EXPERIMENTAL EVALUATION OF THE EFFECTS ON ADDITIONAL LOSSES IN SMALL TRANSFORMERS USED FOR SUPPLYING NON-LINEAR LOADS

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***Abstract* – The use of electronic devices has experienced a significant expansion, since their costs have decreased with the same proportion that their capability in controlling ever larger amounts of energy has increased. While this expansion represents an important contribution of these devices for the welfare of the society, it is a fact that most of these devices present non-linear currents that can bring several problems to the electric network. One of these problems is related with additional losses within the transformer intended to supply these devices, these losses can increase dangerously, leading to the overheating. Thus, with the aim of studying a very representative example of this problem, a commonly found situation is analyzed in this work. A small transformer that is usually assembled within a voltage stabilizer for personal computers has its performance evaluated in terms of the additional losses, with respect to the influence of various types of loads, distinguished by their harmonic current contents. The result is the need for de-rating this transformer in view of it presenting winding losses and temperatures within values predicted in project. Obtained results can be extrapolated to larger transformers.**

***Keywords* – eddy losses; harmonic; transformer; winding temperature;**

I. INTRODUCTION

It is a fact that in the modern society electronic devices have significant importance. After all, such these devices have been dealing with an ever increasing amount of energy, for bringing comfort, energy saving and safety for people. It thus means that rated power of electronic devices is increasing significantly as well as that the use of electronics, which has been increasing in presence within an ever growing number of devices. Some examples like showers, appliances, computers, light dimmers and compact lamps are easily found in our homes. They are also found in industries, furnaces, frequency converters, soft-starters and several other motor drivers are examples of the increased application of electronics. Nevertheless, one of the various consequences of the growth of electronic devices use, is the proportional increase of the harmonic pollution in the electric power grid [1,2]. This pollution has become more significant due to sudden increase of the rated current of electronic devices, with an ever larger amount of harmonic components and the power associated with these harmonic components. Standards and rules were deployed to control and reduce this pollution and its several problematic consequences but, however, they will take several years for their complete implementation. The demand for such devices keeps on growing, which causes this to be an important problem to be solved. With the aim of contributing for the study and solution of this problem, this work presents the analysis of an common situation that is how the presence of harmonic components, due to the use power electronic devices, is related with the design of small transformers. Thus, a typical small transformer used commonly within voltage stabilizers for personal computers has its performance evaluated in two different conditions. In the former condition, this transformer supplies a rated linear load, resulting in a sinusoidal current. Then, the linear load is disconnected and another rated but non-linear load is used. The performance of this transformer is compared for these two conditions, regarding winding losses as well as its temperature. For the sake of an even better significance of this work, a personal computer, with its considerable amount of harmonic components, is used as the non-linear load for this transformer. As result, it is shown that a small transformer that is designed to an inherent sinusoidal condition of load is not only subjected to a sudden ageing of its insulation as well as its losses increase significantly if the load is not sinusoidal. This matter represents an expressive interest of transformers industry, since obtained results can be extrapolated to transformers of several sizes.

II. CONCERNS OF THE HARMONICS ON THE PERFORMANCE OF A TRANSFORMER

Harmonic components do harm transformers [3]. No matter whether these harmonics are present in the voltage or in the current, the fact is that most of times the transformer is designed to operate in an inherently sinusoidal condition. According to [3-6], voltage harmonics cause intense increase of the of core losses within a transformer. Fortunately, it is not the usual condition since it is quite hard to find facilities in which voltage harmonics is high enough to cause the increase of core losses in a transformer. This is so because most of electric networks are so interconnected that its equivalent circuit can be seen as an infinite bus. An infinite bus is an ideally sinusoidal voltage source with null series impedance. In consequence, voltage distortion is indeed low, even for large non-sinusoidal loads. On the other hand, current harmonics are much easier to find in any facility and their main effect in transformers is a considerable increase of the additional losses [3,5]. These losses are relatively low at 50 or 60 Hz but, at higher frequencies, they are highlighted due to magnetic field distortion, to the skin effect within windings of transformer as well as due to eddy current induced in tank, clamps and several other metallic components. This additional losses frequency response is due to the dependence of the power on the square of the order of every harmonic component [3,5]. In consequence, these additional losses can cause an excessive and dangerous increase of the mean temperature of the transformer. This temperature increase will contribute for accelerating the ageing of the insulation, which will cause the transformer to be more vulnerable to voltage transients, while it also wastes energy. To overcome this issue, in the United States, special design of transformers using a concept known as K-Factor transformers [5,7] were developed, and worldwide assimilated. Generally, it considers that for non-sinusoidal condition of operation, winding losses are K times those losses for the purely sinusoidal condition. Value of K depends on the current spectrum of the current load. On the other hand, European practice has not adopted such this concept of K-Factor transformers. Instead, Europe has adopted the practice known as of de-rating. That is, a common type transformer has its rated power, in kVA, reduced if a non-sinusoidal load is to be supplied. The degree of de-rating similarly depends on the spectrum of the load current, which yields a Factor K for de-rating[4,8]. Even though for both cases it is necessary to know the spectrum of the load current, this is such a condition that is hardly found, since several non-linear loads with different spectra of harmonics are randomly connected in most of the facilities. As a consequence, any supplying transformer will likely experience a dynamic and high level of additional losses. Thus, this issue has been under strict interest of transformer manufacturers, since a solution for this problem has not been reached yet. This work analyzes these concerns in a very commonly found situation in Brazil, that is related to the performance of a transformer assembled within voltage stabilizer applied to supply a personal computer's power. Usually, a personal computer is a non-linear load and the transformer has no special feature for supplying it, which suggests that Brazilian's practice is closer to European's one. Therefore, the question that arises is how much de-rating should be taken into consideration. For analyzing this situation, an experimental approach is presented.

III. EXPERIMENTAL TESTS AND RESULTS

A 220 V / 107 - 115 V, 600 VA, 60 Hz dry type auto-transformer was chosen for the tests. Auto-transformers like this, as the one shown in Figure 1 are usually assembled within 220 V / 110 V voltage stabilizers for supplying personal computer. Still regarding Figure 1, even though it is not ease to depict, there are seven temperature probes installed in the transformer. Four of them were installed in the winding, while three others were installed in the magnetic circuit for computing the mean temperature of the whole transformer. Figure 2 shows a schematic diagram of its windings under rated condition is presented.

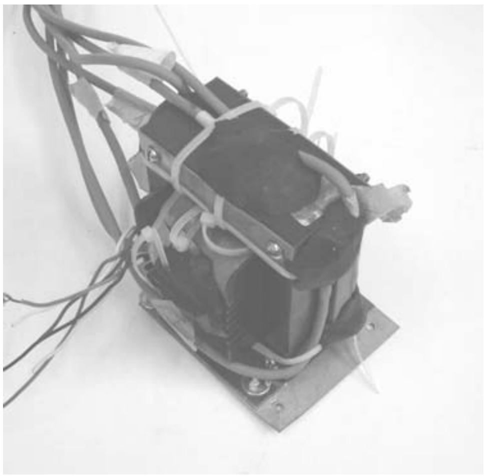

Fig. 1. Auto-transformer used for tests of evaluation of the effects of current harmonics.

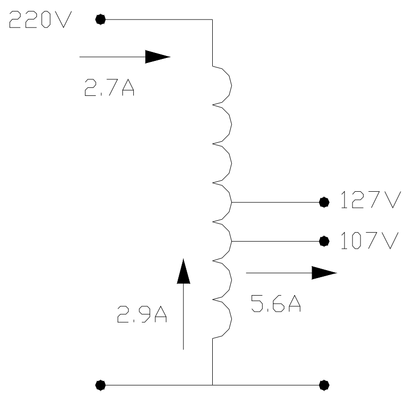

Fig. 2. Schematic diagram of the auto-transformer under rated conditions at 60 Hz.

Regarding Figure 2, the two leads available, one for 107 V and one for 127 V, represent the extreme values of the range within which the electronic circuit of the voltage stabilizer uses to obtain the output voltage stabilized in 110 V. Thus, the tests were chosen to be performed by considering the condition of highest current. Therefore, it was used only the 107 V output lead. Except for this auto-transformer, no other circuit or component of the voltage stabilizer took part of the tests. Nevertheless, it is important to quote that during the tests the auto-transformer was kept within the plastic container of the voltage stabilizer, reproducing its actual housing condition. From the seven temperature probes above quoted an average temperature was obtained to be considered as the temperature of the transformer. These seven temperatures as well as the room temperature were read every 15 minutes during the tests.

Figure 3 shows a photo of the test apparatus, consisting of temperature readers, high precision current and voltage multi-meter, voltage regulator, a DC power source, and the plastic box containing the transformer under test.

Fig. 3. Test apparatus for the performed tests of the auto-transformer.

A. DC current test

This test was intended to determine the ohmic losses within the winding of the transformer, which is such a basic value for the evaluation of the Factor K [3,8]. Thus, since the dc current is applied to the whole winding with open output, the current should be the same for simplifying the test. So a unique value of dc current was applied, which was chosen to be a representative value of winding currents, 2.7 A. Figure 4 shows the schematic diagram of this test.

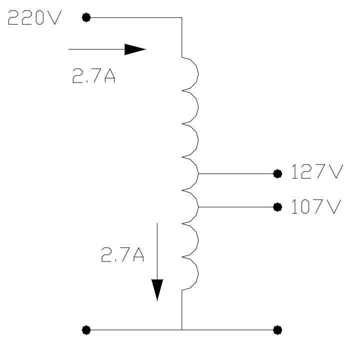

Fig. 4. Schematic diagram for the dc test. For simplifying the test, an unique dc current was applied to the whole winding.

The value for loss obtained was 23.4 W, while the average temperature of the transformer reached 61.4 °C for a room temperature of 22 °C. Both temperatures stabilized after about 1 hour of test, while readings were taken every fifteen minutes.

B. Short-circuit test at 60 Hz

For determining the total losses in the windings, that is the ohmic losses added to eddy losses [3,8], the auto-transformer was submitted to the short circuit-test. Thus a short circuit was caused at its low voltage side (107 V) while a voltage of 11.44 V was applied to its high voltage side (220 V) side until the current of the autotransformer reached the rated values, as shown in Figure 2. For this test the losses were 29.5 W and the final temperature reached 61.8 °C for a room temperature of 23 °C . The procedure for the readings was the same for the DC test .

C. Open circuit test at 60 Hz

For determining the total losses of the transformer, the core losses were obtained by submitting the auto-transformer to its nominal voltage at the 220 V side. For this test the losses were 18.5 W and the final average temperature of the transformer reached 61.6 °C for a room temperature of 21 °C , after about two hours.

D. Rated load at 60 Hz - Purely sinusoidal

The transformer was then submitted of full load condition. Thus, a 600 W resistive load was connected to the low voltage that presented a voltage of 102 V for a quite sinusoidal current of 5.9 A. At the high voltage side an input voltage of 220 V was applied for a current of 2.95 A. For this condition, after a little more than one hour, the measured winding losses added to core losses totalized 52 W, while average temperature of the transformer reached 100 °C for a room temperature of 23 °C .

E. Typical load at 60 Hz - with harmonics

The same transformer was then submitted to the condition for which a voltage stabilizer is made for. That is, a personal computer and a printer were connected to the 107 V side, as a typical load of the transformer. For a measured output voltage of 106 V the respective current was 1.42 A rms, that is lower than the rated current. After about one hour measured losses within transformer were 21.5 W, while its average temperature reached 63.7 °C for a room temperature of 24 °C . Figure 5 shows the current spectrum for this test, while Figure 6 shows the respective waveform.

It is important to quote that even though this may be the typical load, it represents only approximately 164.5 VA, which is close to 3.6 times lower than rated power of the transformer.

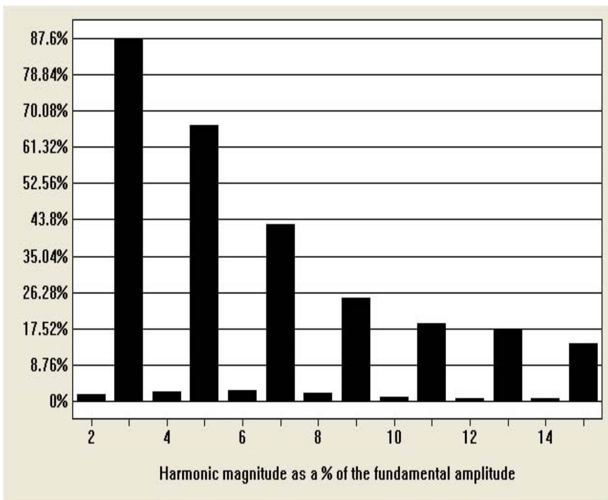

Fig. 5. Harmonic spectrum of the load current of 1.42 A rms.

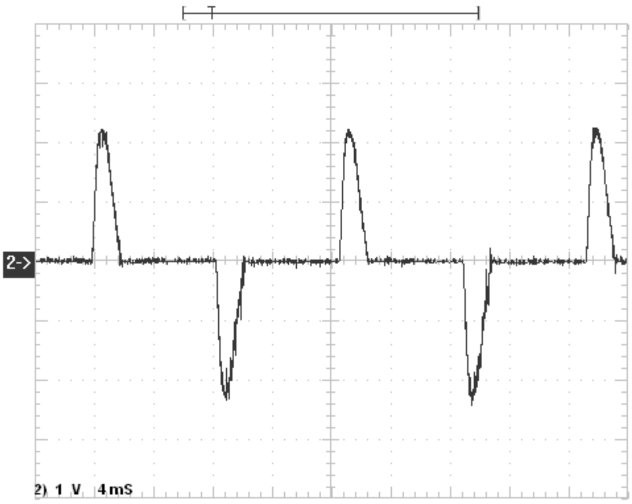

Fig. 6. Wave form of the load current of 1.42 A rms – Horizontal scale of 4 ms per division and vertical scale of 1 A per division.

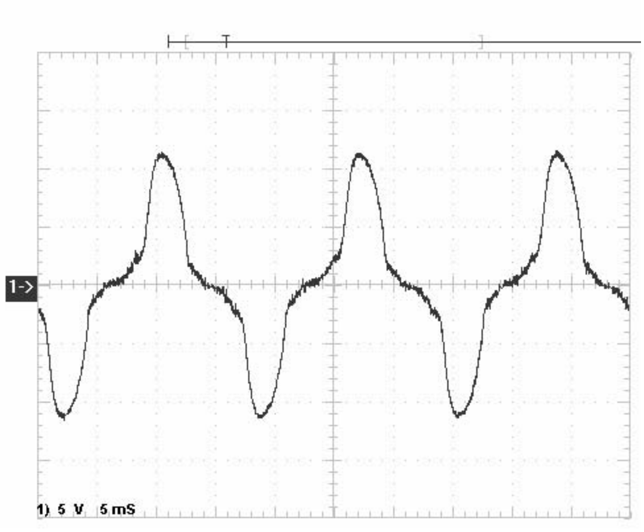

Fig. 7. Wave form of the load current of 6.1 A rms – Horizontal scale of 5 ms per division and vertical scale of 5 A per division

F. Rated load at 60 H z- with harmonics

Finally, the same transformer was submitted to the condition that it is made for. That is, personal computers were connected to the 107 V side until its respective current could reach a value close to the nominal. Thus a 6.1 A rms was measured on the low voltage side for a voltage of 100.5 V, which resulted in an apparent power of 603 VA. Measured active power to this load was 222 W. After about one hour measured losses within transformer were 494.4 W, while its average temperature reached 122.1 ^{o}C for a room temperature of 19.5 ^{o}C. Figure 7 shows the current spectrum for this test, while Figure 8 shows its waveform.

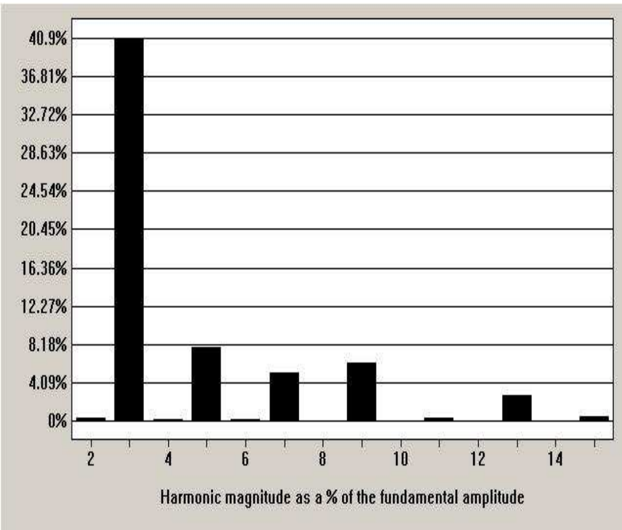

Fig. 6. Harmonic spectrum of the load current of 6.1 A rms.

IV. ANALYSIS OF THE RESULTS

Based on presented results, it can be obtained values of K-factor of 2.87 for the condition of rated load with harmonics. Thus, in accordance with US standards, a K = 4 transformer should be used for supplying such a load. This is a specially designed transformer, easily available on the US market. For the condition of the typical load with harmonics there is no need to evaluate K, since that load is quite under the rated one. This practice of K rated transformer is not usual in Brazil, for several reasons, especially due to costs. On the other hand, in accordance with European standards factor k for the same condition of typical load is 1.47 (e = 0.174 and q = 1.7 [4]), which implies that this 600 VA transformer should supply a load with that same spectrum of that of Figure 6 with the following rated power :

$$S = \frac{600}{1.47} = 408.1 \text{ VA} \qquad (1)$$

European practice seems to be more adequate for Brazilian condition since it requires no special project of transformer, like US practice does. In fact European practice suggests a degree of de-rating of a standard transformer for it to supply a non-linear load. For both practices the current spectrum of the load is required to be known. Nevertheless, in most of cases this data is indeed too difficult to be determined since it varies dynamically during a day.

Thus, US practice as well European suggest alternative approaches for accommodating the problem that is here presented. That is, if this 600 VA transformer supplies a load with a purely sinusoidal its winding losses and temperature of the transformer are within predictable values 29.5 W and 100 C, respectively. On the other hand, if a 600 VA load presents several harmonics, like presented on Figures 5 and 6, application of Factor K or de-rating procedures should follow for avoiding the excessive heating of the transformer. This heating not only represents and excessive loss as well as it causes the ageing of the insulation, which can cause reduction of its life-time.

V. CONCLUSION

This work has presented an experimental work to study and evaluate the losses of a typical voltage stabilizer transformer. It represents how concerns of harmonic pollution for large power transformers can be used for analyzing similar problems within small transformers. Thus, it was evaluated the steady temperature, as well as additional power losses for tree different types of loads, which are rated linear load, reduced non-linear load and rated non-linear load. Based on the discussion of the presented results, it can be seen that the steady temperature of the transformer on supplying rated non-linear loads exceeded the temperature as for rated linear loads. Also, additional losses have increased significantly when rated non-linear loads replaced rated linear load.

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