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Energy Efficiency Study for the Distribution System Using Low Voltage Transformer Under Harmonic Conditions

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Abstract: In Brazil, technical energy losses in power distribution systems are determined by power flow studies considering medium and low voltage systems, according to ANEEL recommendations, presented in PRODIST Module 7. These technical losses occur due to physical phenomena and are intrinsically associated with the energy distribution process. However, standards currently do not consider energy losses from harmonic components generated by nonlinear loads, which represent almost all the loads present in electrical systems worldwide. Thus, this paper aims to analyze the operation of a low voltage transformer under harmonic current conditions and to evaluate not only the operation temperature of the equipment, but also to verify the energy losses in it. This test is performed on a laboratory platform and the results are experimental using an adjustable three-phase source and a 3kVA three-phase transformer.

Resumo: No Brasil, as perdas técnicas de energia nos sistemas de distribuição de energia elétrica são determinadas por fluxo de potência para os sistemas de média e baixa tensão, de acordo com as recomendações da ANEEL, apresentadas no Módulo 7 do PRODIST. Estas perdas ocorrem devido a fenômenos físicos intrínsecos ao processo de transporte de energia. Todavia, as normas correntes não consideram as perdas de energia decorrentes das componentes harmônicas geradas pelas cargas não lineares, as quais representam a quase totalidade das cargas presentes nos sistemas elétricos em todo o mundo. Assim, este artigo tem como objetivo analisar o funcionamento de um transformador de baixa tensão sob condições de correntes harmônicas e avaliar não somente a temperatura de operação do equipamento, mas também verificar as perdas de energia no mesmo. Este teste é realizado em plataforma laboratorial e os resultados são experimentais utilizando uma fonte trifásica ajustável e um transformador trifásico de 3kVA.

Keywords: Transformers; Power Distribution; Energy Loss; Operating Temperature; Energy Efficiency.

Palavras-chaves: Transformadores; Distribuição de Energia; Perdas de Energia; Temperatura de operação; Eficiência Energética.

1. INTRODUCTION

The constant technological evolution allows the electric equipment's to be increasingly efficient, mainly by electronics, which provides its users with many functionalities. However, the massive use of electronic products causes several disturbances in current and voltage due to the nonlinear characteristic of this type of load (Shmilovitz et al 2007.). This characteristic is equivalent to saying that the relationship between the voltage and the electric current of these charges cannot be represented by a linear function.

Because of this nonlinearity, non-sinusoidal currents arise in the mains, composed not only of the fundamental frequency component at 60 Hz, but also of integer multiple components of the fundamental frequency, named as harmonic components. Harmonic components, when present in the power grid, increase the effective value of the current, causing a series of undesirable consequences to the system equipment, including the increase of energy losses in the distribution and transmission systems.

One equipment that suffers from the harmonic components is the electrical transformer that is damaged due to temperature increasing above the standard operational value. Given this situation, the harmonics influence on an electrical transformer temperature behavior should be studied. It is crucial to understand how the temperature of the transformer change with a harmonic amplitude and frequency, and how these changes affect the electrical transformer lifespan.

An industry without a good design and without adequate input standard and protection may suffer from extra maintenance of its transformer because of overheating, resulting in a considerable loss in its life cycle. Although, at some point, it may be too expensive to install equipment with a higher capacity to prevent these effects from nonlinear loads and at other situations, it is not possible to avoid them.

The main objective of this paper is to present a study of the thermal impact of harmonic components in a typical three-phase transformer, in order to investigate its heating under nonlinear operating conditions and to verify how it is affected. It was observed that by measurements, a three-phase transformer, without filter and connected to nonlinear loads, undergoes a massive temperature increase for different amplitude types and harmonic frequencies.

2. SYSTEM MODELING

Prior to temperature checks on an electrical transformer, it is important to have the geometrical understanding of the system and its domain regions for further studies, where it is desirable to simulate more complex situations, so such studies can be facilitated. Therefore, to understand the electromagnetic problem, the Finite Elements Method must be studied and applied in the frequency domain and in the steady state.

Finite Element Method (FEM) modeling is performed to verify whether predefined design specifications are achieved through the dimensional model of the studied transformer. Results of magnetodynamic modeling shall be presented for a transformer in question. Then, simulations are studied and thus can be performed via COMSOL software in a magnetodynamic modeling with FEM application. Regions should be included later. With this, we seek to present the structural sizing of the transformer core and windings, taking into account initial design specifications, as well as the determination of global quantities such as winding losses, core losses and dispersion reactance. (Alves, Bruno de Sousa et al. 2016).

In this study, we should verify the relationship that describes the behavior of the magnetic field density in nonlinear magnetic materials that is the transformer core. For this, it is necessary that the relationship between the magnetic flux density vector and magnetic field vector obey the mathematical equation given in (1) and the hysteresis curve seen in the Figure 1.

$$B = \mu H \tag{1}$$

Where,
μ is the magnetic permeability.

To solve this thermal problem in two dimensions, were used the heat flow equations given in (2) (Penabad et al. 2015, Hwang et al. 1988, Bjerkan et al. 2007, Taheri et al. 2012, Lee et al. 2011):

$$d_z \rho C_p u \nabla T + \nabla . q = Q_{source} \tag{2}$$

Where,
d_z is the outer plane thickness. (m)
ρ is the material density. (kg/m^3)
T is the temperature. (K)
q is the heat flow. (W/m^2)
Q_{source} is the heat source. (W/m^3)
σ is the electrical conductivity. (S/m)

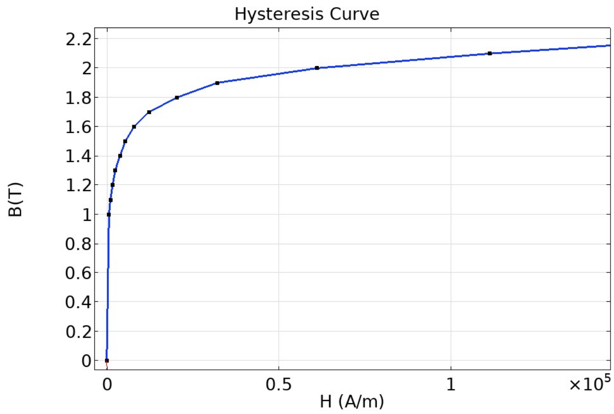

Fig. 1 – Hysteresis Curve

To couple the electromagnetic problem into the thermal problem, the transformer losses, as Loss by Joule Effect, Hysteresis Loss and Eddy Current Loss, were accounted for as heating sources. They were implemented into the copper coil for the Loss by Joule Effect and the transformer core for Hysteresis and Eddy Current Losses. These losses can be calculated by the expressions given in (3):

$$\begin{aligned} P_{joule} &= \sigma \, |J|^2 \\ P_{hysteresi} &= k_h v f |B_{m,h}^n| \\ P_{eddy\ current} &= k_e v \, (t_l \, f |B_{m,h}|)^2 \end{aligned} \tag{3}$$

Where:
P_{joule} is the loss due to current circulation in the copper coil. (W/m^3)
$P_{histerese}$ is the loss due to core hysteresis. (W)
$P_{eddy\ current}$ is the loss due to Eddy current in ferromagnetic material. (W)
k_h is the constant of the ferromagnetic material.
ke is the constant of the ferromagnetic material.
v is the volume. (m^3)
t_l is the thickness of the core sheet of ferromagnetic material. (m)
f is the frequency. (Hz)
$B_{m,h}$ is the maximum magnetic field density for each harmonic component . (T)

In this case, the constant k_h has a specific value that depends on the core material. k_h can be seen in the Table 1 (Turan et al. 2012). The constant k_e for leakage current losses should be calculated, after some mathematical treatment, by the expression given in (4):

$$k_e = \frac{\sigma\pi^2}{6} \quad (4)$$

Table 1. Material Constant K_h

Material	K_h
Soft iron	0.025
Silicon Sheet Steel	0.001
Perm alloy	0.0001

After determining the hysteresis and Eddy current losses, it is necessary to consider each harmonic effect. Since the problem has many different harmonics, the better solution is to implement these losses as a sum of losses, where each element of this sum is a harmonic component of its respective load (5):

$$P_{joule} = \sigma \sum_{h=1}^{max} |J_h|^2$$

$$P_{hysteresis} = \sum_{h=1}^{max} k_h\, v\, f_h\, |B_{m,h}^n| \quad (5)$$

$$P_{eddy\ current} = k_e v \sum_{h=1}^{max} (t_l\, f_h\, |B_{m,h}|)^2$$

After the material characterization, it is mandatory to implement the electrical source and the electrical load. In this part, some factors should be observed, like THD and the K factor. (Taheri et al. 2012, Fuchs et al. 2015, Singh et al. 2014, Singh et al. 2016, Topalis et al. 2001, Topalis et al. 2010), defined in (6):

$$THD = \frac{\sqrt{\sum_{h=2}^{max}[h.(V^h)^2]}}{V_1}$$

(6)

$$k_{factor} = \sum_{h=1}^{max} I_h^2 . h^2$$

These factors are used to indicate the harmonic level of the system. THD definition can be found in IEEE-519 standard (IEEE Std 519™-2014 - Revision of IEEE Std 519-1992) - (Blooming et al. 2006) and show the limits of these factors in some specific situations. The k_{factor} is used in the ANSI / IEEEStdC57.110 standard (Wagner et al. 1993, Fuchs et al. 2000) to show the depreciation of the equipment due to harmonic loads.

Analyzing the equation (5) can be observed that the maximum magnetic flux density vector B_{max} has a relationship to the harmonic load current applied to the secondary coil of an electrical transformer. Thus, the power losses can be expressed by k_i factors according to equations shown in (7):

$$P_{joule} = \sigma \sum_{h=1}^{max} |k_h J_h|^2$$

$$P_{hysteresis} = k_h v \sum_{h=1}^{max} f_1 |B_{m,1}^n| (1 + k_h^n.h) \quad (7)$$

$$P_{eddy\ current} = k_e v \sum_{h=1}^{max} (t_l\, f_1 |B_{m,1}| (1 + k_h.h))^2$$

Where,
K_h ranges from 0 and 0.5 of nominal load.
h ranges from 3ª, 5ª and 7ª harmonic order.

Thus, the measurements can be performed by checking distortions and following the increasing temperature behavior of the transformer.

3. EXPERIMENTAL TESTS

The tests were implemented using the electrical transformer shown in Figure 2 and its characteristics are described in Table 2. The transformer was powered by the power source, which can be controlled by software. The desired waveform was implemented in a computer and sent to the source via the USB. The transformer was connected to the source through its primary winding. The transformer secondary winding was connected to incandescent lamps. These loads are almost linear and have a power factor closer to the unit. Therefore, the nonlinear characteristic of the current waveform does not change due to the load. Thus, these waveforms will have the same characteristics of the voltage waveforms applied by the power source. To analyze the input and output voltage and current, a four-channel oscilloscope is employed, measuring primary and secondary voltages and currents. Furthermore, a FLUKE VT02 thermal display, shown in Figure 3, were used to observe the temperature.

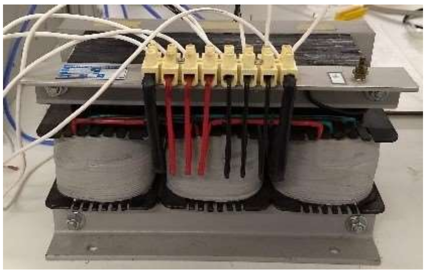

Fig. 2 Electrical Transformer used in the tests

The generated waveforms applied by the source are shown in Figure 4 to Figure 7. Note that for some values, the electrical transformer acts like a filter and the secondary winding does not have a distorted voltage waveform. The transformer Y-grounded connection helps to filter the harmonic input, so all zero sequence components are canceled and the transformer acts like a filter for these harmonic orders.

Table 2. Transformer Tests

Bench's test transformer		
Transformer's model	three-phase	
Power	3000	*VA*
Primary Voltage	220	*V*
Secondary Voltage	127	*V*
Transformer's class	B	-
Frequency	60	*Hz*

Fig. 3 Infrared thermometer with thermal visor

Thus, the tests verify the influence of amplitude and harmonic orders. They verify a sequence of voltage and current measures for input and output, as well as the temperature for a given harmonic level. The tests and their temperature results are shown in Table 3.

In the first five measurements, note that the temperature values increase as the amplitude of k_3 increases. The same analyses can be done for other harmonic orders variations, where the temperature value increases with the harmonic order, that is, not only amplitude, but also the increasing orders of harmonics make the temperature of the transformer to rise. The thermal results range from 30°C to 45°C.

It should be noted that the measurements made on a laboratory platform, using incandescent lamps as loads, and inserting harmonic content at the input (primary side of the transformer). Thus, to verify the gradual increase of the temperature, as well as its decrease, that is, the cooling of the equipment, two forms were used, natural ventilation and forced ventilation. Using natural ventilation, the time taken to increase the temperature was 15 minutes and for cooling, with equipment turned off, took just over two hours. Otherwise, when forced ventilation is used, the cooling time is reduced to 15 minutes as well, optimizing the time between measurements. In these measurements, because it is a low power transformer, only 3kVA, the temperature would certainly increase significantly, but it was left in just 15 minutes, since it was enough to verify the temperature variation for this study.

Figures 8 and 9 show what is observed with the thermal display. Figure 8 shows the result with no harmonic orders and the number presented in this figure ("30.48") represents the temperature of the hottest measured point by the thermal display, in Celsius degree.

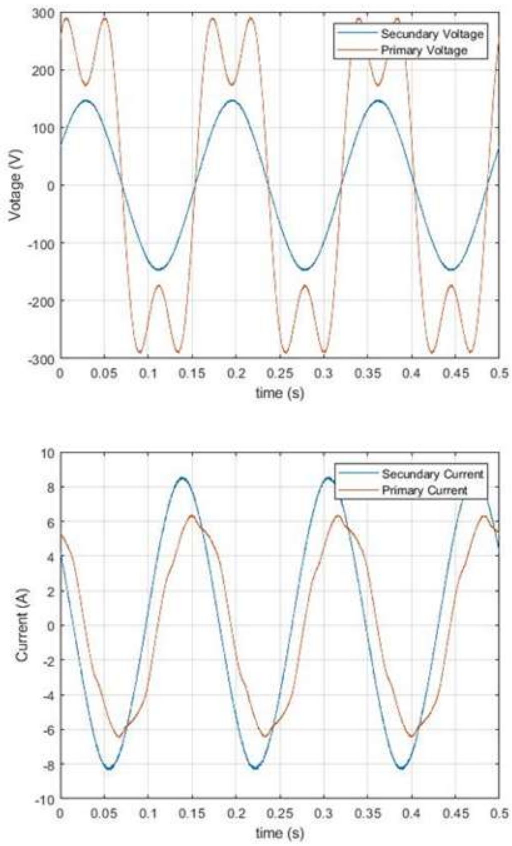

Fig. 4 Voltage and current of primary and secondary with k3= 0.4, k5 = 0 and k7 = 0

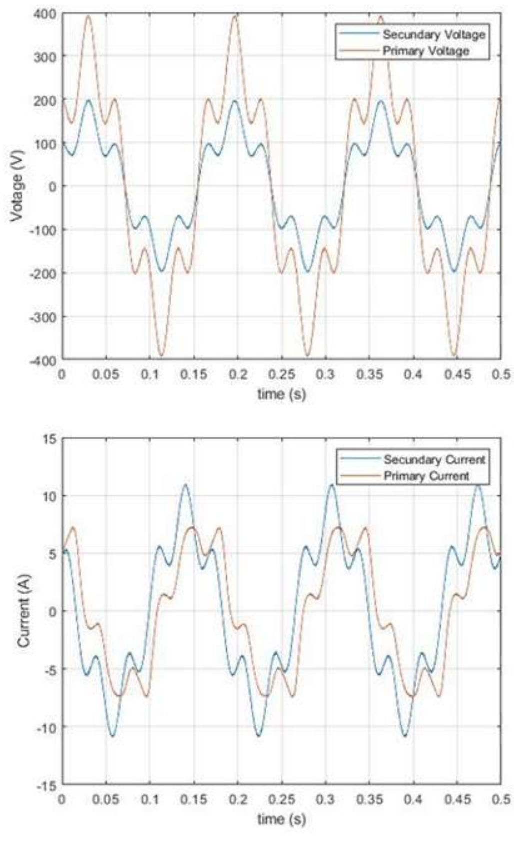

Fig. 5 Voltage and current of primary and secondary with k3=0.1, k5 = 0.2 and k7 = 0

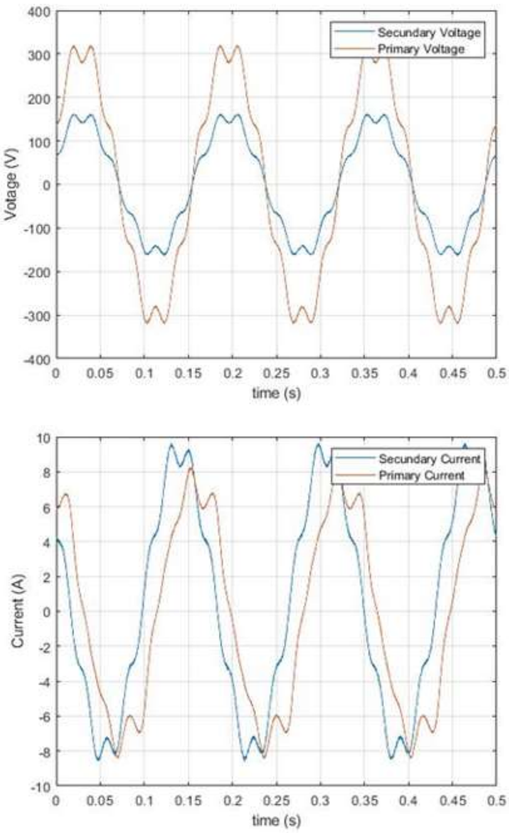

Fig. 6 Voltage and current of primary and secondary with k3= 0, k5 = 0.1 and k7 = 0.1

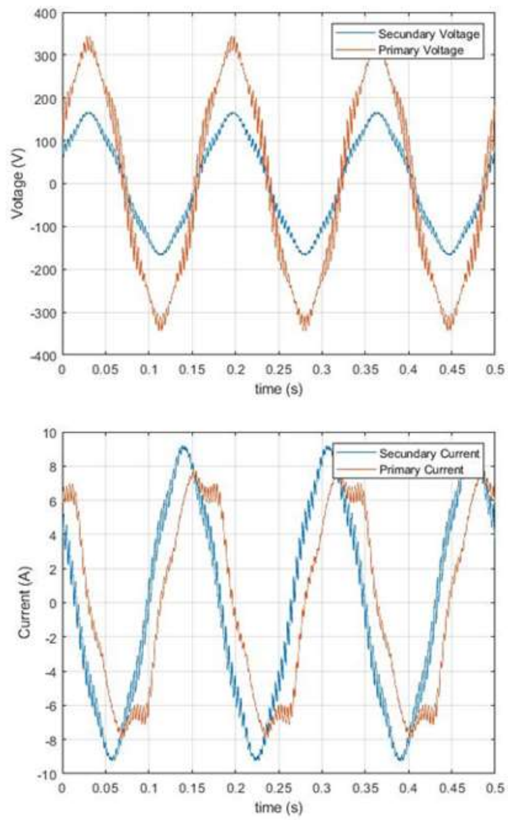

Fig. 7 Voltage and current of primary and secondary with high orders

Table 3. Measured temperature due to harmonic orders

Harmonics' Amplitude (p.u.)				Temperature in bench's test (°C)
1	3	5	7	
1	0	0	0	30.5
1	0.1	0	0	33.5
1	0.2	0	0	33.9
1	0.3	0	0	34.5
1	0.4	0	0	37.5
1	0.5	0	0	38
1	0	0.1	0	43.2
1	0	0.2	0	45
1	0	0	0.1	45.4
1	0.1	0.1	0.1	33.4

Table 4, as a reference, was based on NBR 5356-11: 2016 with the limit temperature elevations for dry transformers, where it is emphasized that the transformer used in this study is class B.

Table 4. Temperature rise limits in dry transformers

Temperature Rise Limits		
Insulation system maximum temperature ° C	Maximum winding temperature ° C	Reference Temperature ° C
105 (A)	95	80
120 (E)	110	95
130 (B)	120	100
155 (F)	145	120
180 (H)	170	145

Figure 9 shows the thermal result for the highest harmonic orders: 5^{th}, 47^{th}, 49^{th} e 51^{th}, where the waveform can be seen in Figure 7. The highest temperature is 45.85°C and it should be noted that, for the results shown in Figure 9, THD is lower than 10%, according to the IEEE 519 standard. However, the calculated *K* factor is 19.09 and, in this case, the temperature is higher than those shown in Table 3.

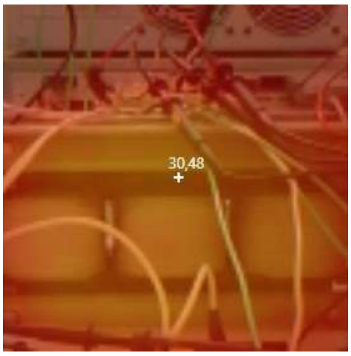

Fig. 8 Thermal measurement without harmonic orders

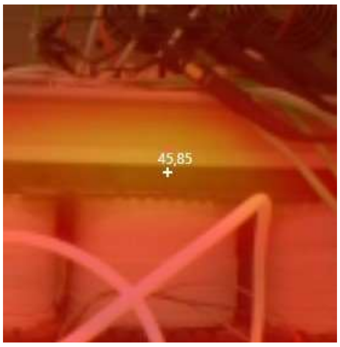

Fig. 9 Thermal measurement with high harmonic orders (1st, 5th, 47th, 49th and 51th)

4. CONCLUSION

This paper presented a method to calculate the amplitude losses and harmonic orders, analyzing three types of different losses: loss by Joule effect, Hysteresis loss and loss by Eddy current. Each one of them is heat source and affect the temperature behavior according to equation given in (7).

It was noted that the higher the harmonic content of the load current, the greater the additional losses in the transformer windings and core, raising the transformer temperature above the appropriate operating temperature. The study demonstrates that winding conductors are the components most affected by harmonic distortion. This means that hot spots have temperatures much higher than operating conditions at rated frequency.
It is noteworthy that the temperatures in the coils are higher than in the surface and the tendency is to exceed the winding operating temperature limit, higher severity of nonlinear load.

Therefore, for this research, it is necessary to prevent the nonlinear load transformer from exceeding the maximum load current. This will prolong the life of the transformer. Other radiation factors, such as transformer level at sea, humidity in transformer, type of oil cooling, viscosity of oil cooling (since the transformer used was dry type) and dielectric losses, are not considered in this research.

Transformer life is directly connected to the power quality conditions and the increasing nonlinear loads affect these conditions. Hence, a transformer temperature increases and to keep its programmed lifespan it is important to know the waveform quality that feeds the transformer.

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