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A new Method for Detecting Over Flux in Power Transformers

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Abstract—This paper presents a new method for monitoring and identifying over-flux in power transformers based on harmonic analysis. Today, over-flux protection of power transformers is done by monitoring the voltage-to-frequency ratio. When the ratio value exceeds the unit value, it should be detected. This method may cause incorrect operation of the power transformer's over-flux protection due to voltage and frequency variations in the network. This paper proposes a new method for detecting and identifying power transformer over-flux based on the total harmonic distribution. In addition, the equation and curve of flux and total harmonic distortion (THD) changes in the power transformer were obtained using *DIGSILENT* software, which can be used to design the over-flux protection. Based on the simulation results, a simple equation was presented to estimate the transformer flux value based on the THD value.

Keywords: Overflux; Harmonic; Flux; Power Transformer, Detecting; Total Harmonic Distortion.

I. INTRODUCTION

Power transformer is one of the main, important and expensive equipment in power transmission and distribution networks. Therefore, protecting this vital equipment is of concern to all electrical industry professionals. The design of the transformer is done in such a way that under normal operating conditions, it is placed in a function close to the maximum magnetic flux without the core going into saturation. The magnetic flux inside the transformer is shown as follows:

$$\Phi = K \frac{E}{F} \quad (1)$$

Where:

Φ is flux, F is frequency, E is voltage and K is constant.

When the voltage increases, the magnetic flux also increases.

This leads to an increase in iron loss and magnetizing current. The core and its connections are heated, and the insulation sheets are affected. Over-flux protection is necessary where it occurs due to long-term overvoltage. Reducing the frequency also increases the flux density and will lead to the same results caused by overvoltage. Usually, up to 10% over-flux does not cause any damage and is allowed. If E/F exceeds 1.1, over-flux protection operates. Therefore, the E/F ratio is controlled to control the flux. When the E/F value exceeds the unit value, it should be detected. Electronic circuits with stable performance relays are available for measuring the E/F ratio [1].

Overexcitation of a typical transformer can occur whenever the ratio of the per-unit voltage to per-unit frequency (V/Hz) at the secondary terminals of a transformer exceeds its rating of 1.05 per unit on transformer base at full load, 0.8 power factor, or 1.1 per unit at no load. The generator connected to that transformer would have a limit of 1.05 per unit on the generator base. When an overexcitation condition occurs, saturation of the laminated steel cores of the generator and transformer can occur. Stray magnetic fields increase in magnitude, particularly at the ends of the cores. Nonlaminated components at the ends of the cores, which were not designed to carry these higher flux levels, begin to heat up due to the higher losses induced in them. This can cause severe localized overheating in the transformer and

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generator and eventual breakdown in the core assembly or winding insulation. The permissible short-time overexcitation capability of a specific transformer or

Overexcitation is of major concern for directly connected generator unit transformers. One of the primary causes of excessive V/Hz on generators and unit transformers is the unit's operation under regulator control at reduced frequencies during generator startup and shutdown. Another cause of excessive V/Hz is inadvertent manual overexcitation during generator startup and shutdown. Overexcitation can also occur during complete load rejection, which leaves transmission lines connected to a generating station. Under this condition, the V/Hz may exceed 1.25 per unit with the excitation control in service; the overexcitation is generally reduced to acceptable levels in a few seconds. With the excitation control out of service, the overexcitation may be sustained, and damage can occur to the generator and/or transformers. Failures in the excitation system or loss of signal voltage [i.e., blown voltage transformer (VT) fuse] to the excitation control can also cause overexcitation [2].

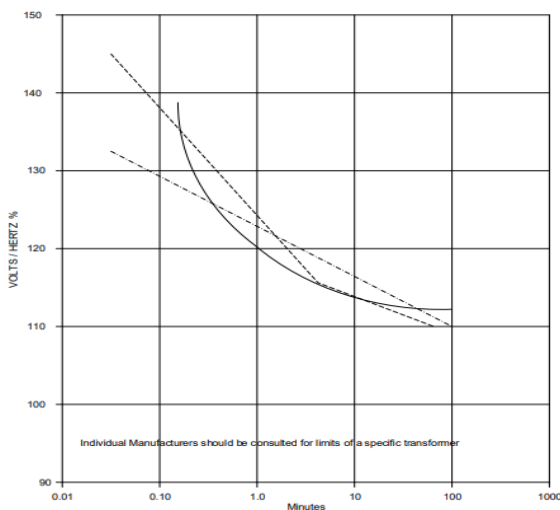


Fig. 1. Overexcitation limits of three transformers of different manufacturers

The transformer works on the principle of mutual induction between the primary and secondary windings. The induction is caused by the constantly varying magnetic flux that links the two windings. The flux density in the windings is directly proportional to the induced voltage and inversely proportional to the frequency and the number of turns in the winding. Transformers are designed to operate at or below a maximum flux density or peak magnetizing flux in the transformer core under steady-state operation at nominal voltage, and the total exciting current is only 0.1% rated current. If the flux density swells more than the maximum, the transformer experiences over fluxing. Nowadays, in transformer design practice, the peak rated value of the flux density is kept about 1.7 to 1.8 Tesla. In comparison, the saturation flux density of the Cold Rolled Grain Oriented (CRGO) steel sheet of the transformer is of the order of 1.9 to 2 Tesla, which is analogous to about 1.1 times the rated value. As per the I.S. specification over fluxing in the transformer shall not exceed 110% [3].

Transformer overexcitation causes transformer heating and increases exciting current, noise, and vibration. A severely overexcited transformer should be disconnected to

generator can normally be obtained from the manufacturer. Fig. 1 shows examples of V/Hz limiting curves provided by three different transformer manufacturers.

avoid transformer damage. Because it is difficult, with differential protection, to control the amount of overexcitation that a transformer can tolerate, transformer differential protection tripping for an overexcitation condition is not desirable. A separate transformer overexcitation element, such as a V/Hz element, that responds to the voltage/frequency ratio could be used instead [4].

During energization of a transformer, abnormal currents may flow in the winding that is being energized. These are known as the magnetizing inrush currents, caused by the saturation of the transformer core for portions of a cycle [5].

During the preliminary studies, it was recognized that a transformer in no-load operation is, in principle, a machine for measuring the magnetic properties of the core steel, similar to an Epstein frame or single-sheet tester, only much larger. In smaller test equipment, impedances in the measurement circuit can distort the flux wave shape. Special techniques must then be employed to compensate for these impedances and achieve the desired wave shape. In a large power transformer, however, the magnetizing impedance of the core is dominant. It is therefore easy to measure the magnetic properties of a large power transformer, and it can be done with high accuracy [6].

The main difficulty of differential protection of the transformer is to prevent mal-operation caused by certain operating conditions like switching magnetizing inrush, recovery, and sympathetic inrush, and over fluxing in which a transformer draws the large current from the source. Hence, accurate classification of currents in a power transformer is considered the key requirement to prevent mal-operation of the differential relay. Conventionally, a harmonic restrain scheme is used for such discrimination. However, some researchers have found the presence of the second harmonic in some winding faults [7].

The transformer is represented by a nonlinear inductance associated with the magnetizing flux, parallel with the core loss resistance, representing eddy current and hysteresis losses in the transformer's steel core. For simplification purposes, the latter element is assumed to be linear. However, it depends on voltage and frequency, and the winding resistance and leakage inductance are ignored since their magnitudes are much smaller than the shunt elements [8].

When a power transformer is powered off, due to the hysteresis characteristics of ferromagnetic materials, there is a residual flux density (B_r) in its iron core. Significant inrush current may be generated if the residual flux is large, and its magnitude may reach 6–8 times the rated current. This leads to failure in reclosing the transformer, which is not conducive to the safe operation of the power grid. The DC demagnetization operation can be performed on the iron core to overcome this issue. However, due to the unknown residual flux, multiple demagnetizations are required to eliminate the residual flux completely. If the residual flux can be accurately measured, the DC demagnetization excitation can be determined, reducing the adverse effects on the transformer caused by repeated operations in direct demagnetization. Therefore, accurate residual flux detection is significant for

reducing inrush current [9].

II. THE PROPOSED METHOD

Various causes and effects of over fluxing in transformers and different techniques for its detection have been discussed.

Some of the common causes and effects are as follows:

Causes of Over fluxing in a Transformer

- Over voltage occurs because of sudden load rejection.
- Power generation at low frequency.
- Lightly loaded transmission line.
- Transmission system over voltage due to improper shunt compensation.

Effects of Over fluxing in a Transformer

- Notable increase in core losses.
- Hot spots creation.
- Leakage flux and magnetizing current rise.
- Operation of inverse-time-over-current relay detains.
- In the case of impedance relays, there are overreach and underreach problems.
- Harmonics introduction in the system.

Whenever there is an over-voltage and when the frequency remains constant, the transformer core is subjected to a higher flux value to support the higher applied voltage. The flux and the voltage applied in a transformer are related through the following expression.

$$V = 4.44 \Phi m f N \quad (2)$$

Thus, flux can be written as

$$\Phi m = V / 4.44 f N \quad (3)$$

V is the voltage's rms value, f is the frequency, and N is the number of turns in the winding. By design, a power transformer operates at the knee of the saturation curve at normal voltage. Hence, any increase in applied voltage and the consequent increase in flux density drive the transformer deeper into saturation. The transformer, therefore, draws an excessive magnetization current. Hence, this condition is described as over-excitation. It can be easily seen that over-excitation can also occur in the case of low-frequency operation of the transformer at rated voltage. Therefore, to keep the working flux within the permissible design limits, the V/f ratio must not exceed the permissible limit [3].

If the residual flux is close to zero, the flux fluctuates between the positive and negative saturation points, and the transformer works in the characteristic linear region. It draws a very small magnetizing current from the network. Assuming the linearity of the magnetic characteristic of the sinusoidal current, but in fact, this current is highly distorted due to the presence of odd harmonics. As a result, the non-linearity of the flux-current characteristic near the zero point is due to this.

Now, assume the condition that the transformer is energized with some residual flux. The shift of the flux waveform is such that the maximum flux is located in the second slope of the magnetization curve. The current transformer draws strong magnetization when the flux exceeds the saturation point.

In this case, the minimum flux is assumed to be smaller than the saturation flux. The transformer draws very little current when the flux is less than saturation.

The change between large and small currents in each cycle creates a special form of inrush current, which consists of large currents with the same polarity separated by small current intervals. In this condition, the magnetizing current is

strong, which is usually higher than the rated current of the transformer and the threshold of triggering the differential protection of the transformer. However, since there is enough second harmonic, it is possible to block the operation of the differential relay.

A condition in which the residual flux is so large that the minimum flux is below the saturation level for a very short time. In this case, the time intervals are smaller than in the previous case, and the current waveform is closer to a sinusoid, which means fewer harmonics. If the residual flux is higher than the saturation point, even if the minimum flux is higher than the saturation level. Strong currents are drawn in this transformer state, but the waveform is not distorted. In this case, the transformer works in the saturation region, but the magnetizing inductance, although small, has a constant value. Therefore, it causes a current similar to a sinusoidal waveform called Ultra saturation.

The harmonic distortion is extremely low because the current waveform during the ultra-saturation phenomenon is almost without distortion. As a result, the transformer differential relay fails to operate during the inrush current.

Also, studies show that transformers with new cores are more likely to be exposed to the phenomenon of oversaturation. As a result, the possibility of incorrect operation of the differential relay for them is higher than that of the old transformers due to the small amount of the second harmonic.

New transformers are more exposed to the phenomenon of ultra-saturation for the following two reasons:

A) lower saturation flux, B) Narrower hysteresis loop

A simple inrush current analysis for a silicon core and an improved core illustrates the point. The new core has a lower saturation level and a steeper slope in the low flux part (before saturation), indicating a smaller transformer excitation current.

The main hysteresis loops of an old core and an improved core for lower losses also show this. Because the area of the hysteresis loop is related to the core loss, the new optimized core should be narrower with the same saturation level. A narrower hysteresis loop intersects the horizontal axis at a higher length and, as a result, creates a higher residual flux.

Ram Ultra saturation phenomenon can be shown by assuming a magnetization curve in the form of two linear regions, similar to Fig.s 2 to 5, and applying a sinusoidal flux to it [10].

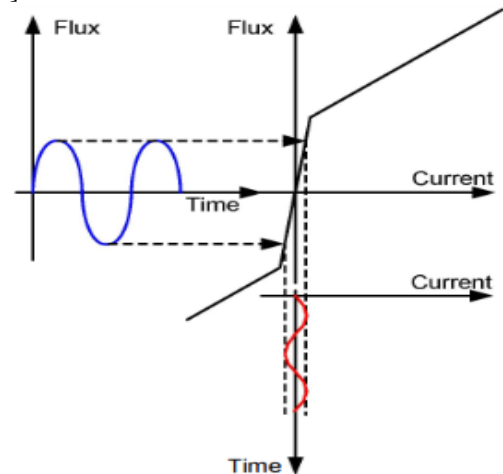


Fig. 2. Current and flux when flux oscillates between the negative and positive saturation levels. [11]

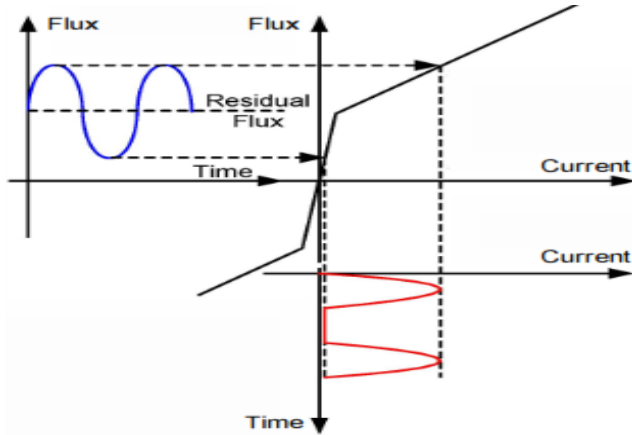


Fig. 3. Current and flux when the maximum flux is above the saturation level and the minimum flux is below the saturation level. [11]

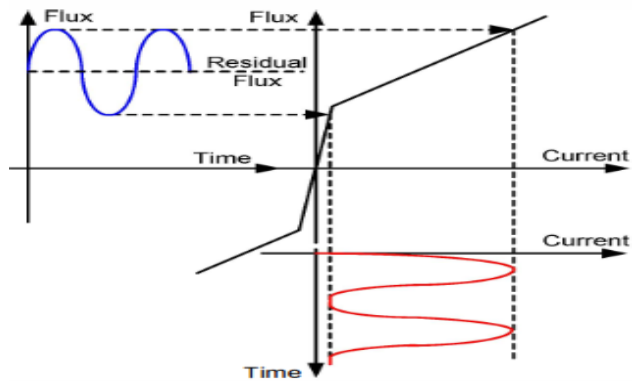


Fig. 4. Current and flux when the minimum flux is close to the saturation level. [10]

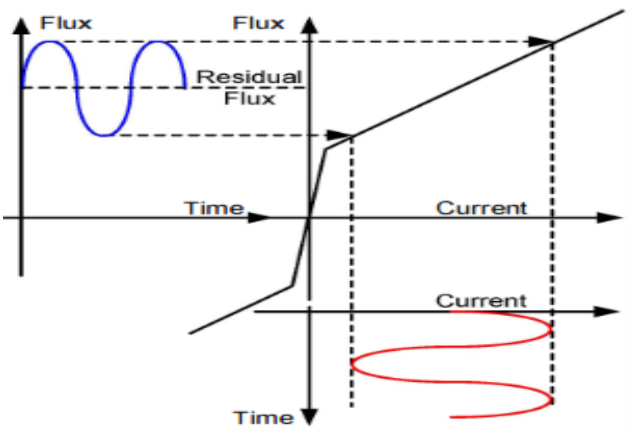


Fig. 5. Current and flux when both the maximum and minimum flux values are above the saturation level. [11]

Harmonic restraint is used to avoid undesired tripping by the percentage differential relay due to the flow of magnetizing inrush currents when a transformer is energized. In addition, the use of harmonic restraint allows for more sensitive settings. Different methods are used in the relays for harmonic restraint.

Typical methods are described in this subclause. The general principle of operation, when harmonic restraint is used, can be expressed as shown in Equation (4):

$$|I_{op}| > s |I_{Res}| + k_{2nd} |I_{2nd}| + k_{3rd} |I_{3rd}| + \dots \quad (4)$$

Where:

I_{op} is the fundamental frequency component of the operating current

s is the slope of the percentage differential characteristics (non-variable slope types)

I_{Res} is the restraining current

k_{2nd} , k_{3rd} are constants of proportionality associated with each harmonic component

I_{2nd} , I_{3rd} are the second- and higher harmonic components of the operating current

The harmonic restraint is high when this approach is used; therefore, it provides security for inrush conditions at the expense of operating speed for high-current internal faults and faults with CT saturation.

The second-harmonic component of the operating current is used to identify inrush currents, and the fifth-harmonic component of the operating current is used to avoid incorrect operations during transformer overexcitation. The basic equation for the operation of one phase of this type of relay can be expressed as shown in Equation (5):

$$|I_{op}| > s |I_{Res}| + k_{2nd} |I_{2nd}| + k_{5th} |I_{5th}| \quad (5)$$

Where:

k_{2nd} , k_{5th} are constants of proportionality associated with each harmonic component

I_{2nd} is the second harmonic component of the operating current

I_{5th} is the fifth harmonic component of the operating current

In some relays, the harmonic restraint is proportional to the sum of the second- and fifth-harmonic components of the three-phase elements of the relay; its operation, therefore, can be expressed as shown in Equation (6):

$$|I_{op}| > s |I_{Res}| + \sum_{n=1}^3 (k_{2nd} |I_{n2nd}| + k_{5th} |I_{n5th}|) \quad (6)$$

Where:

n is the phase element

k_{2nd} , k_{5th} are constants of proportionality associated with each harmonic component

I_{n2nd} is the second harmonic component of the operating current in phase n

I_{n5th} is the fifth harmonic component of the operating current in phase n

Fig. 5 shows the logic of a second- and fifth-harmonic restraint differential relay element defined by Equation (6) and a high set element for the fifth-harmonic component.

Note that in this harmonic restraint element, the operating current is expected to overcome the combined effects of the restraining current and the second and fifth harmonics of the operating current. As previously stated, the fifth-harmonic current is experienced when the transformer is overexcited due to excessive voltage applied to it. Overexcitation with excessive magnetizing current can damage the transformer; therefore, some relays include a high-current setting for I_{5th} . The fifth-harmonic restraint is removed if the I_{5th} exceeds the setting. Common harmonic restraint increases the security of the differential relay, but it is likely to delay the relay operation for internal faults combined with inrush currents in the non-faulted phases.

There is a fundamental difference between the second-harmonic component of the operating current, used to identify inrush currents, and the fifth-harmonic component, used to avoid incorrect operations during transformer overexcitation. The difference is that overexcitation V/Hz, if caused by high voltage even at nominal frequency, can create an incipient fault, especially with older insulation. When the insulation is stressed, the risk of an internal fault increases. As a result, if an incipient fault occurs in the transformer, there may be enough fifth harmonic to still restrain the differential element.

The fifth-harmonic restraint may well prevent the differential element from tripping until a more severe fault develops.

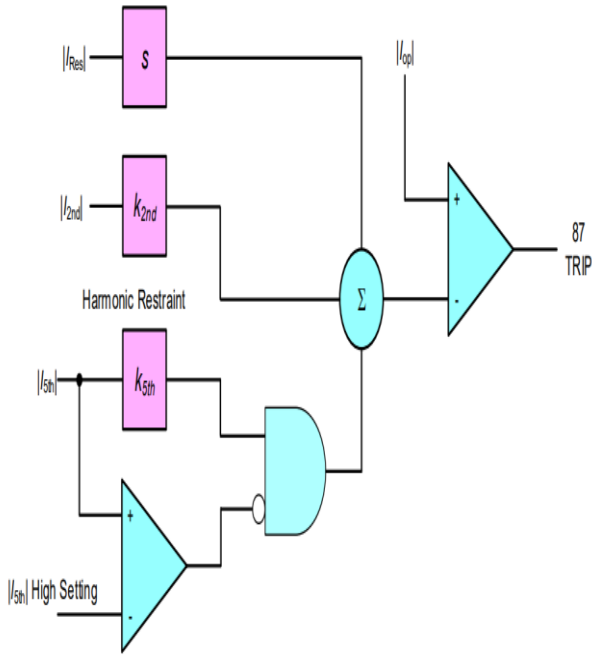


Fig. 5. Second- and fifth-harmonic restraint logic of a differential element [2].

It is not the excessive fifth-harmonic current that damages a transformer but the excessive magnetizing current that heats up the core. Transformers are rated with V/Hz withstand curves and limits, not fifth harmonic withstand limits; therefore, overexcitation protection is voltage and frequency based (V/Hz). The fifth harmonic is only a symptom of overexcitation. If a high-current setting for I5th is used to remove the 5th harmonic restraint, there is no way of knowing if or when an insulation failure would occur. So, this setting could false trip the differential when no fault exists or delay a differential trip until a more severe fault develops. For a given overexcitation event, if there is no incipient fault, and therefore no reason for the differential element to operate, a given I5th high-current setting could trip too early, since overexcitation is a heating phenomenon, and the V/Hz function has a relatively long inverse time delay. Conversely, a given I5th high-current setting could be above a given level of overexcitation and fail to trip. This high current setting for I5th is not appropriate to use for protecting a transformer from overexcitation, as it does not coordinate with the damage curve published by the manufacturer. When used, V/Hz protection is applied as specified by manufacturers to protect a transformer from overexcitation properly.

A strategy depicted in Fig. 6 is employed in some relays, using the fifth-harmonic level to adaptively raise the pickup level of the differential element to ride through the increased differential currents caused by the transformer overexcitation. The differential element with the remaining percentage differential characteristics still in place can now trip if, during overexcitation, an internal incipient fault occurs due to increased insulation stress [2].

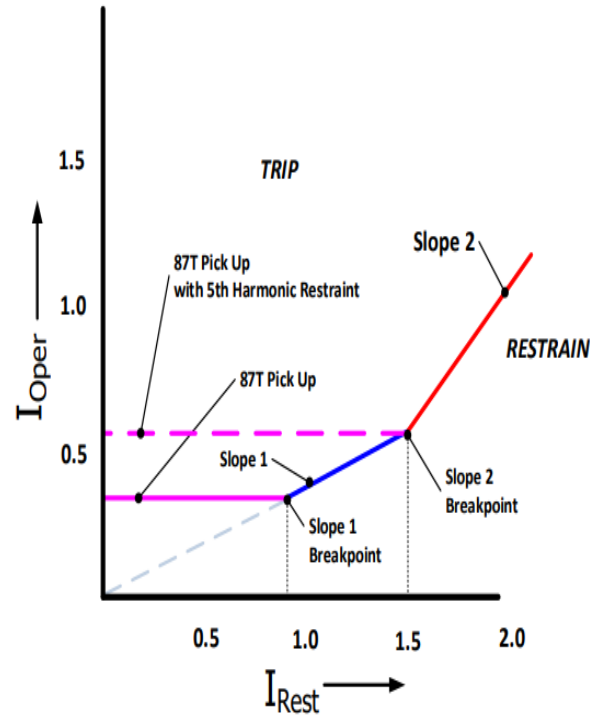


Fig. 6. Differential element with adaptive 5th harmonic pickup [2].

III. THE PHENOMENON OF HARMONIC DISTORTION

Harmonics are a mathematical way of describing distortion to a voltage or current waveform. Harmonic refers to a waveform component that occurs at an integer multiple of the fundamental frequency. Power quality refers to the perfect sinusoidal property of voltage and current waveforms in a power system. These behaviors of the waveform are measured and studied through different signal processing, and at the end compared to the standards given. Fourier theory tells us that any repetitive waveform can be defined in terms of summing sinusoidal waveforms, which are integer multiples (or harmonics) of the fundamental frequency. For a steady state waveform with equal positive and negative half-cycles, the Fourier series can be expressed as follows [12]:

$$f(t) = A_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega_0 t + \varphi_n)) \quad (7)$$

One of the important indicators in determining the amount of harmonic distortion is the total harmonic distortion. This coefficient, which represents the amount of all harmonic components in the waveform, is important. The THD coefficient is usually expressed as a percentage [5].

THD can be used to describe voltage or current distortion and is calculated as follows:

$$THD\% = \frac{\sqrt{\sum_{i=2}^{\infty} (U_i^2)}}{U_1} \quad (8)$$

Where: U_i is the magnitude of the i th harmonic [13].

This method, which is based on harmonic analysis of transformer parameters, calculates the total value of the harmonic voltage distribution on the secondary side of the power transformer based on the magnetization curve.

IV. SIMULATION AND RESULT

In the model prepared in the DIGSILENT software, a 160 MVA transformer has been used. Its magnetic curve is also shown in Figs 7 to 23. In the normal state and without

additional current and voltage flux on the secondary side, as well as its total harmonic distribution curve, have been drawn.

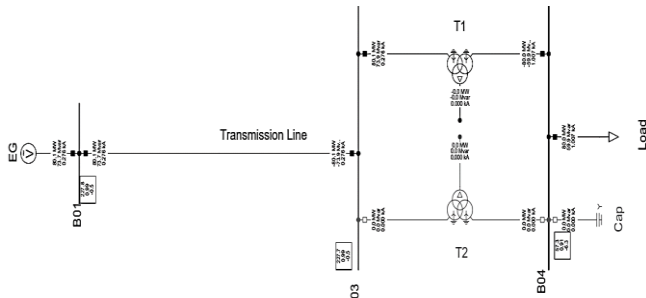


Fig. 7. Transformer under study

Fig. 7 is the model prepared using DIGSILENT software, and a 160 MVA transformer is used.

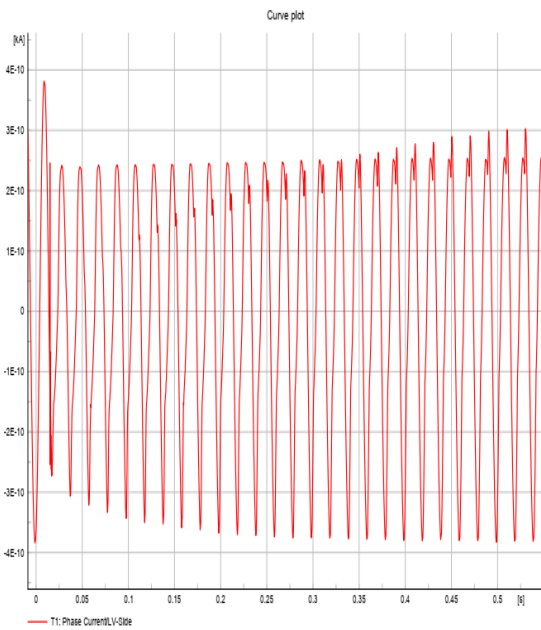


Fig. 8. LV side phase current with flux 1.2

Fig. 8 is the output curve from the software related to the phase current of the secondary side of the transformer for an increase in flux of 1.2.

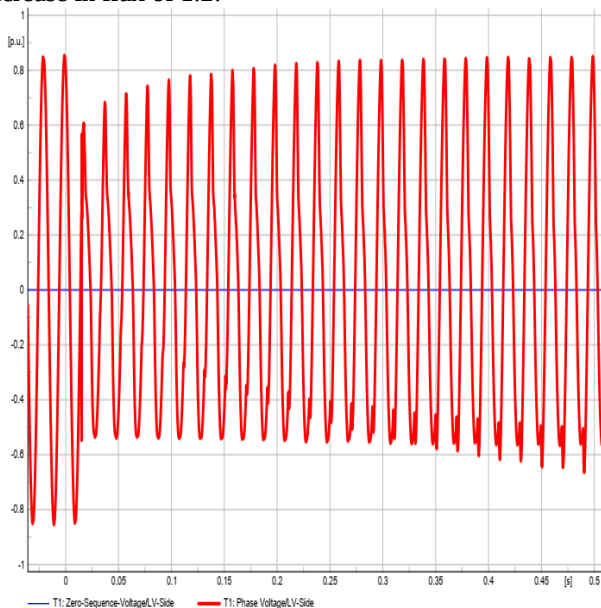


Fig. 9. LV side phase voltage with flux 1.2

Fig. 9 is the output curve from the software related to the phase voltage of the secondary side of the transformer for an increase in flux of 1.2.

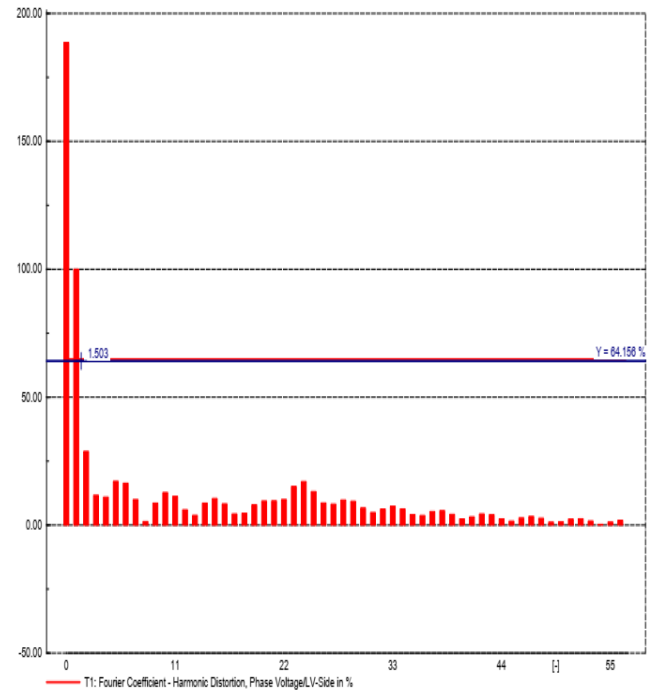


Fig. 10. LV side phase voltage harmonic with flux 1.2

Fig. 10 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.2.

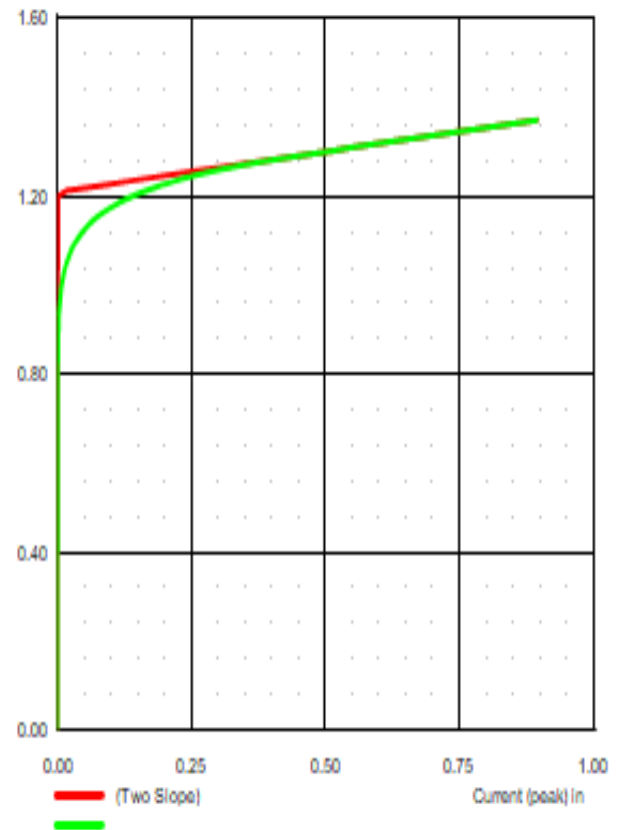


Fig. 11. Transformer flux curve

Fig. 11 is the transformer flux curve for an increase in flux of 1.2

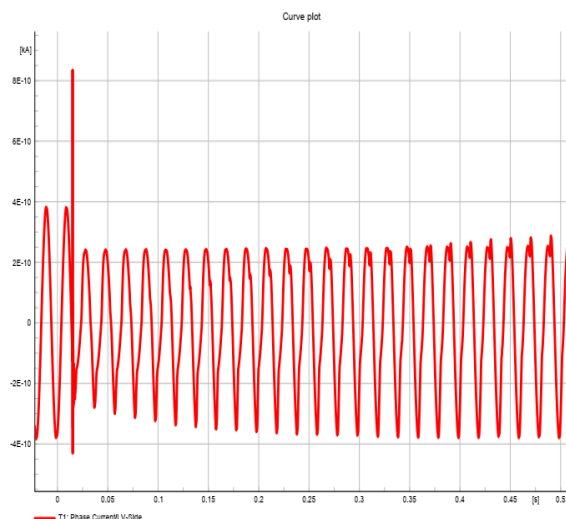


Fig. 12. LV side phase current with flux 1.3

Fig. 12 is the output curve from the software related to the phase current of the secondary side of the transformer for an increase in flux of 1.3.

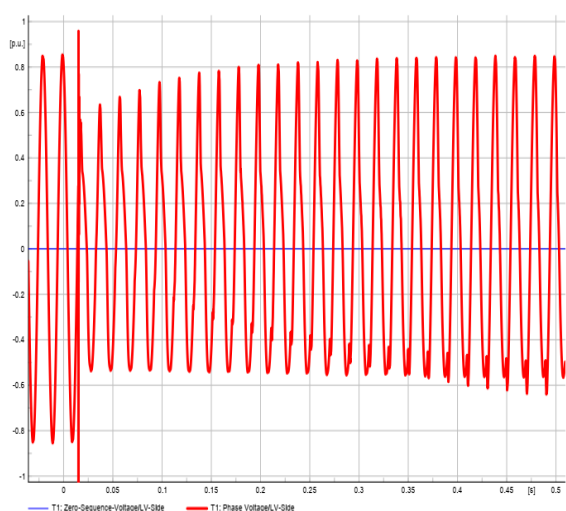


Fig. 13. LV side phase voltage with flux 1.3

Fig. 13 is the output curve from the software related to the phase voltage of the secondary side of the transformer for an increase in flux of 1.3.

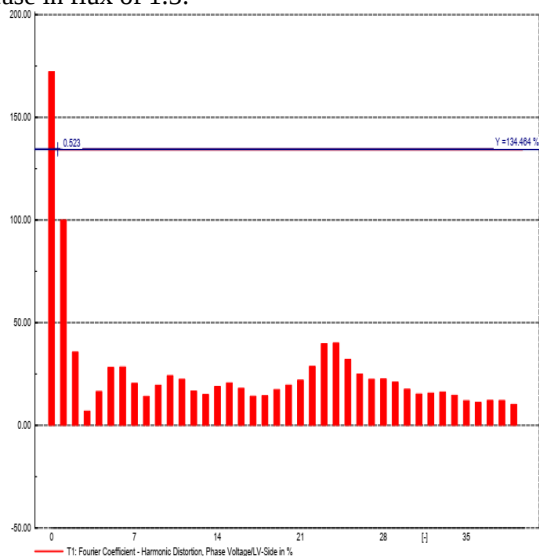


Fig. 14. LV side phase voltage harmonic distribution with flux 1.3

Fig. 14 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.3.

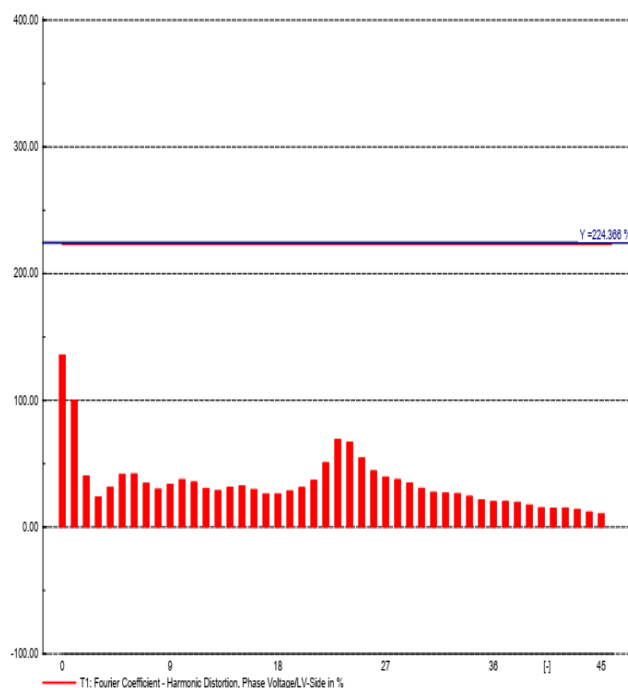


Fig. 15. LV side phase voltage harmonic distribution with flux 1.4

Fig. 15 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.4.

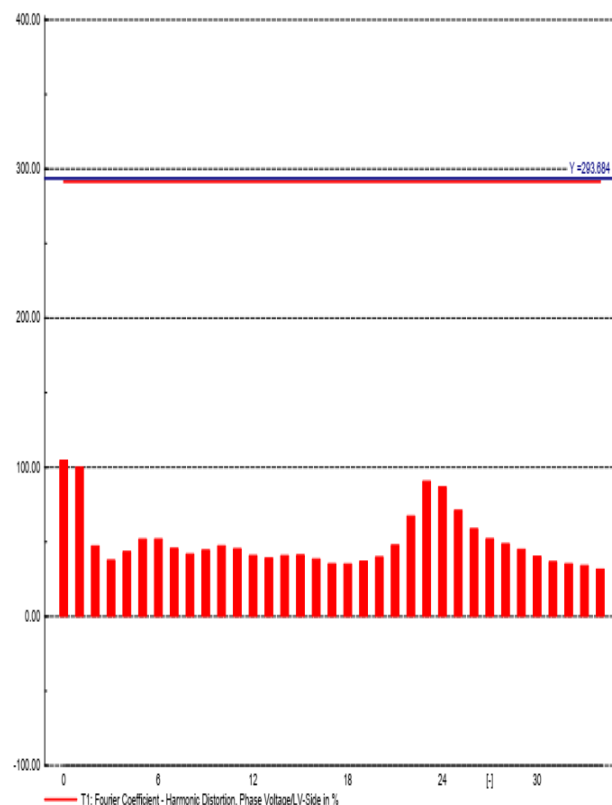


Fig. 16. LV side phase voltage harmonic distribution with flux 1.5

Fig. 16 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.5.

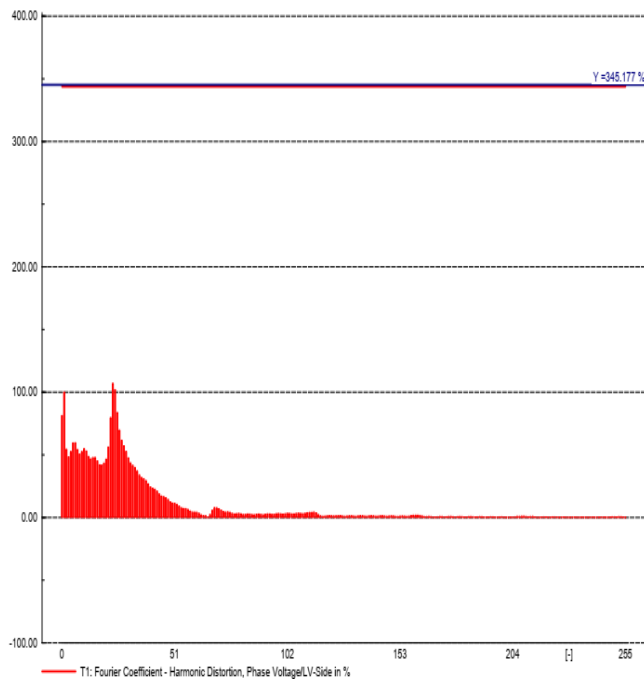


Fig. 17. LV side phase voltage harmonic distribution with flux 1.6

Fig. 17 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.6.

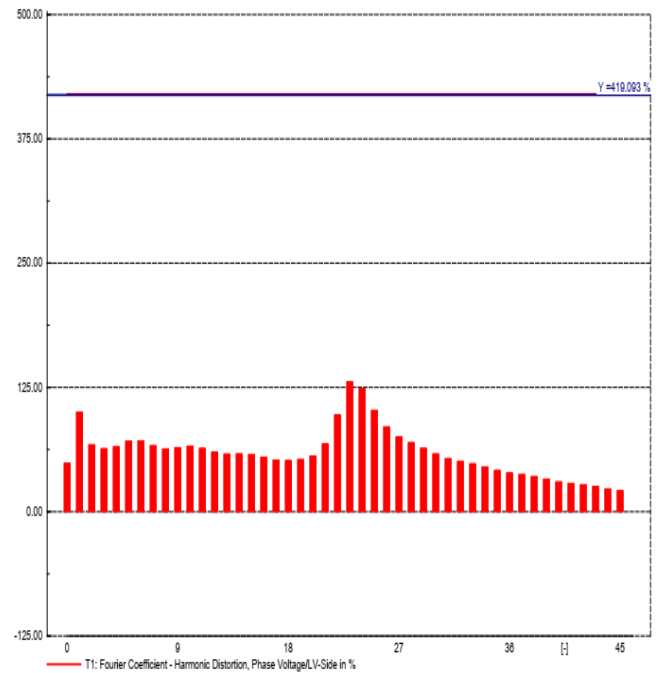


Fig. 19. LV side phase voltage harmonic distribution with flux 1.8

Fig. 19 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.8.

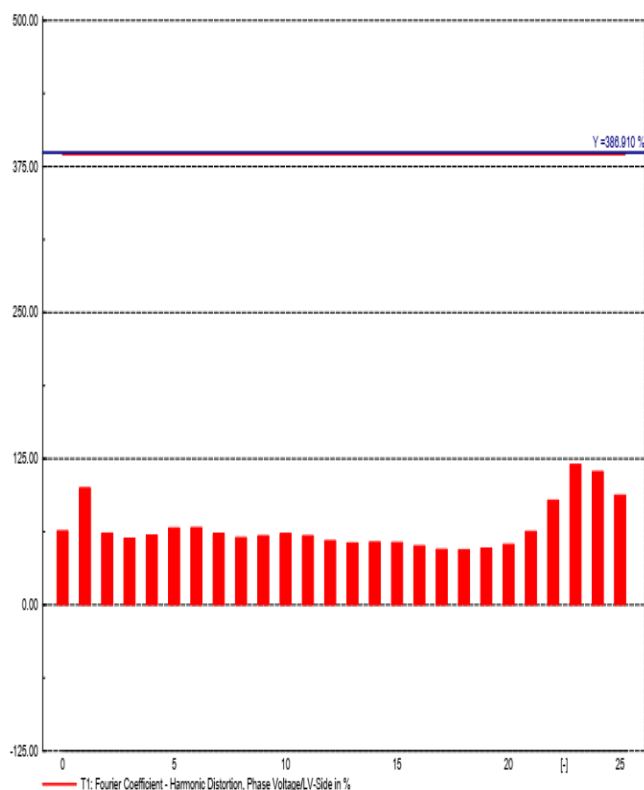


Fig. 18. LV side phase voltage harmonic distribution with flux 1.7

Fig. 18 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.7.

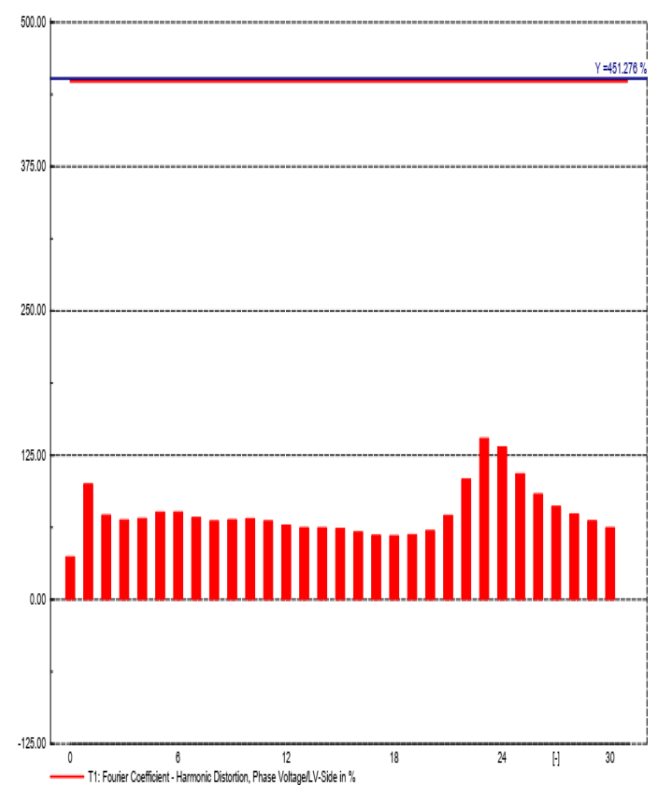


Fig. 20. LV side phase voltage harmonic distribution with flux 1.9

Fig. 20 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.9.

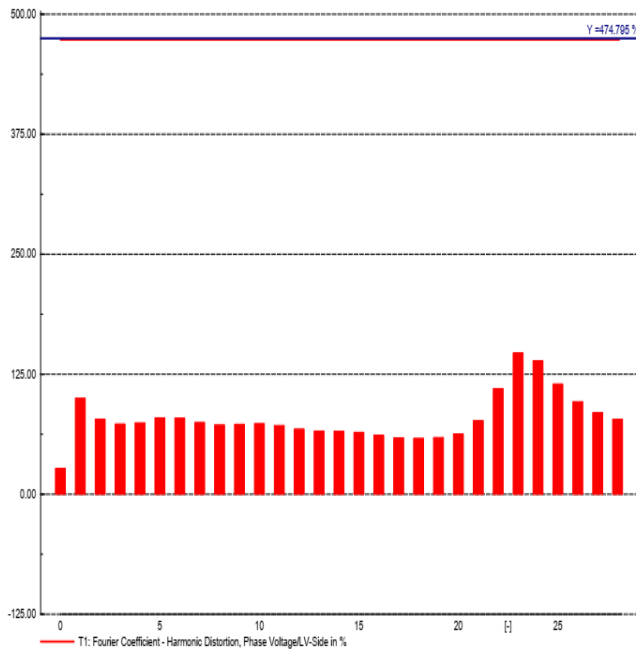


Fig. 21. LV side phase voltage harmonic distribution with flux 1.9

Fig. 21 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 1.9.

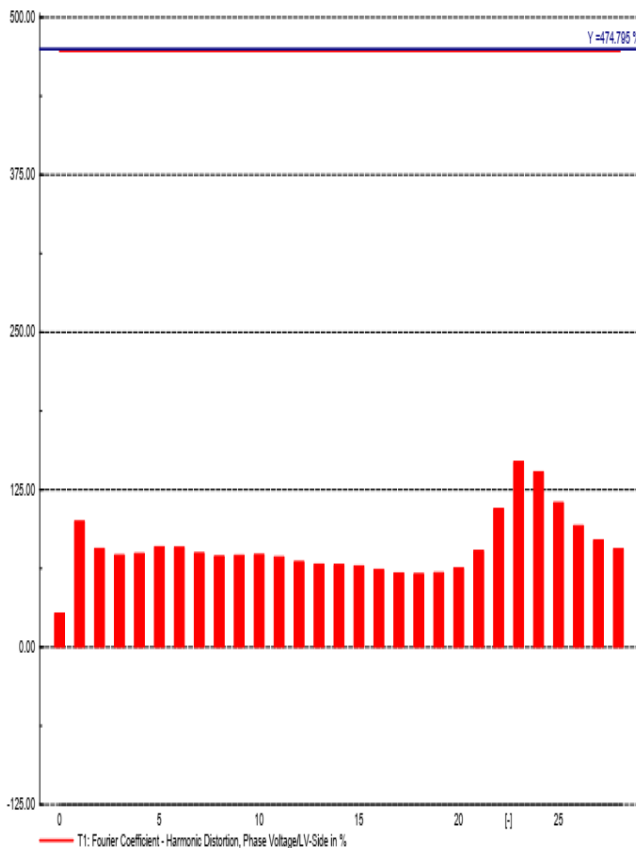


Fig. 22. LV side phase voltage harmonic distribution with flux 2

Fig. 22 is the output curve from the software related to the phase voltage harmonic of the secondary side of the transformer for an increase in flux of 2.

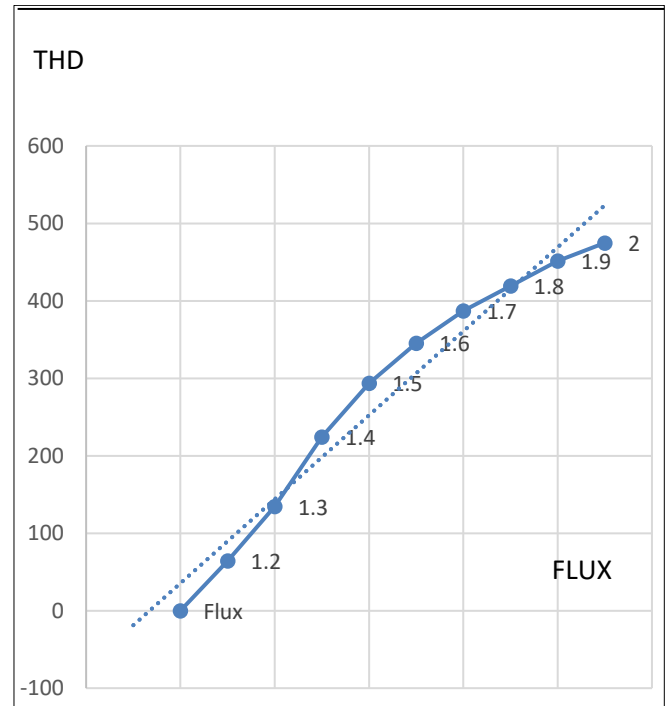


Fig. 23. Normalized curve resulting from THD value and flux.

Fig. 23 is the Normalized curve resulting from the THD value and flux of the transformer for an increase in flux to 2 .

TABLE I
Flux Values per THD

Flux	THD (%)
1.2	64.2
1.3	134.5
1.4	224.4
1.5	293.7
1.6	345.2
1.7	386.9
1.8	419.1
1.9	451.3
2	474.8

Then, the flux value is increased with a change amplitude of 0.1, the THD variation curve is extracted from the secondary output voltage of the transformer, and a table of the obtained values is available. Then the resulting graph of these values is normalized, and the resulting equation is obtained from the curve.

$$\text{THD} * (0.002) + 1 = \text{Flux knee point} \quad (9)$$

Using this equation and having the voltage THD value, the value of the transformer flux knee point can be obtained. It determined whether the magnetic flux curve of the transformer was normal or increasing. Based on that and according to the amount of flux increase, it decided to stay in the circuit or disconnect the transformer.

V. CONCLUSION

A power transformer was used in the model prepared using the DIGSILENT software. The transformer flux value is gradually increased, and the voltage and current waveforms and the total harmonic distribution on the secondary side are extracted. The resulting values are displayed as a graph whose components are the gradual increase in the transformer flux value and the total harmonic distribution due to this increase. The resulting curve is normalized, and based on it, a relationship between the transformer flux and the total harmonic distribution is obtained.

In this article, using the total harmonic distribution curve of the transformer voltage based on changes in the magnetic flux value, a simple equation was presented to estimate the transformer flux value based on the THD value. Based on this, the excess flux condition of the power transformer can be well detected, and its protection against increased magnetic flux can be taken.

Conflict of Interests

Professor Zahra Moravej, the author of this paper, is the Co-Editor-in-Chief of the Journal of Modeling and Simulation in Electrical and Electronics Engineering (MSEEE). Still, she has no involvement in the peer review process to assess this work submitted to the journal. This paper was evaluated, and the Chief Editor of the MSEEE Journal managed the corresponding peer review.

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BIOGRAPHIES

Cyrus Ghodraati was born on July 8, 1976, in Zanjan. After earning a diploma in mathematics and physics in Sari, he was accepted into Shahid Sattari University of Aeronautical Sciences and Technology in Tehran, where he pursued studies in electrical and electronic engineering. Later, he received a scholarship from the Ministry of Energy to study electrical and power engineering, earning an associate degree. He then completed his bachelor's degree in electricity and power at Azad University of North Khorasan Branch, followed by a master's degree in the same field from the Science and Research Department. Currently, he is a doctoral student in electricity and power engineering at Semnan University, continuing his academic and research pursuits in the field.