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Influence of Harmonics on the Working Efficiency of a 6/1.2 kV Transformer in a Pit Mine

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Abstract. Explosion-proof transformers 6/1.2 kV is important electrical equipment responsible for supplying electricity in underground mine electrical networks. A failure of this transformer will cause an interruption in the power supply and loss of safety in underground mining. Usually, explosion-proof transformers in underground mine electrical networks are designed and manufactured to work with ideal parameters such as sinusoidal currents, and the network structure is symmetrical. However, today in underground mine electric networks, many power electronics are connected to the network, such as inverters and soft starters. As a result, a current flowing through the transformer is non-sinusoidal, overloading the transformer even by working with the design specifications. This paper studies the influence of harmonics on the working efficiency of a 6/1.2 kV transformer in a pit mine. Research results suggest reasonable solutions for transformer operation to ensure longevity and not cause damage to the transformer.

Keywords: Harmonics, Working efficiency, Transformer, Pit mine

1. Introduction

The explosion-proof transformer is one of the most important electrical components in an underground power distribution network. The operation and proper preventive maintenance of transformers will ensure a continuous and reliable electrical power supply to end-user customers without power outages or interruptions. Furthermore, the increasing cost of electricity generation has reinforced the importance of using low-loss transformers. Therefore, reducing transformer losses is of interest in today's competitive environment [1].

Traditionally, explosion-proof transformers are designed to operate at a sinusoidal power frequency to provide a linear load. However, the 6kV power network in open-pit mining has characteristics such as long feeder lines, large-capacity equipment, various branches, overuse of power electronics on the grid, which degrades the power quality, leading to increased power loss [2, 3]. Consequently, the performance of the transformer will be impacted. Non-linear loads generate non-sinusoidal currents from electrical networks, and therefore they are considered sources of harmonic currents that produce reverse currents into electrical networks. Such harmonic currents passing through the distribution lines then cause harmonic voltages [4].

Harmonic voltage creates unwanted additional losses, leading to excessive heat generation in the transformer. Excessive temperature rise due to harmonic pollution accelerates the aging of transformer insulation, thereby reducing their service life. As a result, harmonic pollution is becoming an increasingly important concern for power companies. To counter the adverse effects of harmonic pollution, power reduction of transformers is one of the approaches to maintain their expected design life [5].

Transformer losses can be classified into two main groups of no-load and loaded losses. The no-load loss represents the energy required to retain the continuously variable flux in the core and is independent of the transformer load. The load loss arises from the resistance loss of the windings, and it depends on the square of the load current [6]. Continuous no-load losses lead to power loss in network-connected transformers for all 24 h.

The study of core loss of a three-phase transformer with a capacity of 300 VA with different harmonic conditions has been investigated using the three-dimensional finite element method [7]. The results showed that the voltage harmonics contribute to the increase in core losses in the transformer, with a value of up to 67.3% when the input voltage is formed based on the highest harmonic order stated in IEC 61000-3-6 international standards about harmonic emission limits.

Arslan et al. (2014) studied 12.5 MVA, 11 kV/31.5 kV transformer no-load loss on the 2D FEM model under excitation voltage with some content on sub-harmonics [8]. The obtained simulation results have shown that the effect of sub-harmonic voltage on transformer core loss is negligible. However, it has also been found that a small amount of auxiliary harmonic voltage can significantly contribute to winding losses under no-load conditions, and they need to be handled with care for power transformer attenuation [8].

In [9], Yazdani-Asrami et al. (2013) used the experimentally combined finite element method to test non-sinusoidal voltage effects on no-load transformer losses. No-load loss ratio increases from 14% to 20% for harmonics with total harmonic distortion (THD) from 31.7% to 38.2% compared to the sinusoidal condition of the test transformer.

The results of a no-load experiment in [5] showed that the additional core loss due to non-sinusoidal excitation could be increased up to 20.8%. A short-circuit test was also carried out to determine the increase in transformer loss due to the increase in impedance and reactance in the transformer equivalent circuit under the distinct effect of the harmonic orders at different times. The short circuit test results showed that the total resistance and inductance of the coil increases with the applied frequency, and its linear variation can explain the linear increase in reactance with the applied frequency ($X = \omega L$). In contrast, the increase in the total impedance of the coil is due to the skin effect.

This paper builds a loss calculation model for a three-phase transformer and studies the effect of non-sinusoidal voltage on transformer losses in case of no-load and short-circuit and their performance under load in the underground mine electrical network. Thereby, the authors recommend users to have appropriate operating solutions to improve the service life and not cause damage to the mining transformer.

2. Theoretical basis

2.1. Simulation model for a three-phase transformer

A typical transformer commonly used in mining is the 630 kVA mine explosion-proof three-phase transformer. It is used in the experiment in this study with its initial parameters from manual [10] given in Table 1.

Tab. 1. Parameters of mine explosion-proof three-phase transformer 630/6-1.2 from manual [10].

Rated power P_n, kVA	No-load voltage (V)		Rated current, A		Short circuit voltage, $V_{sc\%}$	No-load current, $I_{NL}\%$	Losses, W	
	HV V_{NL1}	LV V_{NL2}	HV I_{1n}	LV I_{2n}			No-load P_{NL}	Short circuit P_{sc}
630	6000	1200	60.6	304.3	3.5	3	2800	4700

This paper uses the "Three-Phase Transformer (Two Windings)" model on MATLAB/ Simulink software as a basis for studying the proposed effects. The Three-Phase Transformer (Two Windings) model uses three single-phase transformers coupled together. Figure 1 shows the equivalent circuit of the single-phase transformer [11]. From the manufacturer's parameters, the paper builds simulation parameters for a three-phase transformer based on linear transformer combined with hysteresis characteristics on MATLAB/Simulink software. The simulation parameters of a single-phase transformer are given in Table 2 and use the proposed hysteresis characteristic as shown in Figure 2.

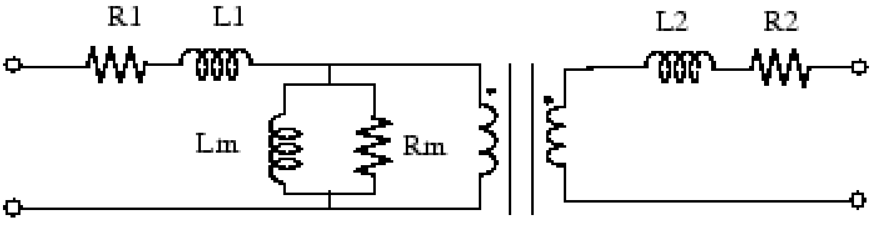

Fig. 1. Equivalent circuit of linear single-phase transformer.

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Tab. 2. Simulation parameters of three-phase transformer.

Resistance (ohm)		Inductance (L)		Magnetization resistance, R_m (ohm)
HV, R_1	LV, R_2	HV	LV	
0.2133	0.0085321	0.0031125	0.0001245	13580

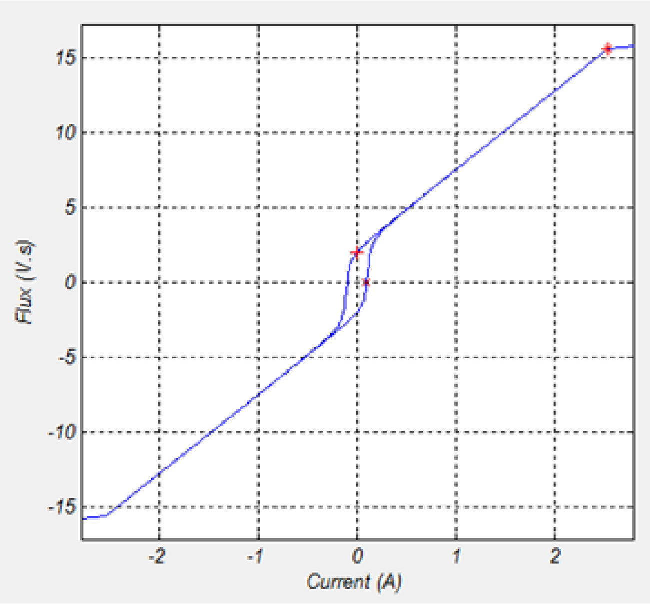

Fig. 2. Hysteresis characteristics.

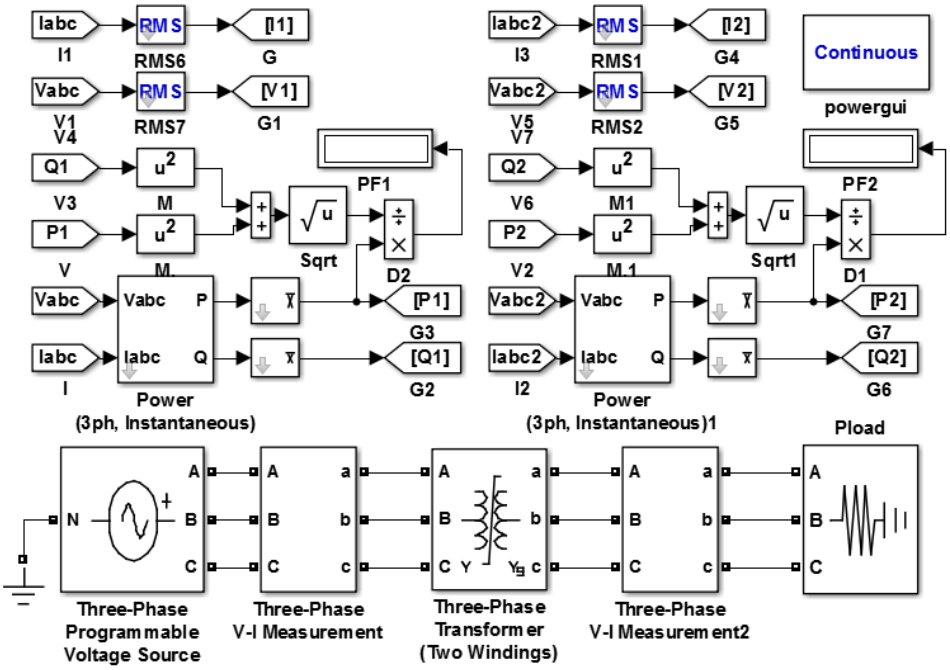

Fig. 3. Simulation model of 3-phase transformer.

The transformer uses a Y/Y connection. In the model, the resistances are constant, which means that the skin effect is ignored. The simulation model of 3-phase transformer on Matlab-Simulink is shown in the figure 3. Where the "Thee Phase Programmable Voltage Source" source block is used, non-sinusoidal modeling is added with a harmonic component to the existing sine source voltage.

2.2. Basis of loss calculation

The losses in the transformer include load and no-load losses, and are calculated by:

$$P_T = P_1 - P_2 = P_L + P_{NL} \tag{1}$$

Where P_1 - 3-phase high-voltage input power, P_2 - low voltage 3 phase power.

The no-load loss is independent of the load and is caused by the induced voltage in the core. It consists of two components: hysteresis loss and eddy current loss [12]. The two-frequency method for transformer [13] to separate the core loss into eddy current loss P_{Fe} and no-load hysteresis loss P_H is expressed by the following formula:

$$P_{NL} = P_{Fe} + P_H \tag{2}$$

Eddy current loss in the proposed model is calculated by:

$$P_{Fe} = 3R_m I_m{}^2 = 3R_m \sum_{h=1}^{h_{max}} I_{m,h,rms}{}^2 \tag{3}$$

Where R_m - magnetization resistance, ohm; I_m - true RMS value of magnetizing current, A; $I_{m,h,rms}$ - RMS value of the h harmonic order of the magnetizing current, A.

The load loss in the proposed model is the copper loss, which is proportional to the square of the true root mean square (RMS) value of the load current increased by the current harmonic components.

$$P_L = 3R_1.I_{1,r}{}^2 + 3R_2.I_{2,h,r}{}^2 = 3R_1.\sum_{h=1}^{h_{max}} I_{1,h,rms}{}^2 + 3R_2.\sum_{h=1}^{h_{max}} I_{2,h,rms}{}^2 \tag{4}$$

Where R_1 - high voltage phase resistor; R_2 - low voltage phase resistance; $I_{1,r}$ - true RMS value of high voltage load current; $I_{2,r}$ - true RMS value of low voltage load current; $I_{1,h,rms}$ - RMS value of the h harmonic order of high voltage load current; $I_{2,h,rms}$ - RMS value of the h harmonic order of low voltage load current.

When the power source has harmonics, PF is calculated according to the following relationship:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \tag{5}$$

Where P - the active input power, W; Q - the reactive input power, Var.

The efficiency of a transformer is the ratio of the 3-phase low-voltage output power P_2 to the 3-phase high-voltage input power P_1:

$$eff = \frac{P_2}{P_1} 100 \tag{6}$$

3. Research results and discussion

3.1 No-load simulation test

The primary purpose of the no-load simulation test is to demonstrate a significant increase in no-load losses when operating at rated voltage and with harmonic distortion. The test transformer is excited on the HV side, and the LV winding is kept open.

In this test, the transformer is operated at different voltages and frequencies, but the V/f ratio is constant. The results are shown in Figure 4. As expected, these losses are proportional to the supply V/f ratio or the frequency ratio applied and the increased voltage level because the flux density is proportional to the excitation. In addition, eddy current losses are the main contributor to core loss. The copper loss component in the no-load test accounts for 0.05-0.1% of the no-load loss.

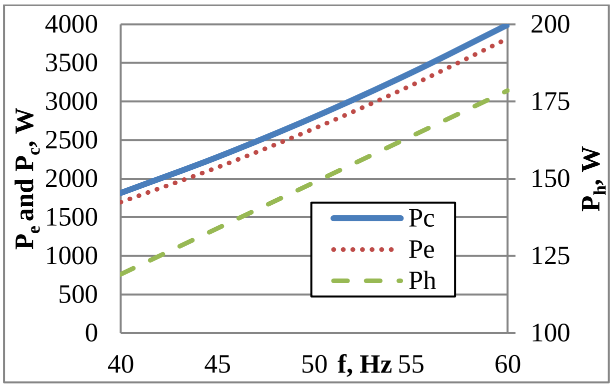

Fig. 4. Core loss in V/f ratio.

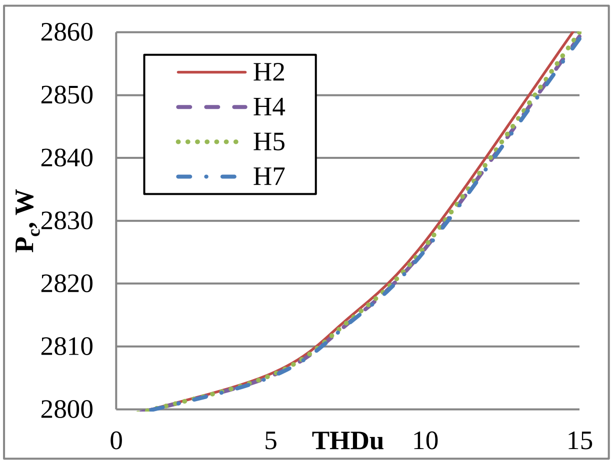

Fig. 5. Core loss under harmonics.

Tests for the effect of harmonics on core losses are carried out by adding high-order harmonic components to the reference voltage with a variable voltage THD, the results of which are shown in Figure 5. It is clear that as the voltage THD increases, so does the core loss proportionally. Tests have also shown that the 3rd and 6th harmonics have no effect and that the 5th harmonic has a significant influence on core losses in the no-load case.

Testing with the effect of input voltage deviation on core losses is also considered. The results in Fig. 6 indicate that when rated voltage increases 8.3%, core loss increases to about 16.6% for the non-harmonic case and 19.4% for the possibility of 5th harmonic sources with a THDu voltage of 15%. These results are significant, considering that the transformer is always on, core losses are always present. Thus, the presence of voltage harmonics will significantly contribute to the total loss in general and the core loss in particular in practice.

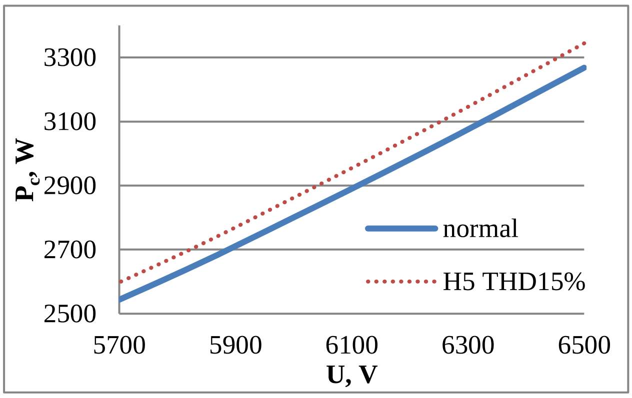

Fig. 6. Core loss under input voltage changer.

3.2 Short circuit simulation test

Here, the short-circuit test transformer is excited on the HV side with the test short-circuit voltage, and the LV winding is kept short-circuited. The results in Table 3 show that the short circuit loss is not affected by the 3rd and 6th harmonics and increases the most when there is the 2nd harmonic. With the increase of voltage THDu, the short-circuit loss also increases correspondingly in Figure 7.

Tab. 3. Short-circuit losses under harmonic with 15% voltage THDu.

Harmonic	H1	H2	H3	H4	H5	H6	H7
P_{SC}, W	4697	4724	4697	4703	4701	4697	4699

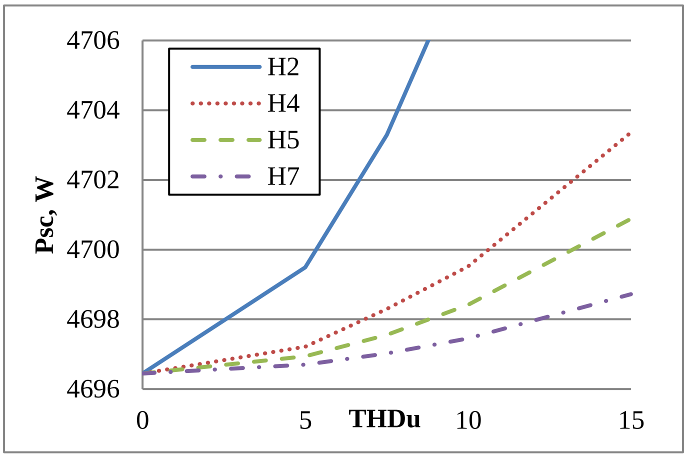

Fig. 7. Short circuit losses with variable THDu.

3.3 Simulation test with load

The simulation test with load gives an overview of the transformer efficiency dependence on voltage harmonics. In Figure 8, the overall efficiency of the transformer depends on the load factor and its power factor PF. Maximum transformer efficiency when unit PF and the efficiency of leading power factor is greater than that of lagging power with the same element. Transformer efficiency with harmonics is lower than the efficiency without harmonics.

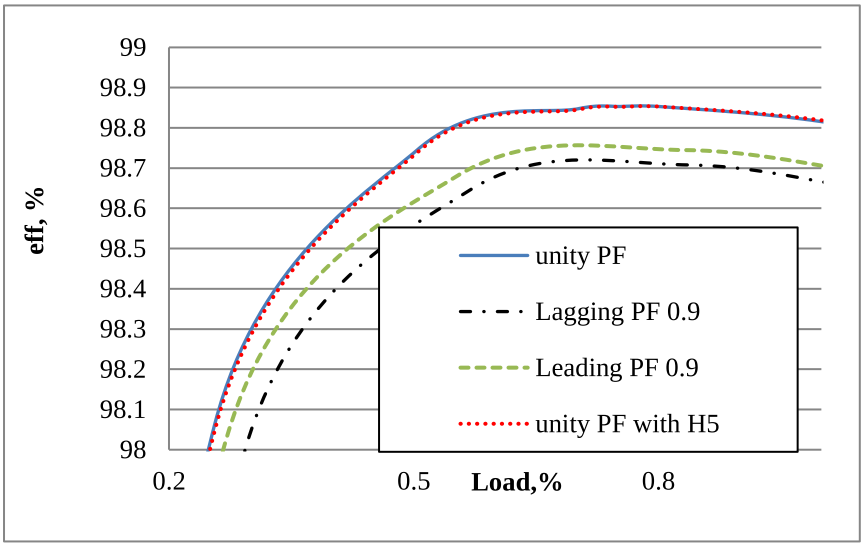

Fig. 8. Transformer efficiency as a percentage of the load.

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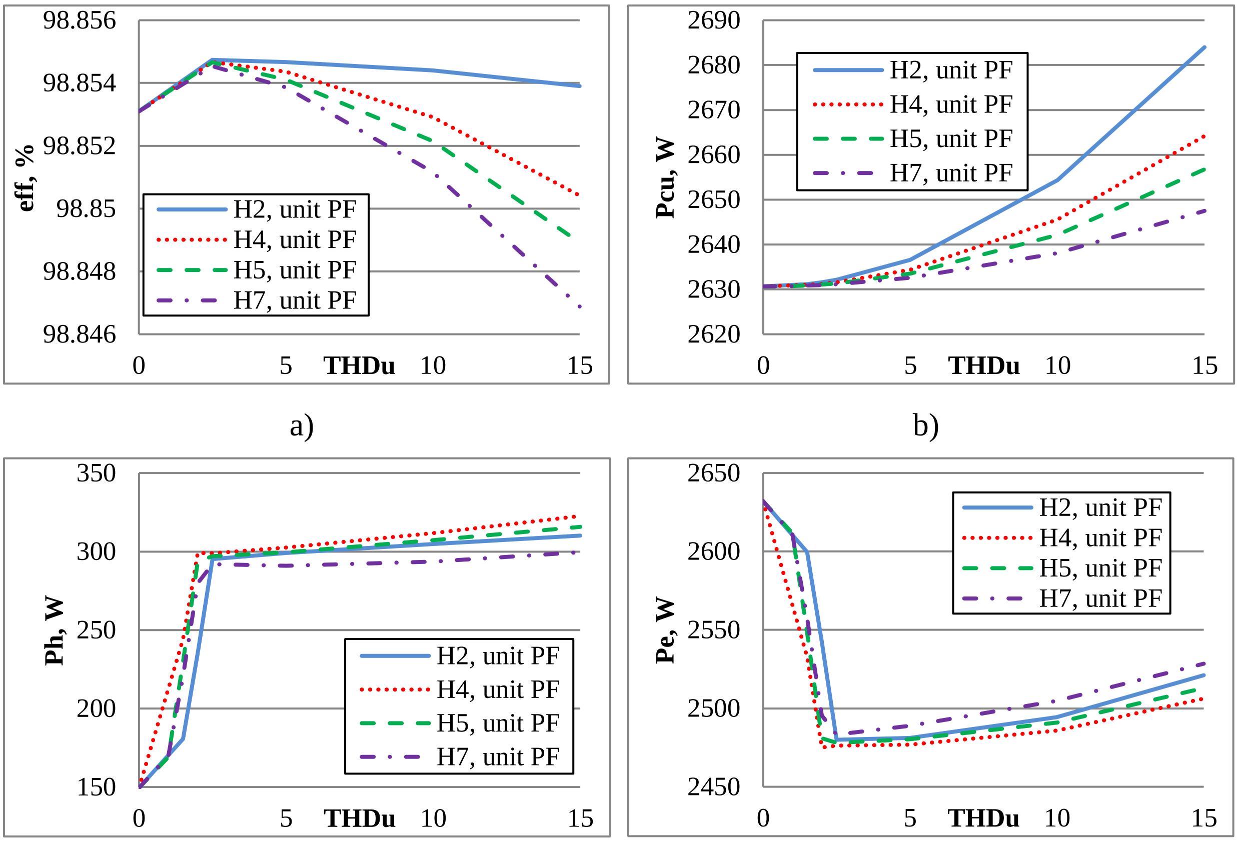

a) b)

c) d)

Fig. 9. The efficiency of 3 phase transformer under load with unit PF according to voltage THD. a) Efficiency; b) Copper loss; c) Hysteresis loss; d) Eddy current loss.

We note that the efficiency peaks at about 2-2.5% voltage THD, plummets as the voltage THD increases, which is explained while increasing THDu from 0-2.5% eddy current loss sharply decreases, hysteresis loss and copper loss increase but not significantly. Hence, the efficiency increases to the maximum point. Then, due to the rise in copper loss and magnetic circuit saturating, the overall efficiency of the transformer gradually decreases with the increase of THD voltage.

The results show that the 5th and 7th harmonics cause the most significant performance degradation, while the 2nd harmonics have a more negligible effect on the overall performance. In addition, increasing voltage THD causes the transformer efficiency to decrease proportionally.

4. Conclusions

This paper has presented a loss calculation model and the influence of non-sinusoidal voltage on 6/1.2 kV transformer loss in underground mines in case of no-load and short-circuit and their performance under load. Simulation tests have shown that the 3rd and 6th harmonics have no influence, and other higher harmonics greatly influence the transformer loss and efficiency. In addition, the increase of THD voltage causes a core loss, and load loss also increases. Testing with the effect of voltage deviation on core losses has also been considered. The results indicated that with an 8.3% increase to rated voltage, core loss increases to about 16.6% for the non-harmonic case and 19.4% for the case of 5th harmonic sources with a THDu voltage of 15%. With the core loss occurring continuously in the transformer, through the influence of harmonics on the core loss, it is possible to determine the total loss in the transformer with a non-sinusoidal operating power supply.

The transformer efficiency is most excellent when the unit power factor and the leading power factor efficiency are more significant than the lagging power with the same factor. Transformer efficiency with harmonics is lower than the efficiency without harmonics. The 5th and 7th harmonics cause the most significant loss of efficiency, while the 2nd harmonics have less impact on overall performance.

From the above analyses, the presence of voltage harmonics in the power supply to the three-phase transformer in underground mines in working modes significantly affects its loss and performance, thereby recommending users to have appropriate operating solutions to improve the service life and not cause damage to the mining transformer.

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