalent AC resistance of $\sqrt{n}$ times of DC resistance applied in the existing research. The above figure shows that the resistance value of the transformer windings is not affected.
when the harmonic number is less than 20 times, and the resistance value changes very little, and the
difference between the two methods is not obvious; but when the harmonic number is more than 20
times, with the harmonic With the increase of wave frequency, the influence of skin effect and
proximity effect on the winding is more obvious, and the harmonic resistance is obviously increased.
The figure above shows that the equivalent resistance calculated by the theoretical model is more
accurate than that of the equivalent AC resistance method with $\sqrt{n}$ times of DC resistance.

![Figure 5. Comparison between the calculated value of the theoretical formula and the experimental
measurement value.](image)

![Figure 6. The calculated value of the theoretical formula is compared with the existing value.](image)

Figure 7 below shows the relationship between the AC resistance coefficient $K_{rh}$ and the skin depth
$\delta$ in the data obtained from our experiment.

![Figure 7. Relationship between AC resistivity $K_{rh}$ and skin depth.](image)
4.2. Practical Model of Winding Harmonic Resistance Engineering

In this paper, the ratio of harmonic resistance to DC resistance is used as the equivalent resistance coefficient, and the experimental data is used to fit the harmonic resistance. The power of each harmonic of transformer winding can be expressed by the following formula, and the AC resistance coefficient is introduced.

\[ P_h = I_h^2 R_{dc} K_{rh} \]  \hspace{1cm} (23)

For the function fitting of the first section of data, that is, when \( \delta < 4.28 \text{mm} \), according to the relationship between coefficient \( K_{rh} \) and skin depth \( \delta \), it is approximately exponential function, so we take the exponential function fitting of formula (24).

\[ y = a x^b \]  \hspace{1cm} (24)

Use the function in MATLAB to fit the curve in sections, and obtain the fitting function. The fitting curve is shown in figure 8 below.

![Figure 8. Skin depth and AC resistivity curve fitting relationship.](image)

Figure 8 shows the first fitting curve between the AC group coefficient of the equivalent resistance of the experimental harmonic loss and the skin depth. The abscissa is the skin depth value under each harmonic, and the ordinate is the AC group coefficient of each harmonic. The confidence degree is 95\%, and the determination coefficient is 0.9437. In the fitting of figure 8, the coefficient \( a = 341.4 \), coefficient \( b = -3.579 \), named.

\[ K_{rh} = 341.4 \cdot \delta^{-3.579} \]  \hspace{1cm} (25)

For the function fitting of the second segment of data, when \( \delta > 4.28 \text{mm} \), the relationship between coefficient and skin depth \( \delta \) is approximately exponential. The fit curve is shown in figure 9 below.

![Figure 9. Skin depth and AC resistivity curve fitting relationship.](image)
Figure 9 shows the second fitting curve between the AC group coefficient of the equivalent resistance of the experimental harmonic loss and the skin depth, coefficient $a = 7.529$, coefficient $b = -0.8613$, i.e

$$K_{th} = 7.529 \cdot \delta^{-0.8613}$$  \hspace{1cm} (26)

Therefore, the harmonic loss of transformer winding under each harmonic obtained by fitting function is:

$$P_r = I_n^2 R_k K_n = \begin{cases} I_n^2 R_k \cdot 324.9 \cdot \delta^{-3.519} & (\delta < 4.28 \text{mm}) \\ I_n^2 R_k \cdot 7.529 \cdot \delta^{-0.8613} & (\delta > 4.28 \text{mm}) \end{cases}$$  \hspace{1cm} (27)

We use another set of experimental data to verify the above fitting formula, and the experimental data is shown in table 4.

| n  | Voltage rms/V | Current rms/A | Power /W | Resistance /Ω | Experimental coefficient | Skin depth /mm | Fitting coefficient |
|----|---------------|---------------|----------|---------------|--------------------------|----------------|-------------------|
| 1  | 25.72         | 20.512        | 498.369  | 1.185         | 1.03                     | 14.2           | 0.766075          |
| 3  | 10.35         | 10.521        | 157.846  | 1.426         | 1.24                     | 8.2            | 1.229333          |
| 5  | 30.740        | 8.089         | 96.31579 | 1.472         | 1.28                     | 6.35           | 1.532175          |
| 7  | 35.760        | 6.214         | 69.09553 | 1.789         | 1.556                    | 5.37           | 1.770152          |
| 9  | 15.67         | 3.86          | 34.95446 | 2.346         | 2.04                     | 4.73           | 1.974601          |
| 11 | 59.04         | 5.78          | 90.6704  | 2.714         | 2.36                     | 4.28           | 2.152161          |
| 13 | 39.768        | 4.836         | 77.9953  | 3.335         | 2.9                      | 3.94           | 2.523379          |
| 15 | 13.46         | 4.25          | 73.117   | 4.048         | 3.52                     | 3.67           | 2.532979          |
| 17 | 12.648        | 5.018         | 127.412  | 5.06          | 4.4                      | 3.444          | 4.084271          |
| 19 | 10.680        | 5.192         | 155.932  | 5.784         | 5.03                     | 3.26           | 4.97116           |
| 21 | 13.262        | 4.352         | 132.863  | 7.015         | 6.1                      | 3.1            | 5.952234          |
| 23 | 15.160        | 5.929         | 291.067  | 8.28          | 7.2                      | 2.96           | 7.022803          |
| 25 | .372          | 4.62          | 199.314  | 9.338         | 8.12                     | 2.84           | 8.143989          |
| 27 | 14.79         | 4.05          | 174.48   | 10.64         | 9.25                     | 2.733          | 9.343945          |
| 29 | 15.672        | 4.212         | 210.14   | 11.85         | 10.3                     | 2.64           | 10.57653          |
| 31 | 17.668        | 4.42          | 280.84   | 14.38         | 12.5                     | 2.55           | 11.97447          |
| 33 | 18.345        | 4.832         | 355.77   | 15.23         | 13.25                    | 2.472          | 13.38268          |
| 35 | 20.668        | 3.784         | 241.23   | 16.85         | 14.65                    | 2.4            | 14.87604          |
| 37 | 16.052        | 3.178         | 191.06   | 18.92         | 16.45                    | 2.334          | 16.4373           |
| 39 | 19.54         | 4.01          | 318.99   | 19.84         | 17.25                    | 2.304          | 17.32366          |
| 41 | 25.512        | 4.129         | 350.95   | 20.58         | 17.9                     | 2.274          | 18.04307          |
| 43 | 30.892        | 4.394         | 439.182  | 22.75         | 19.78                    | 2.22           | 19.66374          |
| 45 | 24.5          | 3.783         | 352.2    | 24.61         | 21.4                     | 2.17           | 21.33409          |
| 47 | 28.051        | 3.904         | 411.8939 | 27.03         | 23.5                     | 2.12           | 23.19036          |
| 49 | 25.5          | 3.388         | 337.9283 | 29.44         | 25.6                     | 2.07           | 25.25839          |
5. Conclusion
Considering the influence of the skin effect and proximity effect of the transformer winding resistance under the background of harmonic current, the distortion characteristics of the winding parameters are analyzed based on the electromagnetic field theory, the calculation model of winding loss is established, and the harmonic loss of winding is further accurately quantified. It can be seen that the theoretical calculation model of harmonic loss is more accurate by setting up an experimental platform to measure the resistance of transformer winding under the background of each harmonic current and observing the law of harmonic resistance changing with frequency. It can also be seen that the practical model of work is established by fitting the resistance of each harmonic of winding according to the experimental data, which has certain guiding value for engineering calculation.

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References
[1] Fu K, You W, Yang Z, et al. 2014 Harmonic sources and harmonic detection methods in power systems Electric Measurement & Instrumentation 51 (12) 81-86.
[2] Jiang Y, Chang J and Tang Z 2017 Study on harmonic distribution characteristics of distribution network system with DG Power System Protection and Control 45 (14) 38-44.
[3] Wu J, Wu K, Feng L, et al. 2017 Distribution network harmonic source identification method based on probability prediction and harmonic current Power System Protection and Control 45 (08) 86-92.
[4] Li C 2008 Causes of generation of harmonics in power systems and their suppression methods Electrical Switch (01) 56-59.
[5] Lin J and Du Y 2009 Harmonic harm and prevention countermeasures in power system Power System and Clean Energy 25 (02) 28-31.
[6] Wang L, Xiao X, Zhang Y, et al. 2017 Distortion power evaluation index and method for nonlinear load harmonics contribution Power System Protection and Control 45 (09) 41-47.
[7] Li J, Huang J, Zhu J, et al. 2017 Line-loss calculation of distribution network based on characterization of process state Power System Protection and Control 45 (10) 55-61.
[8] GAO J 2016 Comparison and simulation of transformer harmonic loss calculation methods Journal World 14 (14) 133-134.
[9] Wang X, Cheng Z, Lin L, et al. 2014 Calculation and validation of iron loss in laminated core of power and distribution transformers Compel International Journal of Computations & Mathematics in Electrical 33 (1/2) 137-146.
[10] Liu H, Li G, Wang Z, et al. 2017 Research on modeling methods and control strategies of power electronic transformers for middle and high voltage smart distribution network Power System Protection and Control 45 (02) 85-93.
[11] Zhang Z, Wang K, Li D, et al. 2011 Analysis of harmonic loss of transformers and influence factors analysis Power System Protection and Control 39 (04) 68-72.
[12] Makram E F and Thompson R L 1988 A new laboratory experiment for transformer modeling in the presence of harmonic distortion using a computer controlled harmonic generator IEEE Trans on Power Systems (4) 1857-1863.
[13] Liu S, Shi H and Feng L 2015 A model of transformer harmonic loss considering skin effect and proximity effect Electric Power Automation Equipment 35 (3) 133-139.
[14] Ding Y, Xu C, Li H, et al. 2015 Computing harmonic loss of transformer considering skin effect Electric Energy and Energy Efficiency Technology (23) 63-68.
[15] Shi D, Tang Z and Chen W 2009 Theoretical study and analytic calculation of skin effect Journal of Chongqing University of Arts and Sciences (Natural Science Edition) 28 (05) 18-21.
[16] Lu Q, Zhang Q and Qin R 2015 Introduction and simulation of skin effect in transmission lines Electronic Measurement Technology 38 (06) 27-30.
[17] Li G, Li P, Xu Y, et al. 2010 Comparison and simulation of transformer harmonic loss calculation method Power System Protection and Control 38 (18) 63-68.
[18] Liu C and Yang R 2008 Calculation and analysis of transformer harmonic loss Power System Protection and Control (13) 33-36+42.
[19] Cai G, Kong L, Pan C, et al. 2011 Analysis of harmonic loss of transformer based on frequency-varying characteristics Power System Technology 35 (11) 120-124.
[20] Jia J, Duan X, Lu J, et al. 2015 A review on the calculation methods of transformer harmonic loss Hebei Electric Power Technology 34 (04) 37-41.
[21] Li Q, Zou L, Liu H, et al. 2013 Calculation and experimental study of harmonic losses in power transformer Power System Technology 37 (12) 3521-3527.