An approach to the transformer core residual magnetism evaluation and demagnetization

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Abstract. Aiming at the problem of transformer inrush current suppression, a method of transformer core residual magnetism evaluation and demagnetization is proposed. Firstly, by setting the amplitude and time of DC current, different transformer core residual magnetism states are obtained. Secondly, under different residual magnetism conditions, the high-voltage winding of the transformer is charged and discharged in the forward and reverse direction alternately. The current change data in the process is collected, and the correlation coefficient of the current data in the forward and reverse charging processes is calculated, which represents the transformer core residual magnetism states. Finally, the DC current with alternating change direction and gradually decreasing amplitude is applied at the high voltage winding to demagnetize, and the variation of residual magnetism is analyzed during the demagnetization process.

1. Introduction
The transformer core material has nonlinear hysteresis characteristics. Residual magnetism will remain in the core after direct current resistance measurement and being out of operation. When the transformer is switched on without load, the residual magnetism in the core may lead to the saturation of the core and produce asymmetric large inrush current. The inrush current value can be as high as 6-8 times of the rated current, and the current contains a large number of high-order harmonics.

The large inrush current seriously affects the safe operation of power transformer. (1) The inrush current can increase the loss in the core, winding and metal structures to produce heat, which affects the service life of power transformers. (2) The current can cause large electric forces, and the vibration of winding and body may form oil surge, which triggers heavy gas protection action. The forces can also lead to winding deformation. (3) The excitation current leads to large difference between input and output current of power transformer, resulting in power transformer differential protection operation. (4) The high harmonic component of current has a strong destructive effect on the sensitive power electronic components in power system. Therefore, eliminating transformer core residual magnetism before power transformer is put into operation is of great significance to ensure the safety of power transformers and the stable operation of power system.

Several models are established in [1-3], such as Preisach model, which studies the nonlinear hysteresis characteristics of transformer core. These papers focus on the analysis of the transformer core characteristics and the residual magnetism influences with inrush current. For demagnetization, these technologies are not involved. Therefore, AC and DC demagnetization are studied and applied. The AC demagnetization appliance is bulky and inconvenient to transport, and can not accurately judge the final result of demagnetization. The DC demagnetization method continuously reduce hysteresis loop of the
core to achieve the purpose of eliminating residual magnetism by injecting forward and reverse direction DC current into the high voltage winding of the transformer respectively. The existing demagnetization devices cannot evaluate the residual magnetism and the demagnetization result is difficult to guarantee. These two demagnetization methods don't consider the residual magnetism detection. Therefore, it is necessary to study the transformer residual magnetism evaluation method and demagnetization device.

This paper presents a method of transformer core residual magnetism evaluation and demagnetization. Firstly, many different residual magnetism conditions are got through applying current into the high voltage winding. Then, the high-voltage side winding of the transformer is charged and discharged by different direction currents in turn. The current change data in the process of forward and reverse charging are collected and recorded, and the correlation coefficient of forward and reverse charging current data is calculated. Using the corresponding relationship, the residual magnetism state is established. Finally, the demagnetization is carried out when the amplitude of the alternating direction of the high-voltage winding is gradually reduced. During the demagnetization process, the variation of the magnetic flux is analyzed.

2. Residual magnetism of transformer core

The transformer core uses silicone plates, whose characteristics can be expressed by the change between the magnetic induction intensity $B$ and the magnetic field intensity $H$. The curve is not linear. Due to the hysteresis characteristics of ferromagnetic materials, the residual magnetism will remain in the core after the transformer is disconnected or the direct current resistance measurement test. The magnitude of residual magnetic flux density is related to the hysteresis loop of the core [4-5]. After the direct current resistance measurement, the residual flux density is related to the applied current and the parameters of the discharge circuit. The residual flux density in the core is related to the current amplitude before the transformer is disconnected. The relationship diagram of hysteresis loop, saturation hysteresis loop, residual flux density and basic magnetization curve in transformer core is shown in Fig. 1.

3. Transformer core residual magnetism evaluation

If the forward direction current is injected, it includes two processes. One is the charging period, and the other is discharging period. If the current is small enough, the residual magnetism changes a little. To evaluate the residual magnetism, the forward and reverse direction currents are injected successively. And the current data in charging periods is used. If there is no residual magnetism in the core, the charging current of forward and reverse direction currents is similar in the same period. If there is some residual magnetism in the core, the charging progress of reverse direction current must experience compensation process, which determines that the charging current curves are different.
Residual magnetism detection and evaluation is mainly divided into three steps:

(1) First, the high voltage winding is injected into a small forward direction current under no load condition, and when the current reaches the set value the high voltage winding is shorted to discharge.

(2) Then, the reverse direction current is injected into the high voltage winding like forward direction current.

(3) Last, the charging period of forward and reverse direction current is used to calculate the coefficient, which is relative to the residual magnetism.

Using the first $N_1$ current data of the forward and reverse direction current, calculate the correlation coefficient. Consider expressing habits, the difference between correlation coefficient and 1 is used to represent the residual magnetism.

The calculation of correlation coefficient $\rho_{XY}$ is shown in formula (1). In the formula, $X$ and $Y$ are the two current vectors respectively. $\sigma_X$ is the standard deviation of $X$, and $\sigma_Y$ is the standard deviation of $Y$. $E_X$ is the mathematical expectation of variable $X$, and $E_{XY}$ is the expectation of the data that $X$ times $Y$.

$$\rho_{XY} = \frac{\text{cov}(X,Y)}{\sigma_X \cdot \sigma_Y} = \frac{E_{XY} - E_X \cdot E_Y}{\sigma_X \cdot \sigma_Y}$$  (1)

When there is no residual magnetism in the transformer core, the correlation coefficient of forward and reverse charging current data is close to 1, and the difference between correlation coefficient and 1 is nearly 0. While the transformer is fully magnetized, the 1-correlation coefficient changes a lot, which is very different. The smaller the data is, the less the residual magnetism is. The larger the data is, the more the residual magnetism is.

4. DC demagnetization method
The DC demagnetization method is to apply DC current to both ends of high voltage winding of transformer in forward and reverse direction respectively. The current is reduced continuously to reduce the hysteresis loop of iron core. And the residual magnetism in transformer core is eliminated to achieve the purpose.
In the process of demagnetization, the alternating direction current are switched according to the charging current value. The value of current amplitude decreases gradually. The current value is monitored by two hall current sensors. The large current sensor is used to monitor the current above 160mA, and the small current sensor is used to monitor the current below 160mA.

In the demagnetization process, the first forward direction charging current is cut when the current value reaches set data and the circuit enters into discharging situation. After the forward direction current, the reverse direction source is applied like the forward direction current. In the demagnetization process, the magnetic flux variation of the iron core in charging and discharging cycle is calculated, which is shown in formula (2). In formula (2), \( t_0 \) and \( t_1 \) are the start and end time of charge discharge cycle respectively. According to the change of magnetic flux, the relationship between the change of magnetic flux with time is drawn.

\[
\Delta \Phi = \int_{t_0}^{t_1} u dt
\]  

(2)

5. implementation process

5.1 Hardware circuit design

5.1.1 Design of residual magnetism evaluation circuit

To realize the function, the residual magnetism evaluation circuit is designed, as shown in Fig. 4. In the circuit, the sampling resistance and transformer winding are in series. And the forward and reverse direction current is measured. In the figure, \( R_3 \) and \( R_2 \) represent the sampling resistance and transformer winding resistance respectively.

![current measurement circuit](image)

Fig. 4. current measurement circuit.

The voltage signal of the sampling resistance \( R_3 \) is amplified by the operational amplifier circuit, as shown in Fig. 5. This circuit uses two stages of operational amplifier, and each stage is amplified 10 times.

![current amplifier circuit](image)

Fig. 5. current amplifier circuit

5.1.2 Main circuit of demagnetization function

In Fig. 6, the main circuit of demagnetization function is shown. \( T_5 \) is the main switch, which is turned on while charging and turned off while discharging. \( T_6 \) and \( T_7 \) are the discharging switches. \( T_6 \) and \( T_7 \) are turned off in the charging process and turned on in the charging process, which can improve the discharge speed by choosing different discharging resistances at different current values. \( T_1 \) and \( T_4 \) are
the forward direction charging switches, and turned on while charging. The resistance $R_0$ is the discharging resistance of the filter capacitor. $R_1$ and $R_2$ are the transformer winding discharging resistances, and $R_2$ is less than $R_1$. $L$ is the transformer winding inductance.

\[ \text{Fig. 6. Main circuit of demagnetization function} \]

5.2 Software implementation process
The process of residual magnetism evaluation and demagnetization are shown in Fig. 7. Firstly, the forward and reverse charging of transformer winding is carried out to collect current data. Secondly, calculate the correlation coefficient, evaluate the amount of residual magnetism, and take appropriate current for demagnetization. Last, the demagnetization process finishes until the residual magnetism decreases to zero.

\[ \text{Fig. 7. flow chart of residual magnetism evaluation and demagnetization} \]

6. Implementation results and analysis
In order to test the effectiveness of the residual magnetism evaluation method, a 220kV transformer is selected for test. The residual magnetism state of the transformer is simulated. The non-magnetic state is simulated by demagnetizing repeatedly, and different residual magnetism situations are simulated by setting charging time. For example, the transformer winding is charged by 30 seconds with 5A current under the non-magnetic situation. The maximum residual magnetism is simulated by charging by 24 hours with 5A current.

In the three situations, the residual magnetism evaluation results are shown in Table 1. In Fig. 8 to 10, the forward and reverse direction current curves are shown. It can be seen from the figures that the residual magnetism evaluation results of transformers in different states are obviously different.
When there is no residual magnetism in the transformer core, the reverse and forward direction currents are similar. In other words, the 1-correlation coefficient is close to 0. When the residual magnetism is maximum, the reverse and forward direction currents are quite different and the 1-correlation coefficient is close to 1. And when the residual magnetism is between the above situations, the 1-correlation coefficient is also between 0 and 1. The more the residual magnetism is, the 1-correlation coefficient is bigger, and the difference between reverse and forward currents are greater. Therefore, the method proposed in this paper is effective to evaluate transformer residual magnetism.
Table 1 Results of residual magnetism evaluation

| Residual magnetism situations              | \( I \rho_{XY} \) |
|------------------------------------------|------------------|
| the non-magnetic situation               | \( 0.5647 \times 10^{-4} \) |
| some residual magnetism                  | \( 0.3124 \) |
| the maximum residual magnetism           | \( 0.9818 \) |

The hysteresis curve is drawn by using the variation of magnetic flux in each charging and discharging cycle during 1A current demagnetization, as shown in the figure below. After multiple forward and reverse charging and discharging processes, the residual magnetism gradually approaches to 0.

Fig. 11. hysteresis curve in demagnetization process

7. Conclusion
Aiming at the problem of inrush current suppression for transformers, a method to evaluate the residual magnetism by using the correlation coefficient of charging current in the process of forward and reverse currents is proposed, and the corresponding relationship between the correlation coefficient and residual magnetism state is established. The evaluation and demagnetization device is studied. During the demagnetization process, the change of magnetic flux is monitored and the residual magnetism is analyzed. The test results show that the proposed method is effective, which overcomes the problem of blind demagnetization of power transformer.

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