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The Effects of Design Parameters on The UNICORE Type Transformer Inrush Current

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Abstract

In this study, it is aimed to fill the information gap about the effects of designed parameters in UNICORE type transformers inrush current. Considered prameters are the flux density, the core construction and the lamination thickness of the transformers. In this context, the UNICORE transformer was compared with the conventional wound core (CWC) transformer by using three-dimensional finite-element configuration. In order to get real system response, the study was carried out experimentally. Analyzing the test results, the effects of the core material and design parameters on the magnitude, duration and harmonic content of inrush current on these types of transformers were detected. Tests were performed by using a programmable power source and analyzed data sets were recorded by scopemeter.

1. Introduction

A transformer is a static machine used for transforming electrical power from one alternating voltage level to another with the same frequency by electromagnetic induction [1].

Transformer energization is a workaday operation which is being performed frequently in an electric power system. A transformer no-load current is generally at a level of 1-2% of the rated current, but it may be as high as 10-20 times of the rated current, which decreases to a magnetizing current over time when the transformer is energized [2-3]. This current is called magnetizing inrush current. The decaying time of the inrush current depends on the resistance and reactance of the transformer equivalent circuit. If the inductance is high, it takes longer time for the circuit to switch to a steady state condition. The critical inductance value here is directly related to the transformer's magnetizing reactance.

So, design parameters of the transformer core have become more of an issue to reduce excitation current and so reducing the inrush current. For the last few years, core design has been getting more importance. The development of the transformer design philosophy has been extended by use of computers and numerical tools. By means of these tools, it is enabled to model the geometrical complexities as well as the nonlinear material characteristics accurately for problem analysis. And using this program, different transformer designs have been generated and tested to get more efficient models. One of these new transformer core designs is called UNICORE.

UNICORE is a new type of magnetic core technology which was developed in 1997 in an attempt to make the conventional machine structure simpler and to improve the performance of electric machine magnetics behaviour [4,5].

Important advantages of this manufacturing technology are the decreased magnetic flux saturation by means of healed magnetic flux density distribution reduced

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eddy-current losses and excitation current by means of uniformed magnetic flux density, increased efficiency and improved performance [6].

In this study, with the present detrimental effects of major inrush currents of transformers in mind, it is intended to understand the effect of core material and design parameters on the inrush current and to present the improved effects of the UNICORE technology.

2. Magnetizing Inrush Current at Transformers and Analized Parameters

Magnetizing current occurs in both no-load and loaded working conditions at transformers. No-load current is the sum of magnetizing current and core-loss, and it is about 1-2% of the rated current of the transformer in a steady-state condition, so it is neglected generally. But this is not always the case. When the transformer is energized, the amount of the current increases dramatically [2,3,7].

When a transformer is de-energized, the excitation current becomes zero by following the hysteresis curve. However, the flux drops to a steady-state Ør (remanent flux) value - not to zero - during the same process. When the applied voltage is zero, and the transformer is re-energized, flux starts to rise from the remanent flux level and reaches its peak value after an energization for a time period of 180° in sine. Because of the increment of the flux in the core, magnetizing current may reach 10-20 times the rated current [9]. This event is called magnetizing inrush [10]. The voltage considering the change in flux can be defined as below.

$$u = N\frac{d\Phi}{dt} \tag{1}$$

where N and Φ are the turns number of the primary winding and magnetic flux in the core, respectively. Applied voltage is:

$$u = U_m sin(\omega t + \varphi) \tag{2}$$

where U_m and φ are the maximum value of the applied voltage wave and the phase angle of the voltage wave, respectively. Substituting Eq. (2) in Eq. (1) and by using integration;

$$\frac{d\Phi}{dt} = \frac{U_m}{N} sin(\omega t + \varphi) \tag{3}$$

$$\Phi = -\frac{U_m}{N\omega} cos(\omega t + \varphi) + k \tag{4}$$

is obtained. Thus, as it is seen in Eq. (5) the maximum flux is equal to coefficient of the cosine function.

$$\Phi_m = \frac{U_m}{N\omega} \tag{5}$$

The k is calculated by considering the initial condition which is t=0 and $\Phi(0) = \Phi_r$,

$$k = \Phi(t) + \Phi_m cos(\omega t + \varphi) \tag{6}$$

where Φ_r is the remanent flux in the core. The final equation of the flux in the core is given by;

$$\Phi(t) = \Phi_r + \Phi_m[cos\varphi - cos(\omega t + \varphi)] \tag{7}$$

The flux in the core is related to the energization angle and the remanent flux as can be seen from Eq. (7). The transient component of the flux wave decreases in conjunction with the primary winding resistance (R1) and the inductance (L1) values of the transformer - with a ratio of R1/L1 [6].

From the above-defined Eq. (7), it can be seen that if the transformer is switched on at the zero angle of the voltage wave, flux starts to rise from a remanent flux level and reaches its peak value after an energization for a time period of 180° in sine. The peak value of flux is two times of nominal maximum (Øm) plus remanent flux (Ør) in the core.

$$\Phi = \Phi_r + 2\Phi_m \tag{8}$$

As in no-load energizing, similar transients can occur when the loaded transformer is energized. However, when the load resistance is included in the transformer equivalent circuit, the damping speeds up and the level of harmonic distortion in total current decreases.

Inrush current magnitude is related to some magnetic parameters like the core material magnetic characteristics, magnetic remanence and mechanical parameters like the moment when the transformer is energized, etc [11,12].

Remanent flux can be positive or negative. This can cause an increment or decrement in magnetizing inrush current. If the remanent flux has same the direction with the created flux at the first instant after switching the transformer, in the positive half cycle the inrush current occurs otherwise causes to reduce the inrush current and in the negative half cycle, the inrush current will be maximized [13,14].

In this study, remanent flux is reduced to zero. For this purpose, transformers were energized randomly and then de-energized at the instant of positive maximum voltage level by using a programmable power source. And then inrush currents of the tested transformers were analyzed in terms of point-on-voltage wave and transformer core material and design.

And also, since the magnetizing inrush current is nonlinear, it contains harmonic components. By using Fourier series analysis, the harmonic levels of the magnetizing inrush current are estimated. During the transformer inrush conditions, even harmonics are dominant and especially the second harmonic component is effective. Thus, the second harmonic component is selected as the basis for inrush current.

2.1. The Effect of Point-on-Voltage Wave

The most significant factor is the point-on-voltage wave at the moment of energization. Transformer energization angle affects the peak value of inrush current. From the above-defined Eq. (7), it can be seen that if the transformer is switched on at the zero angle of the voltage wave, flux starts to rise from the remanent flux level and reaches its peak value after 180° of energization. The peak value of flux is two times of nominal maximum Φ_m plus remanent flux Φ_r in the core.

Under normal operating condition, the core flux is Φ_m and the core of the transformer is operating at the knee of the B-H curve. In order to produce the flux in Eq. (8), the current required will be extremely high because of the nonlinear nature of the B-H curve and drives the core material into saturation. This results in heavy inrush current into the transformer.

2.2. The Effect of The Core Material and Design

The power transformer design affects the transformer core saturation during inrush events. The design of the core, the flux density of the steel and the connection method of the laminations all impact the magnitude and characteristics of the magnetizing inrush current [16].

Due to ongoing research and development efforts [17] by steel and transformer manufacturers, core materials with improved characteristics are getting developed and applied with better core building technologies. Remarkable stages of core material development are cold rolled grain oriented (CRGO), hot rolled grain oriented (HRGO), high permeability cold rolled grain oriented (Hi-B), non-oriented, mechanically scribed and laser scribed. Thus, using lower thickness laminations eddy losses are reduced. The decrease in the lamination thickness leads to a quadratic decrease of the classical eddy current loss [18-20]. The popular thickness range is 0.23 mm to 0.35 mm for power transformers. Core materials are generally sorted as M2 (H1), M3 (H0), M4, M5, M6 and MOH.

A more significant change has been in the construction of the core. Stacking laminations on top of each other, an air gap between each lamination is created. As a result of this, the reluctance of the core increases. Laminations are now constructed such that they overlap each other to provide a continuous path for the flux when the laminations are stacked one above the other. The reluctance in the core is reduced in this construction, and, therefore, the flux density increases, and the exciting current reduces. But there is still an air gap.

The most common used transformer joint types are non-mitred and mitred joints. Manufacturing of nonmitred joints, in which the overlap angle is 90°, is quite simple, but the corner joint losses are more since the flux in the joint region is not along the direction of grain orientation. In the case of mitred joints, the angle of overlap (α) is of the order of 30° to 60°, the most commonly used angle is 45°. In mitred joints, the flux crosses from limb to yoke along the grain orientation minimizing losses.

In recent years, studies about core designing for decreasing the core loss have been continued. In this study, test transformers with core designs, which are called UNICORE, are examined in terms of inrush current. The test transformers were analyzed at the energization conditions. Magnitude, decaying time and the harmonic component of inrush current of the test transformers were examined in terms of core material and design.

3. Unicore Transformers and Performed Analysis

3.1. Unicore Transformers and Comperation with The Conventional Wound Core (CWC) Transformer

In a bolted yoke construction, which ensures rigidity of the core, holes are punched in the yoke laminations. Small guiding holes are needed to facilitate the placement of laminations and core buildings.

There is a significant contribution of limbs and yokes joints to the core loss due to cross-fluxing and crowding of flux lines in them. Hence, if the corner area and weight are higher, the core loss will be higher. So UNICORE type transformers have less core loss from classically designed transformers.

UNICORE constitutes a new line of cores of magnetic circuits. It was the aim to simplify the existing technology and improve the parameters of electrical machines of the manufacturing technology development in 1997. The technology of OWC (octagonal wound core), called Unicore technology [21], is very flexible, highly accurate, repeatable, and reliable. Unlike the production of CWC [20,21]. Cores can be supplied with an annealed or unannealed finish. Depending on the core size, subsequent annealing of cores decreases losses by 10 to 30%. The core angle of a UNICORE can be either 30°, 45° or 90° depending on their use.

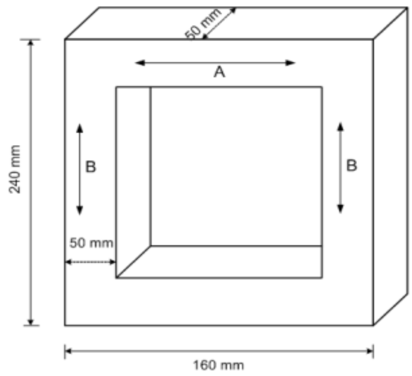

Figure 1. Dimensions of the tested transformers.

To compare the UNICORE transformer and CWC transformer, sample transformers were designed. The dimensions of the designed transformer are seen in Figure 1. It is targeted to determine the magnetic flux distributions and excitations currents of these two types of transformers. So three-dimensional finite-element method (FEM) was used.

The magnetic flux density of shell-type tested transformer is seen in Fig.2-a. It is seen that the distribution of magnetic flux density in the corners is so weak.

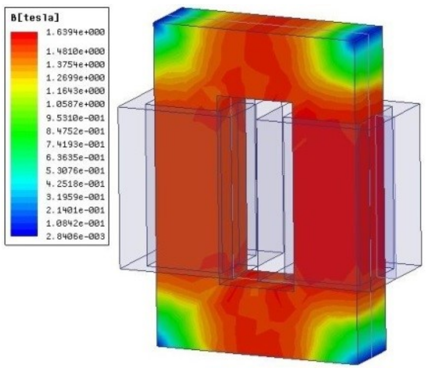

Figure 2. (a) Shell-type single phase transformer core analysis

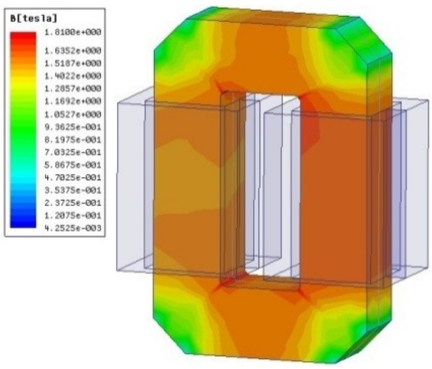

Figure 2. (b) UNICORE single phase transformer core analysis.

The same transformer parameters are used for analyzing the UNICORE transformer. It is seen in Fig.2-b that there is no unused region in the core. So, the eddy-current losses of this type of transformer are less than the conventional transformers. And also, excitation currents of these two types of transformers are shown in Fig.3. It is shown that the no-load current of the UNICORE type transformer is less than classical core type transformer one.

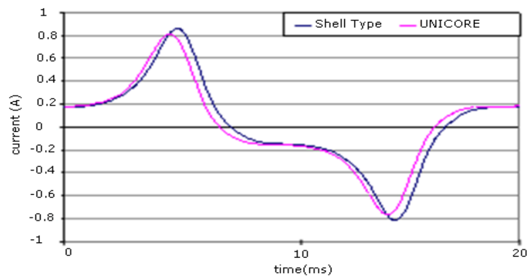

Figure 3. No-load currents of CWC and UNICORE transformers [22].

So, in this study for the detailed analysis of the UNICORE transformers, nine different UNICORE transformers whose constructions and design parameters are different from each other were used. The parameters of the designed transformers are given in Table-1.

3.2. Laboratory Test Set Up for The Measurement and Performed Analysis

The experiments were set up according to Fig.4. Nominal voltage magnitude was applied to the test transformers by using California Instruments 4500LX programmable power source. Data sets were recorded by Scopemeter 199-C. Obtained data sets were analyzed by using MATLAB software. Recorded data sets are sampled at 1kHz (which means 20 samples on 50 Hz power frequency) and harmonic components are obtained by using Fourier Analysis in MATLAB.

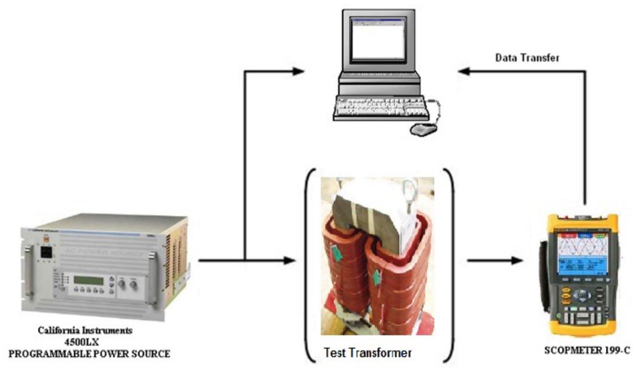

Figure 4. Experimental set up

To compare the transformer's true behaviors, test transformers were energized at the zero-flux level. For this purpose, transformers were energized randomly and after the transformer has reached steady state-conditions deenergized at the instant of positive maximum voltage level by using a programmable power source.

After that, each tested transformer is energized at different points of the sine wave. The applied energization angles (t_i) are 0º, 10º, 20º, 30º, 40º and 50º. (Fig.5)

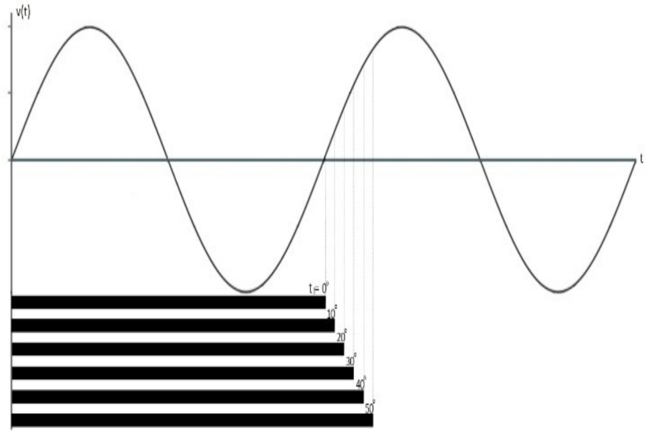

Figure 5. The transformer energization points of sine wave

Before each energization, residual fluxes of all tested transformers were made zero.

Comparing inrush currents of transformers, it is seen that the relationships of these currents are similar for each energization angle. So that in this study the current waveforms are given for just energization at 0º of sine wave.

3.3. The Tested Unicore Transformers and The Analyzed Parameters

In this study, 1kVA, 220/110V single phase UNICORE transformers with core materials M5 and MOH, were analyzed. All used transformer design parameters and core materials are given in Table-1 and construction of the core is given in Figure 1.

The flux density of the steel, the material of the core, and the method of connecting the laminations all affect the amount and characteristics of the magnetizing inrush current. In this section, maximum value, harmonic components, decaying time of inrush current and the ratio of second harmonic current to the fundamental current were analyzed using test transformers. The transformers are grouped such that only one of their design parameters is different.

Table 1. Design parameters and core materials of the test transformers.

Core construction	Core material	Designed flux density	Primary and secondary winding turn numbers
	TR1-M5	1	396/198
	TR2-M5	1,5	264/132
	TR3-M5	1,7	232/116
	TR4-M5	1,5	264/132
	TR5-M5	1,5	264/132
C-CORE 	TR6-M5	1,5	264/132
	TR7-MOH H2-0.23	1,5	264/132
	TR8 MOH-0.27	1,5	264/132
	TR9-MOH-0.35	1,5	264/132

3.3.1. The Effect of Core Design on Unicore Transformer

In this section, four transformers (tr2-tr4-tr5-tr6) are compared. Primary and secondary winding section areas and turn numbers, lamination thickness and used materials, yoke and leg dimensions and designed flux densities of these transformers are the same. The only difference is the core construction. Each tested transformer is energized at different points of sine a wave. The applied energization angles are 0º, 10º, 20º, 30º, 40º and 50º. Before the energization residual fluxes of all tested transformers were made zero by deenergizing the randomly energized tested transformers at the instant of positive maximum voltage level. Comparing inrush currents of transformers, it is seen that the relationships of these currents are similar for each energization angle. So that in this study the current waveforms are given for just energization at 0º of sine wave. Inrush currents of these transformers are as in Figure 6.

It is seen that tr-6 has maximum inrush current magnitude in the first cycle. When core constructions are examined, it is realized that the air gap in this transformer is larger than the others. Core reluctance increases by the air gap so that magnetic efficiency of the core decreases. So, the flux density decreases and exciting current increases. An increase in the required exciting current leads to an increase in the magnetizing inrush current. Steady-state exciting currents can be seen in Figure 6 (in detail).

Harmonic content is as important as the magnitude of inrush current when inrush detection is in question. To maintain the security of the system, transformer differential relays are restrained by the second harmonic component during transformer inrush case. So harmonic components and ratio of the second harmonic component to fundamental harmonic component of inrush currents are analyzed too. In Figure 7 the ratio of second harmonic current to the fundamental current of four transformers are given.

Maximum inrush current is observed in tr-6, but decaying time of the ratio of second harmonic component to the fundamental component is the shortest one. Because the exciting current of this transformer is maximum (zoomed part in Figure 6), the fundamental component of this current is also maximum (Figure 8). So that decaying time is shorter than the others.

3.3.2. The Effect of Core Lamination Thickness on Unicore Transformer

In this section, three transformers (tr7-tr8-tr9) are compared. Primary and secondary winding section areas and turn numbers, used materials, yoke and leg dimensions, designed flux densities and core constructions of these transformers are the same. Only the core lamination thickness is different.

Transformer core is made of thin isolated steel called laminations and carries flux linked to windings. If the laminations have lower thickness, the eddy losses will be lower too for the same level of flux density (Eq. (9)).

$$P_e = k_1 f^2 t^2 B_{rms}^2 \tag{9}$$

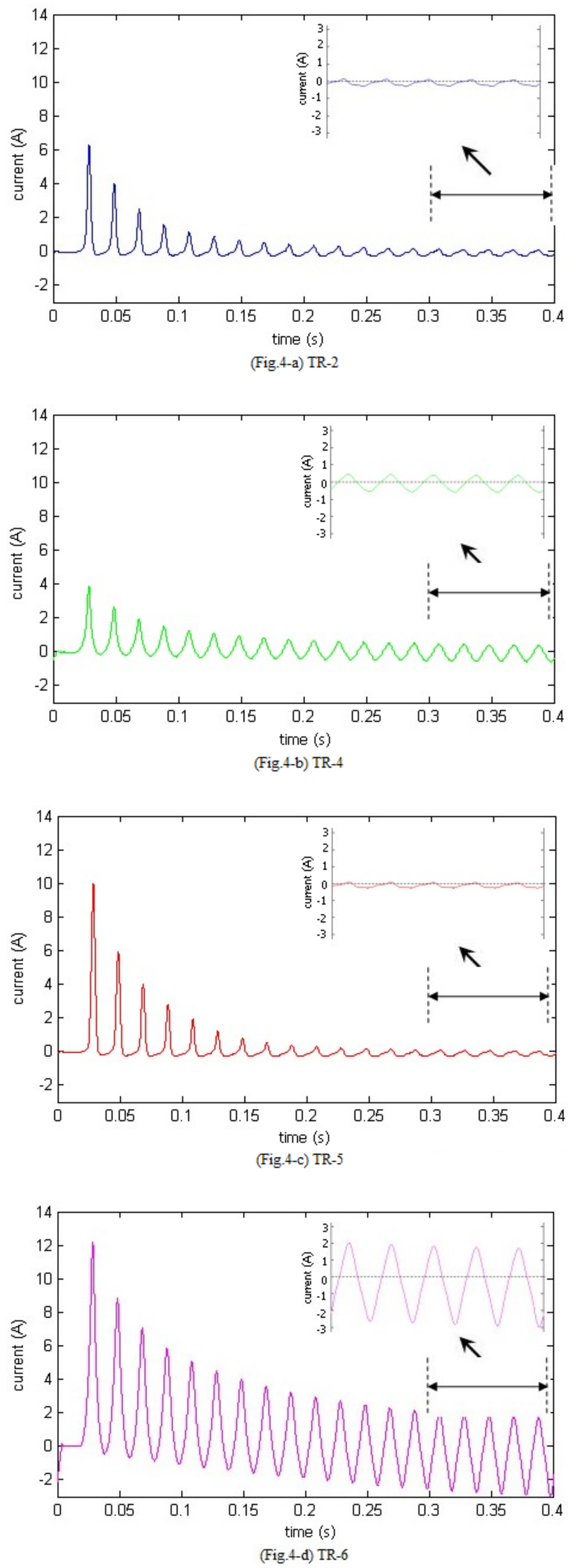

Figure 6. Inrush currents of the transformers-2-4-5-6.

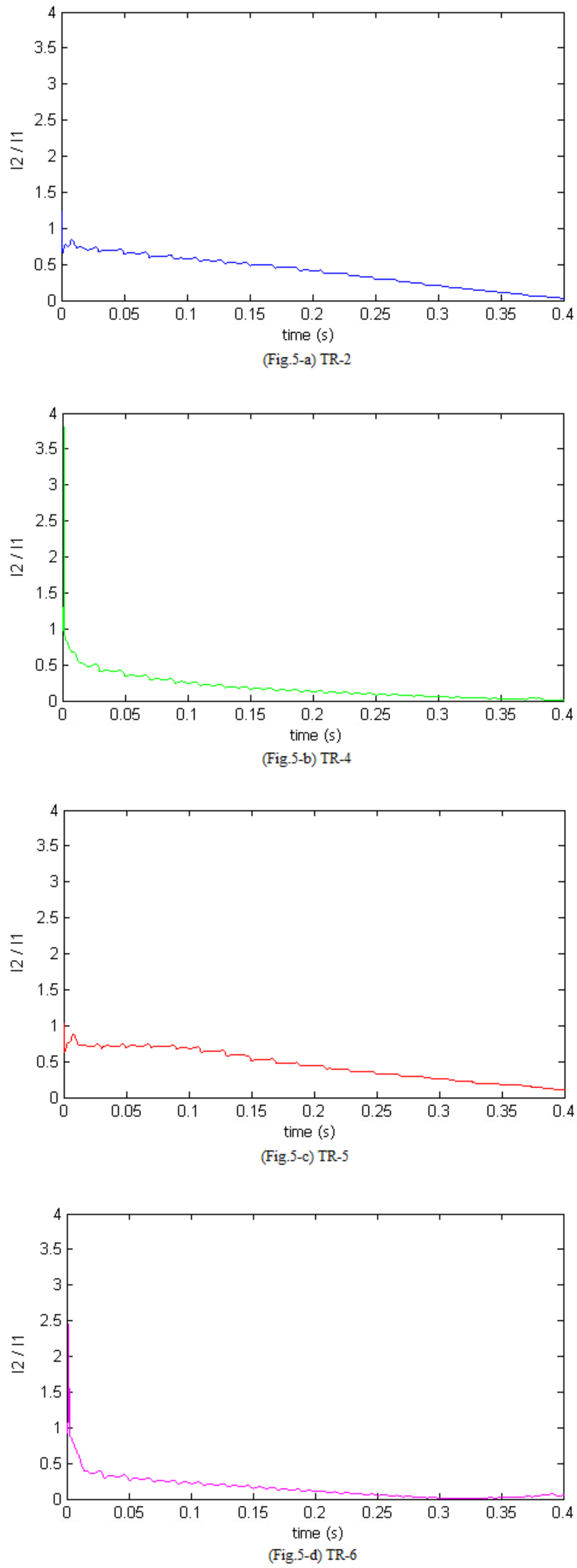

Figure 7. The ratio of the second harmonic current to the fundamental current of the transformers-2-4-5-6.

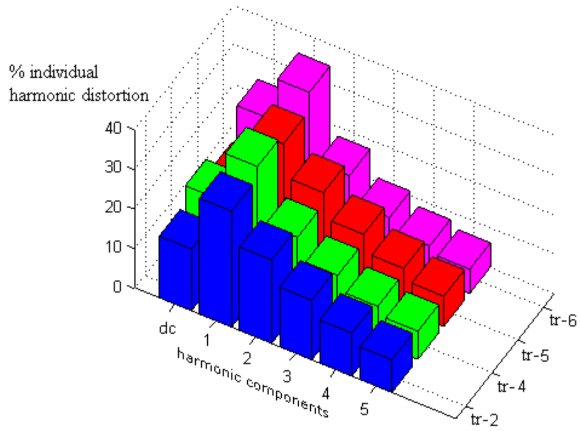

Figure 8. Harmonic components of inrush currents of the transformers-2-4-5-6.

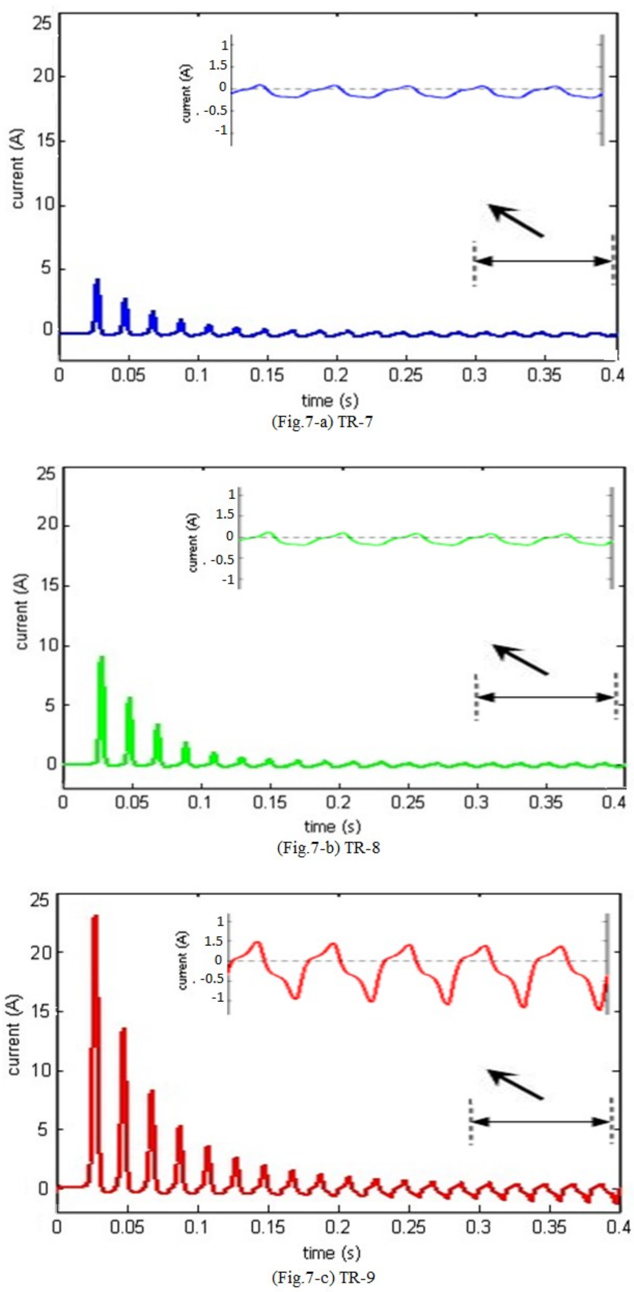

Figure 9. Inrush currents of the transformers-7-8-9.

where P_e, t, k_1, f and B_{rms} are the eddy loss, thickness of individual lamination, constant which depends on material, frequency and the rated effective flux density related with the actual rms voltage on the sine wave basis, respectively.

In this test group, the lamination thickness of the TR-9 is the greatest one, so eddy losses of this transformer are greater than the others. If eddy losses of a transformer, which is a part of iron losses that is called no-load losses of a transformer, are high, then the no-load current will also be high. At the zoomed part in Figure 9, it is seen that the steady state no load current (exciting current) of the TR-9 is higher than the others. An increase in the required exciting current leads to an increase in the magnetizing inrush current (Figure 9).

Because the exciting current of the TR-9 is the maximum (zoomed part in Figure 9), the fundamental component of this current is also maximum (Figure 11). So that, decaying time is less than the other transformers (Figure 10). On the other hand, the exciting current and therefore inrush current of the tr-11 is higher than the others, that's why the harmonic components of the tr-9 are higher. It is seen in Figure 11.

3.3.3. The Effect of Designed B (Flux Density) on Unicore Transformer

In this section, three transformers (tr1-tr2-tr3) are compared. Primary and secondary winding section areas, used materials, yoke and leg dimensions, core constructions and core lamination thickness of these transformers are the same. The only difference is the designed flux densities obtained by different turn numbers.

If the transformer design induction level increases, the hysteresis loss will increase. Because the hysteresis loss is a part of the no-load loss; the no-load loss will increase at the same time. High no-load loss causes high steady state no-load current. At the zoomed part in Figure 12, it is seen that exciting current of the TR-3 is higher than the others. Increase in the required exciting current leads to an increase in the magnetizing inrush current (Figure 12). Peak inrush current increases as the design induction level increases. The reason of this is the core saturation for a greater part of the voltage cycle [23].

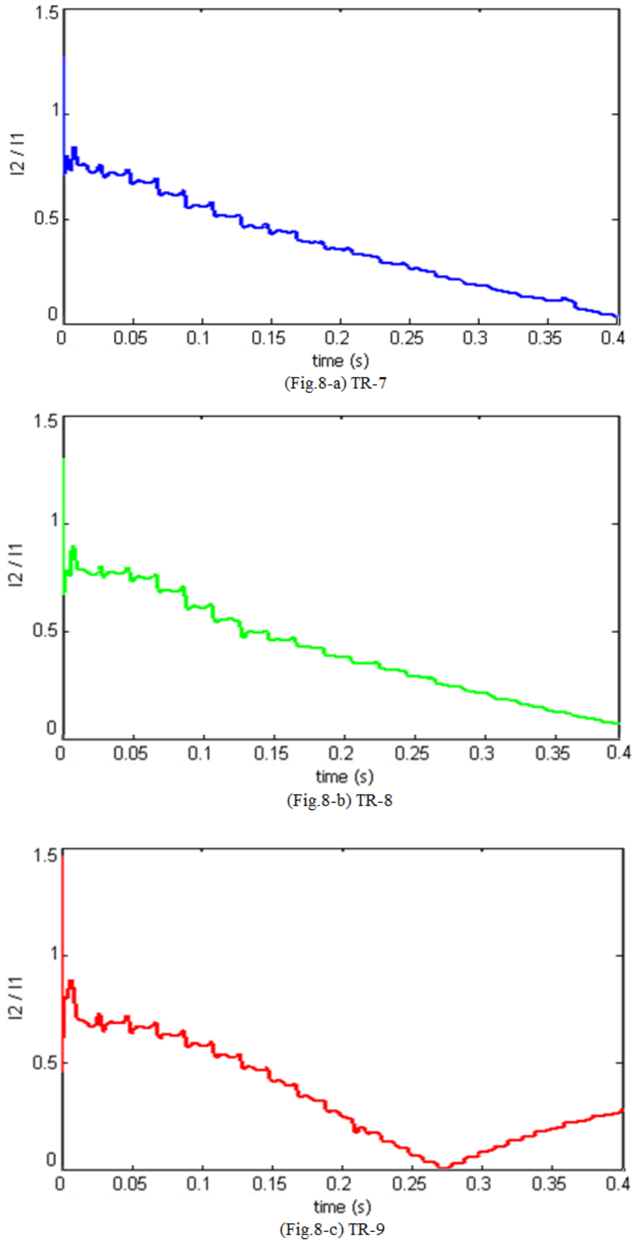

Figure 10. The ratio of the second harmonic current to the fundamental current of the transformers-7-8-9.

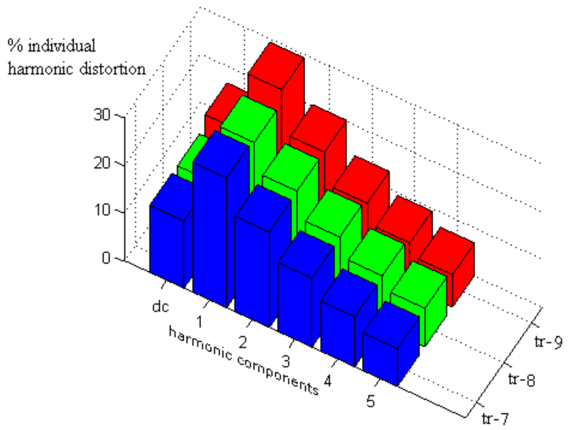

Figure 11. Harmonic components of inrush currents of the transformers-7-8-9.

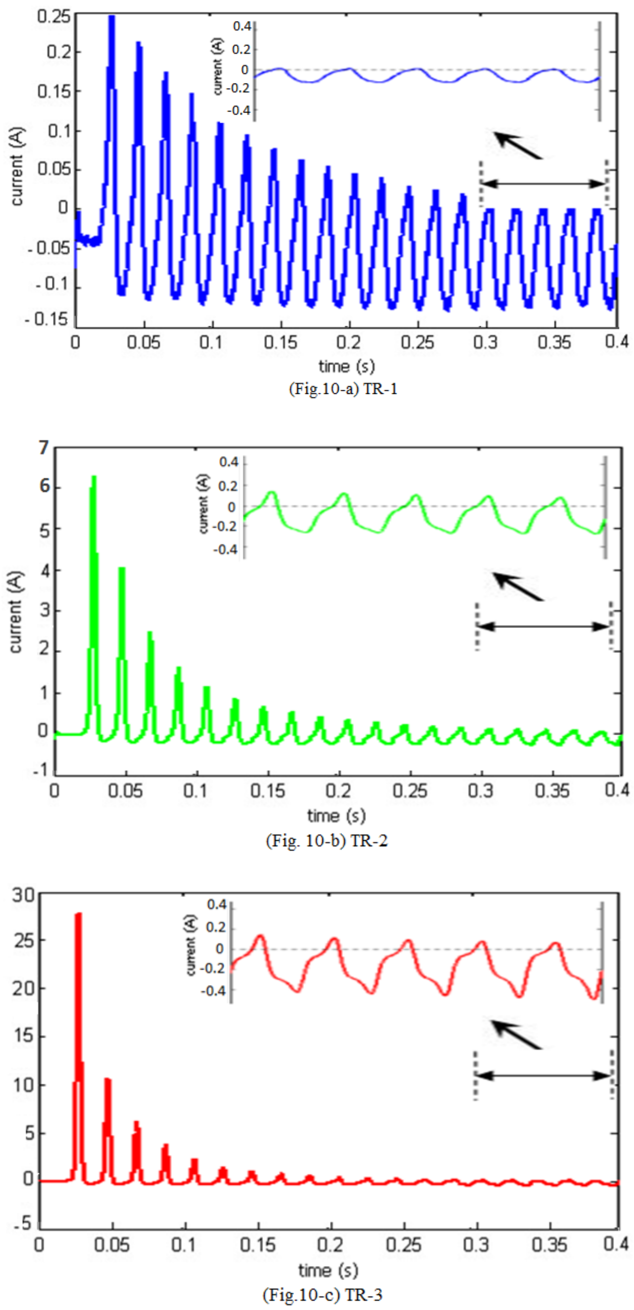

Figure 12. Inrush currents of the transformers-1-2-3.

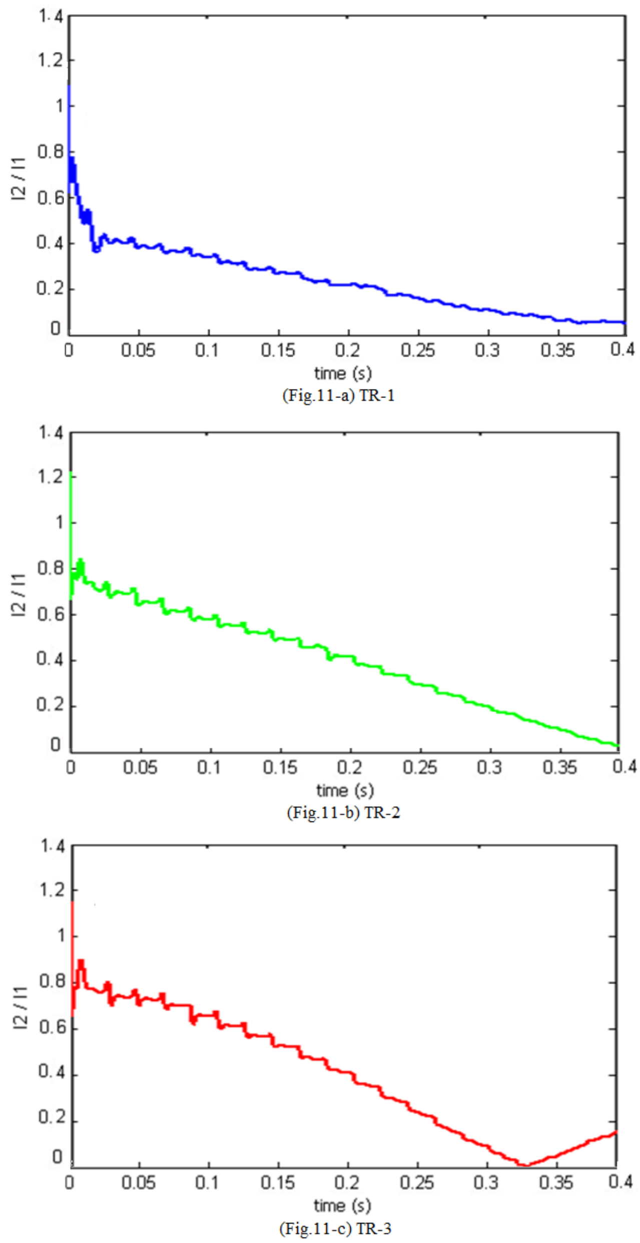

Figure 13. The ratio of the second harmonic current to the fundamental current of the transformers-1-2-3.

The distortion of the exciting current may be reduced if the transformer core is designed for and operated at very low flux densities. The TR-1 is designed at low flux density, and it is seen that the exciting current is nearly linear. So, the inrush current of this transformer contains a low level of harmonic currents. If the designed flux level of a transformer is increased, the exciting current waveform will be away from linearity (zoomed part in Figure 12) and so harmonic components of this current will increase. It is seen in Figure 14.

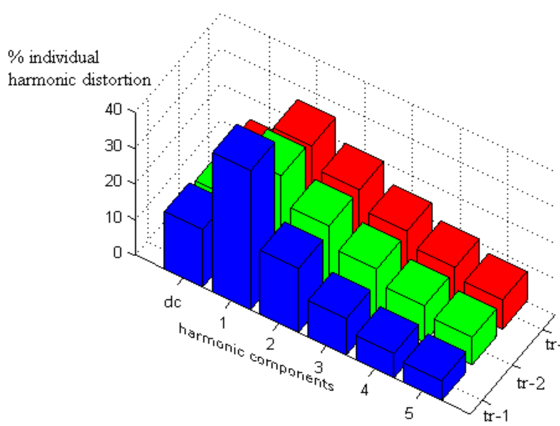

Figure 14. Harmonic components of inrush currents of the transformers-1-2-3.

4. Conclusions

Comparing the CWC transformers with the UNICORE transformers, it is seen that the excitation current and eddy-current losses are less in the UNICORE transformers. So, in this study, the transformers which are constructed by using this new line cores were analyzed in terms of magnetizing inrush current magnitude, duration and harmonic content. To reduce the exciting current and the magnetizing inrush current, it is important to construct the transformer with lower losses. For this purpose, more efficient steel must be used in the core and designed flux density must be limited. In this study, inrush currents of the nine different UNICORE transformers were compared by considering the parameters below:

If the length of the air gap in the joint regions increases, the reluctance of the core increases. So, the flux density decreases and exciting current increases. Increase in the required exciting current leads to an increase in the magnetizing inrush current. If the exciting current increases, the fundamental component of inrush current increases. So, the decaying time of the ratio of the second harmonic component to the fundamental component is reduced.

If the lamination thickness of the transformer is increased, eddy losses of the transformer increase. If the eddy-current losses are high, the excitation current will also be high. An increase in the required exciting current leads to an increase in the magnetizing inrush current. If the exciting current increases, the fundamental component of inrush current also increases. So, the decaying time of the ratio of the second harmonic component to the fundamental component is reduced.

If the design induction level of a transformer is higher, the hysteresis loss will be greater. Because of the fact that hysteresis loss is a part of the no-load loss; the no-load loss will rise at the same time. High no-load loss causes high steady state exciting current. Increase in the required exciting current leads to an increase in the magnetizing inrush current. So, the decaying time of the ratio of the second harmonic component to the fundamental component is reduced.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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