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Experimental Investigation of Parameters Influencing Transformer Excitation Current

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Abstract-- **This paper quantifies experimentally the impact of ten parameters on transformer excitation current. These parameters belong to the following six categories: (1) annealing process, (2) mechanical process, (3) operating conditions, (4) magnetic material, (5) assembly process, and (6) core design process parameters. The conclusions of this research are very useful during both the design and production phases of transformers. Consequently, transformers can be designed and manufactured to fulfill the excitation current specifications.**

Index Terms—**Excitation current, distribution transformers, shell-type core, silicon steel, step-lap core.**

I. INTRODUCTION

THE excitation current is measured through the no-load test, which consists in letting open the secondary winding while the primary winding is connected to the line at rated voltage [1], [2]. Under these conditions only the excitation current flows through the winding. The no-load test is commonly carried out at the low voltage winding.

According to the Mexican standard [3], the excitation current should not exceed 1.5% for all single-phase transformers and for three-phase transformers with capacity greater than 45 kVA. The excitation current of three-phase transformers of up to 45 kVA should not exceed 2.0% of the rated current.

This paper investigates the impact of ten different parameters on transformer excitation current in a quantitative manner and nine parameters in a qualitative manner. As shown in Table 1, these nineteen parameters are classified into the following six categories: (1) annealing process, (2) mechanical process, (3) operating conditions, (4) magnetic material, (5) assembly process, and (6) core design process parameters. The conclusions of the experimental investigation of parameters influencing excitation current, presented in this paper, are very useful not only during the design stage, but also during the production phase. They allow the appropriate setting of production parameters so as to manufacture transformers with excitation currents within the specifications.

Table 1: Parameters influencing transformer excitation current

Category	Parameter
1. Annealing process	1. Geometry of the core pile during annealing 2. Thermal cycle 3. Atmosphere of the furnace
2. Mechanical process	4. Liquid to lubricate cores before cutting 5. Slitting process of lamination 6. Handling of the electrical steel
3. Operating conditions	7. Impulse test 8. Frequency 9. Residual magnetism
4. Magnetic material	10. Lamination thickness 11. Amorphous versus conventional material
5. Assembly process	12. Length of air gap 13. Core dimensions
6. Core design process	14. Stacking techniques 15. Overlap distance 16. Laminations per layer 17. Magnetic flux density 18. Lamination width for the wound-core distribution transformers 19. Number of turns of low voltage

Many parameters impact the excitation currents and as a result, transformer manufacturers sometimes produce transformers with high excitation current that exceeds the standard levels. Consequently, the contribution of this article is very useful during both the design and production phases of transformers. If there is a good industrial control on parameters that impact excitation currents, transformers can be designed and later produced to fulfill the excitation current specifications.

II. PARAMETERS INFLUENCING EXCITATION CURRENT

A. Annealing process

1) Geometry of the core pile during annealing for a batch-type furnace

Extensive experimental investigation, carried out in the context of this paper, has shown that the arrangement of the core pile during the annealing process influences the excitation current. Fig. 1 shows a pile of cores after the

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annealing process. If the cores are not annealed in a homogeneous way, they will present high gradient of temperature [4]. The industrial experiments carried out by the authors have shown that when the arrangement of the cores in the furnace is not appropriate (the cores should be arranged in such a way that heating of any core is not appreciably affected by others due to obstruction), then the values of excitation current can increase up to 10%.

Figure 1. Arrangement of the core pile after the annealing process. Four superior cores of this pile are fallen due to incorrect movement of the furnace cover and these cores should be re-annealed.

2) *Thermal cycle*

The duration of the thermal cycle depends on the coldest point in the core pile. This cold point should reach a minimum temperature of 800^{o}C for at least one hour before beginning the cooling cycle [5]. The annealing process relieves stresses after the core has been formed into its final size and shape.

The annealing cycle is divided into three phases [6], [7]:

1. *Starting and heating up phase*, to avoid oxidation and to normally achieve temperature of 800^{o}C.
2. *Soaking phase*, to achieve homogeneous temperature distribution for all cores.
3. *Cooling phase*, to slowly cool the load to avoid the development of internal stresses in the cores. This is applied until the temperature reaches 300^{o}C, which also avoids oxidation of cores when they are exposed to the natural environment.

Table 2: Cooling time and cooling rate

Cooling time (h)	Cooling rate (^{0}C)	
	Test 1	Test 2
1	160	200
2	90	90
3	70	70
4	65	57
5	55	47
6	43	35
7	30	30

The authors have observed that if the soaking phase temperature does not reach the threshold value of 800ºC or if it surpasses this threshold value, then the excitation current can increase up to 10%.

To avoid distortion of laminations and cores, it is required that the core pile should be cooled slowly to a temperature of about 300^{o}C at a rate not exceeding 100^{o}C per hour for core piles weighing only a few tons. The measurements of two cooling rates are reported in Table 2. The numbers in Table 2 show that after the first hour, the temperature is reduced by 160^{o}C and 200^{o}C for Tests 1 and 2, respectively; after 2 hours, the temperature is reduced by 250^{o}C and 290^{o}C, respectively, and so forth.

3) *Atmosphere of the furnace*

In order to avoid the oxidation of the electric steel sheet, it is required that the atmosphere inside the furnace is of pure nitrogen with less than 2% of hydrogen and with a dew point of 0^{o}C or less [4], [6].

When the electrical steel is contaminated with carbon during the process of annealing, its electric and magnetic properties are degraded. To avoid this, it is necessary to remove the oil, and other organic compounds that can adhere to the steel during the manufacturing process. The materials that are in contact with the cores during the annealing process should be of low carbon content. These materials can be in the molds to form the core windows, the steel cover that is placed between the furnace and the core pile, and the base on which the cores are placed.

The concentration of the carbon varies with the silicon content as shown in Table 3 [8]. Industrial experiments have shown that excessive carbon adversely affects the magnetic properties (e.g., increasing hysteresis loss).

Table 3: Content of carbon varies with the silicon content

Nominal silicon content	1%	2.5%	3%	4%
Nominal % carbon	0.06	0.05	0.03	0.007

B. *Mechanical process*

1) *Liquid to lubricate cores before cutting (air gap region) of wound-type cores*

In the cutting process, the cores are impregnated with a mixture of three substances to lubricate the sheets (chlorothene, per chlorine, methyl chloride). This way, the laminations are not damaged and the sheets are cut in a uniform way. Otherwise, burs are formed and these cause a short circuit among the neighboring sheets. In this case, industrial experiments that have been conducted by the authors have shown that the excitation current can increase by 5-10% of the mean value.

2) *Slitting process of lamination*

When core steel is slit to appropriate widths, burr minimization is very important. If burr is present, inter-lamination short circuits can occur, which increase the excitation current by 5-10%, as measured experimentally by the authors. A recommended maximum tolerance for burr is 0.005".

3) *Handling of the electrical steel*

If during the manufacturing process the cores are not appropriately handled (especially after annealing), then the excitation current is increased due the reintroduction of stresses into the steel [5]. Inadequate handling can occur during storage of the cores, transportation, and assembly of the core-winding set. Fig. 2 shows problems that should be avoided in the process. According to the figure, the steel sheet can lose the insulation when it is hauled over sharp corners.

Figure 2. Stress introduced when the steel roll is hauled to manufacture the core.

C. *Operating conditions*

1) *Impulse test*

There is no effect of high-voltage impulses on the no-load current of transformer cores [9].

2) *Frequency*

Given the high variability nature of the measured exciting current of even the same design, it is recommended that the measured 60-Hz exciting current is taken to be the same as the 50-Hz exciting current [10]. In other words, the recommended conversion factor for exciting current is 1.00.

3) *Residual magnetism*

The transformer core may have residual magnetism as a result of being disconnected from the power line, or as a result of measurements of dc winding resistance [11]. Industrial measurements carried out by the authors have shown that the residual magnetism results in exciting current increased by more than 10%. However, smaller changes in exciting current may also be indicative of problems associated with the core and should be investigated. If a significant change in the exciting current is observed during the no-load test, then the only reliable method of excluding the effect of residual magnetism is to demagnetize the transformer core. It is recommended that the measurements of the dc resistance be performed after the exciting test. The basic theory of recommended procedures for demagnetization has been described in the literature [12].

D. *Magnetic material*

1) *Lamination thickness*

Fig. 3 compares the design values of excitation currents for a shell-type single-phase transformer from 5 to 50 kVA using three different laminations for the core. In Fig. 3 we can see that transformers with lamination M4 have smaller excitation current for transformers with rated power from 5 to 50 kVA.

Eighteen optimum transformer designs were created for comparison of excitation current in the range of 5 to 50 kVA. This experiment consisted of minimizing the transformer bid price, which is the objective function for transformers that are purchased by industrial and commercial users. The transformer bid price, *BP* (in $), is computed as follows [7]:

$$BP = \frac{MC + LC}{1 - SM} \quad \text{or} \quad BP = \frac{TMC}{1 - SM}, \tag{1}$$

where *MC* (in $) is the cost of transformer materials, *LC* (in $) is the labor cost, *TMC* (in $) is the transformer manufacturing cost, and *SM* (in %) is the sales margin.

All the results have been obtained with a field-validated transformer design optimization computer program that has been used for many years in a mid-size transformer factory using equivalent loss for each transformer rating (See Figs. 4 and 5).

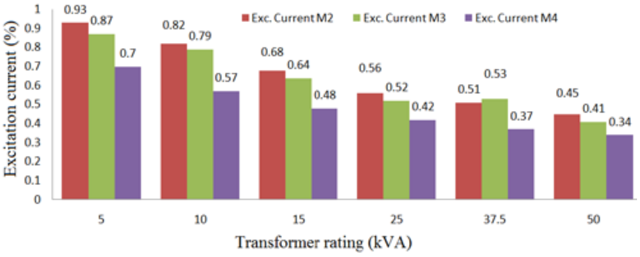


Figure 3 Excitation current versus transformer rating (kVA) for three lamination thickness for different laminations.

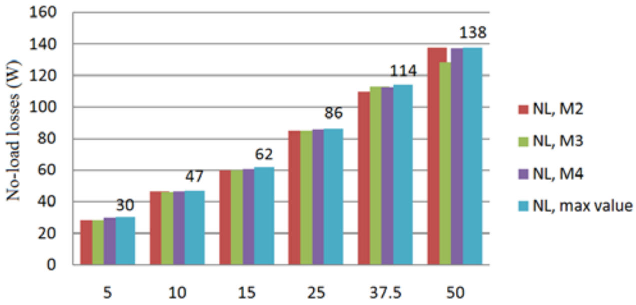


Figure 4. Design values of no-load losses (W) versus transformer rating (kVA) for different laminations. NL= No load losses.

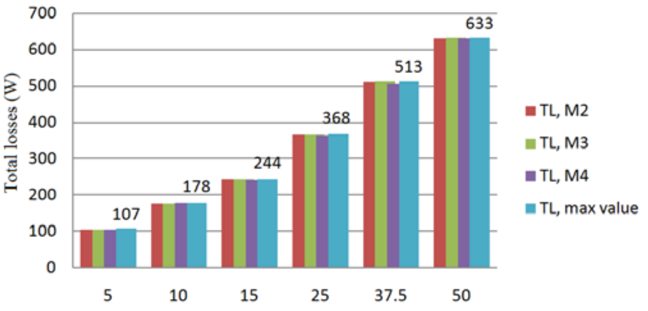


Figure 5 Design values of total losses (W) versus transformer rating (kVA) for different laminations. TL= Total losses.

2) *Amorphous versus conventional material*

Excitation current is reduced when using amorphous cores. Industrial measurements, carried out by the authors of [13], have shown that for the same 25 kVA transformer, the excitation current of amorphous core transformer and silicon steel core transformer was 0.14% and 0.36% of the rated current, respectively.

E. *Assembly process*

1) *Length of air gap*

As the air gap of the core is increased, the excitation current is also increased. This is validated with the control diagram of Fig. 6. The diagram shows the excitation currents of 32 cores of the same production batch. It is observed that the first 16 cores have higher values of excitation current as compared to the average value because these cores were manufactured with air gaps of the order of 4-5 mm. The remaining 16 measurements give lower values. These last cores have air gap length of the order of 1-2 mm.

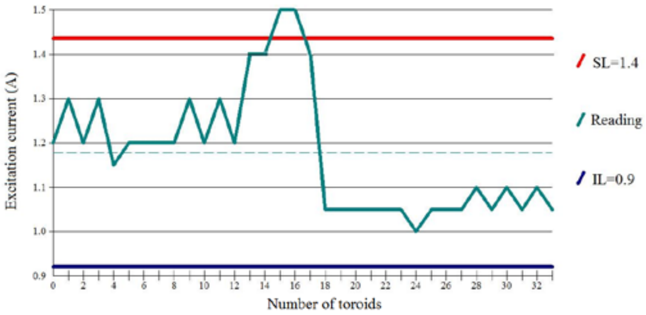


Figure 6. Control diagram of the excitation current of 32 cores of the same production batch. SL= Superior limit control, IL=Inferior limit control

2) *Core dimensions*

If the transformer core manufactured has a smaller thickness than design thickness, the excitation current is increased. A decrease of the thickness of the core in 3.22 mm due to manufacturing error can increase the excitation current by 50% in a 10 kVA transformer (see Table 4). Thus, by removing only 14 laminations from the core the excitation current exceeds the maximum value of 1.5%. Frequently, some laminations are removed from the core during assembly due to difficulties in assembling the core and winding.

Table 4: Excitation current in a 10 kVA transformer by reducing the core thickness

Core thickness (mm)	Excitation current (%)
30	0.84
29.54	0.92
29.08	1.01
28.62	1.11
28.16	1.23
27.70	1.37
26.78	1.71

F. *Core design process*

1) *Stacking techniques*

The stacking techniques affect the excitation current. There are two main stacking techniques for the transformer core: step-lap joint and butt-lap joint. The step-lap technique results in lower excitation current compared to the butt-lap technique. Two 13.8kV-231V, 500 kVA transformers were manufactured and the excitation current mean values were 5.9 A and 3.6 A for butt-lap core and step-lap core, respectively. Also, the rms value of the excitation current of the butt-lap core is much higher than that of the step-lap core [14].

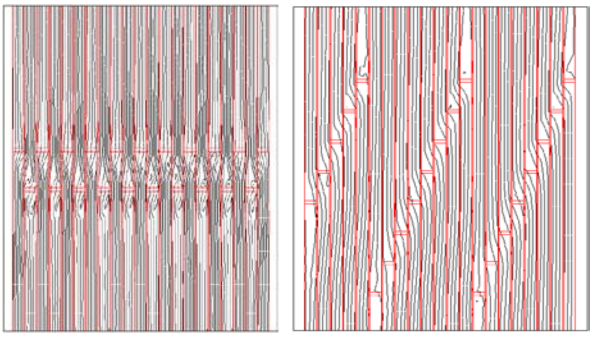
2) *Overlap distance*

The authors carried out experiments, in which they examined a sample of twelve 37.5 kVA transformers cores, in which 85% of the cores were manufactured with an overlap length of 1.0 cm and 15% of them were manufactured with an overlap length of 2.0 cm. In these experiments, only one core was tested in each measurement. The samples with an overlap length of 2.0 cm result in higher excitation currents. The average difference was 8%.

There is a detectable difference between the single and double overlap cases [15]. It can be seen that with or without an air gap, the step-lap with an overlap in the range 0.25 cm-0.75cm results in significantly lower exciting current.

3) *Laminations per layer*

Fig. 7 shows the influence of the number of laminations per layer in the magnetic flux. When the number of laminations is small, the region close to the air gaps is saturated, and some of the magnetic flux passes through the air gaps and the excitation current is increased. When the number of laminations is large the percentage of the magnetic flux passing the gap is reduced and the excitation current is reduced.



a) b)

Figure 7. Magnetic flux lines for an air gap of 3 mm and overlap length of 1 cm, a) Two laminations per layer, b) Eight laminations per layer.

4) *Magnetic flux density*

By increasing the magnetic flux density the excitation current is notably increased; this behavior is explained because the increase of apparent losses in volt ampere of core material is increased with the increase of magnetic flux density. This can be seen in Fig. 8, which was obtained with the use of a field validated transformer design software for distribution transformer.

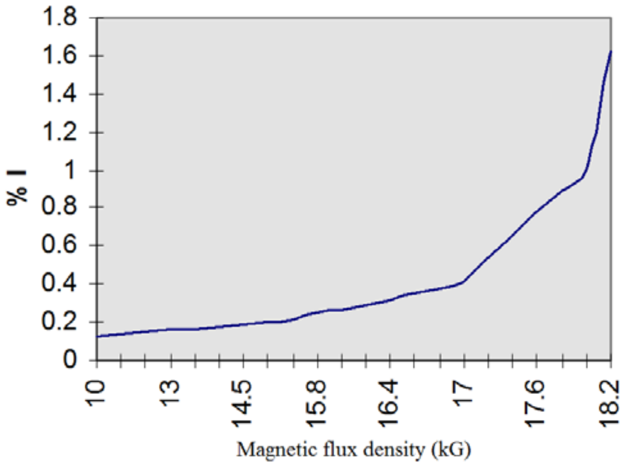


Figure 8. Excitation current (in %) versus magnetic flux density (kG).

5) *Lamination width for wound-core distribution transformers*

Lamination width between 152.4 and 304.8 mm is recommended for wound type distribution transformers. Fig. 9 shows the reductions of excitation current with the increase of lamination width. Results of Fig. 9 were obtained with a design optimization software for distribution transformer.

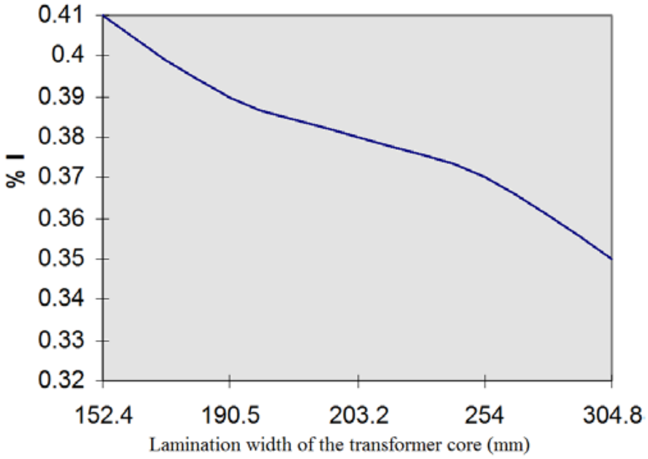


Figure 9. Excitation current (in %) versus lamination width of the transformer core (mm)

6) *Number of turns of low voltage*

The number of turns for low voltage winding for single-phase distribution transformers $\left(N_{LV}\right)$ is in the range of 10 to 45 (for transformer sizes of 5 to 167 kVA), and it is given by:

$$N_{LV} = 89.6828 \cdot kVA^{-0.5}, \tag{2}$$

as we can see in Fig. 10, where small circles represent manufactured transformers, and $N_{LV} = 89.6828 \cdot kVA^{-0.5}$ is an exponential function that fits the small circles in a least squares sense. From Fig. 10, we see that few low voltage turns correspond to high transformer ratings and many low voltage turns correspond to low transformer ratings (for example, 40 turns for a 5 kVA transformer and 6 turns for a 167 kVA transformer). Fig. 11 shows the variation of excitation current versus the number of low voltage turns. It is possible to reduce the excitation current during transformer design phase by increasing the number of low voltage turns.

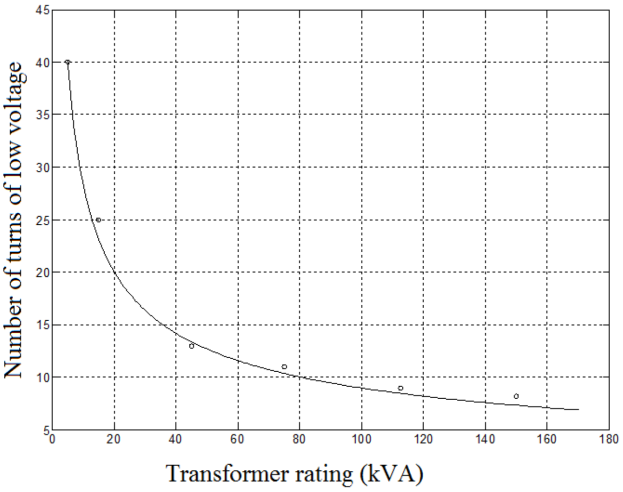


Figure 10. Number of turns of low voltage (in %) versus transformer rating (kVA) for single phase transformers. Small circles represent manufactured transformers.

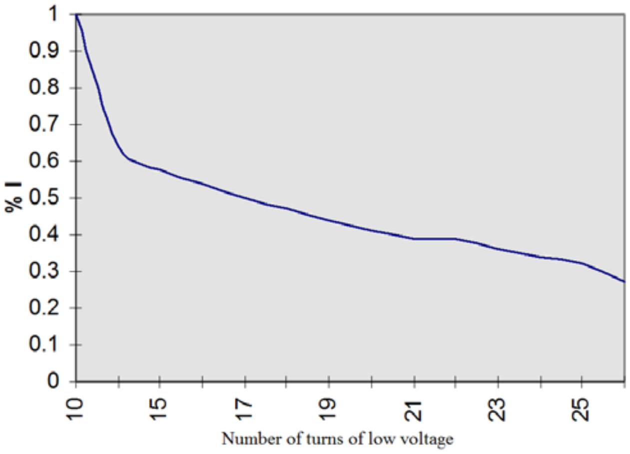


Figure 11 Excitation current (in %) versus number of turns of low voltage.

III. FUTURE RESEARCH

In the near future, an extension of this study will be made; we are planning to find an analytical expression to calculate excitation currents that take into account all the factors analyzed in this paper and we are planning to discuss in a quantitative manner all the parameters that were just only discussed in a qualitative manner in this paper.

IV. CONCLUSIONS

This paper analyzed experimentally the impact of ten parameters on transformer excitation current. These parameters are classified into six categories: (1) annealing process, (2) mechanical process, (3) operating conditions, (4) magnetic material, (5) assembly process, and (6) core design process parameters. The way these parameters influence the excitation current is very useful since it helps producing transformers having excitation current that satisfies the specification of transformer users. Additionally, we plan to find an analytical expression for the determination of the excitation current based on geometric and electric parameters. The formula would be a valuable tool for designing transformers meeting the excitation current specification.

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VI. BIOGRAPHIES

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