EFFICIENCY AND ECONOMICAL VIABILITY OF COUNTRYSIDE TRANSFORMERS BASED ON PERCENT IMPEDANCE OPTIMIZATION AND AMORPHOUS CORE

Arimatéa NUNES
UNIFEI – BRAZIL
nunesarimatea@lat-efei.org.br

Manuel MARTINEZ
UNIFEI – BRAZIL
martinez@lat-efei.org.br

Estácio WANDERLEY NETO
UNIFEI – BRAZIL

Hermes DE OLIVEIRA
AES Sul – BRAZIL

Edson BATISTA
AES Sul – BRAZIL

Alan NÓBREGA
UNIFEI – BRAZIL

Aellfclêniton DINIZ
UNIFEI – BRAZIL

Rogério SALUSTIANO
UNIFEI – BRAZIL

ABSTRACT

This paper presents a study aiming the project of efficient single-phase distribution transformers to be used in countryside. Single-phase distribution transformers applied in these regions presents high core losses, due to the lower load profile of consumers. Therefore, it is necessary to design transformers aiming core design to reduce no load losses. Thus, two solutions are proposed: percent impedance optimization and transformers using amorphous metals in the core design. Transformers designed based on both solutions are obtained from a computational routine developed in the High Voltage Laboratory (LAT-EFEI) of the Federal University of Itajubá (UNIFEI). This study was realized by LAT-EFEI during a Research & Development project in partnership with AES Sul, a Brazilian power distribution company. The methodology of the percent impedance optimization consists in increasing it, resulting in a transformer operating with lower magnetic flux density, implying in smaller no load losses. It also results in more compact cores, implicating in a cheaper . The other solution is to use transformers with amorphous technology. Transformers using amorphous metals present smaller no load losses, thus they are efficient equipments to be used in countryside. This paper presents a comparison of both technologies. Different transformers projects, using conventional design based on percent impedance modification and amorphous core will be generated based on standard requirements so that efficiency and economical viability will be evaluated. The results will make possible to indicate the best project to be used in countryside areas.

INTRODUCTION

Distribution transformers present high efficiency, near 99% [1], when working under nominal operational conditions. However, when such equipments are used in rural areas, with low demand profile clients, these equipments operate in unfavorable conditions. Thus, studies were realized providing an efficient utilization of transformers in rural areas, operating in a way that load losses are reduced by means of a feasible project in technical and economical aspects. When transformers operate with low demand, the load losses are relatively low when compared with no load losses. Therefore, in the standard efficient transformers design to be used in conditions of low demand, it is more important to reduce no load losses. This is usually achieved by modification of core dimensions, usually resulting in larger and more cores.

An alternative solution for core losses reduction consists in utilization of amorphous core technology. The amorphous alloy shows lower core loss, so it may be a viable alternative for use in rural areas

Another alternative solution for core losses reduction consists in increasing percent impedance. This can be realized increasing the initial number of turns, resulting in smaller magnetic flux density (magnetic induction), which results in smaller no load losses, considering that the core section is constant. In this work, it was obtained a reduction of no load losses for the projects developed through the increase of the number of layers of low and high voltage coils, resulting in a reduction of the coil and window heights. As consequence, the core becomes more compact, implicating in a cheaper transformer with reduced manufacturing costs if compared to a similar transformer with smaller percent impedance.

APPLICATION OF TRANSFORMERS IN RURAL AREAS

Singlephase distribution transformers usually present low losses in copper when used in rural areas, as the client's profile in this regions request low demands. However, the transformer presents significant no load losses as the equipment operates most of the time with reduced loading. These kind of losses should have their reduction prioritized during the design of the transformers to be used in these areas.

The load profiles for clients located in AES Sul rural concession areas were obtained through a study realized by LAT-EFEI during a Research & Development project in partnership with AES Sul. From this study, it was obtained an average TSMP (Time Supplying Maximum Power) of 1 hour per day [2].

The TSMP reflects, in comparative terms, the equivalent time that the transformer operates under rated power presenting losses equivalent to a normal load cycle. Thus, a TSMP value of 1 hour per day indicates that, in one day, the transformer operates 1 hour under rated power and in no load condition during the 23 remaining hours, presenting the series losses of an average load normal cycle [3]. The TSMP value can be obtained by equation (1).

$$\text{TSMP} = \frac{24}{n_d} \cdot \sum_{i=1}^{n_d} \left(\frac{S_i}{S_n} \right)^2 \quad (1)$$

In this equation n_d is the number of time intervals used for the discretization of the daily load; S_i is the instantaneous power (W); S_n is the rated power (W);

Figure 1 shows the graphical meaning of TSMP, where the green line depicts a transformer the load curve and the blue line depicts the equivalent TSMP curve.

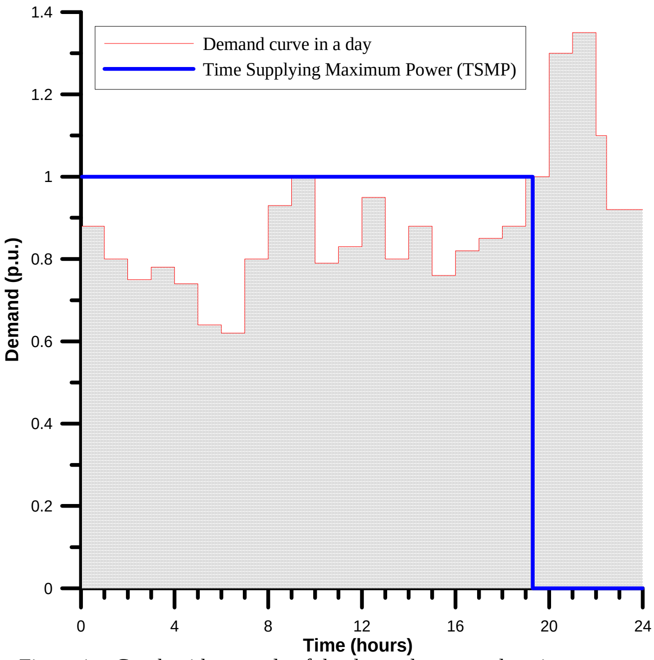

Figure 1. Graph with example of the demand curve and equivapent TSMP curve.

The analysis of rural load behavior was achieved from a statistical study for the TSMP and for the maximum demand data collected from 69 transformers from AES Sul concession network. Statistical distributions were used to build models that best represented the collected data.

Data obtained for the transformers were grouped according to the rated power: 5 kVA, 10 kVA and 15 kVA. Still, for the study realized and described in this paper, it was chosen to use only transformers with rated power of 10 kVA and insulation class of 15 kV.

Figure 2 shows the load profiles from three analyzed 10 kVA transformers, represented according to the concessionaire codification: CSU-687, LIV-6171 and AGU-239. This graphic indicates that transformers operate with low demand, achieving a maximum of the 0.45 p.u. during peak hours. It demonstrates the need to design transformers with prior focus on no load losses.

The developed projects considered monophase transformers with high voltage terminals (HV) to phase-phase connection with rated voltage of the 13.8 kV, and low voltage terminals (LV) only to 220 V.

The transformers follow the conventional design, meaning that they present core constituted by 2 columns and composed by blades of oriented grain silicon steel. In each column there is a group of coils connected in series. Each group is constituted by 2 coils, being one HV and one LV. The HV and LV coils are concentric, LV presenting the smallest radius. For all cases oil was used as insulation between coils, and paper was used between layers [5]. Circular and rectangular cooper conductors were used for HV and LV windings, respectively.

The transformers were designed having as starting point an standard transformer obtained according to the limits imposed by NBR 5440 standard [6]. The purpose of using a standard transformer as starting point is to allow low variations of the standard parameters during the new design development and optimization process, resulting in a new transformer that will be close to a design that is already considered efficient (for high loading conditions).

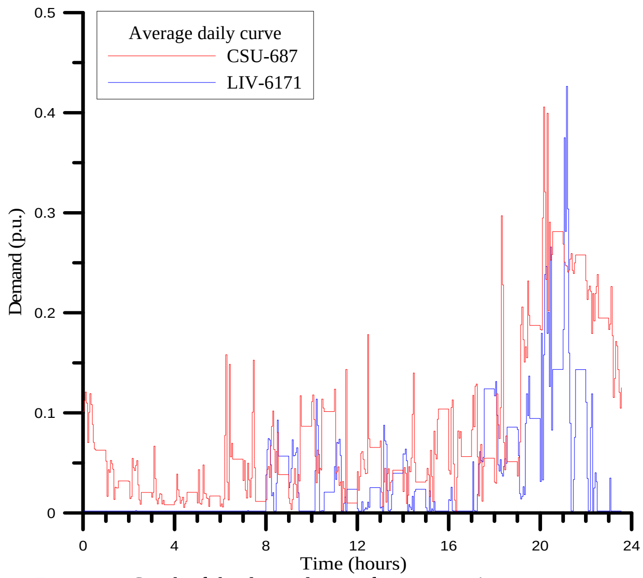

Figure 2. Graph of the demand curve for company's concession network transformers.

PERCENT IMPEDANCE

The percent impedance, also called short-circuit impedance, is a parameter that represents a percentage of rated voltage that, if applied to the primary of a transformer, causes the circulation of the rated current in the secondary under short-circuit.

The short-circuit impedance is composed by two parcels: percent dispersion reactance and the percent resistance. The percent dispersion reactance is composed by the sum of the dispersion reactances of primary and secondary windings, considering the reflection of the secondary winding on the primary side [5,9,10,11]. The other parcel of the impedance is the percent resistance, composed by the sum of the resistances of primary and secondary coil reflected to the primary [5,9,10,11]. For the design of low load monophase distribution transformers, number of turns can be raised implicating in the increase of percent resistance. As a consequence, the rated losses under load become higher, but this can be considered a minor effect, once the transformer operates with reduced loading.

Analyzing the influence of the percent impedance in the design of the monophase transformers with low loading, it was perceived that its increase results in transformers that can work with lower flux density. This implicates in lower no load losses that, if associated with smaller refrigeration process, can result in a smaller manufacturing cost. Thus, the transformer can present a reduced manufacturing cost if compared to the similar transformer with smaller percent impedance.

The percent impedance can be increased by raising the resistance of the windings through the number of turns. This increase implicates in the reduction of the flux in the core, φ, as show in (2).

$$ns = \frac{10^8 \times (US/2)}{4{,}44 \times f \times \varphi} \qquad (2)$$

Where *ns* is the number of turns in the secondary; US is the voltage in the secondary (V); f is the frequency (Hz); and φ is the flux in the core.

Starting from the standard transformer, 3 projects were created by changing some parameters: number of turns per winding and low voltage layers. The characteristics of the standard transformer and of the 3 developed designs can be seen in Table 1. The standard transformer presents two layers in the LV coil, and the 3 projects developed presents 3 layers in the LV coil.

TABLE I. TRANSFORMERS DESIGNED FOR THE POWER OF 10 KVA AND INSULATION CLASS OF 15 KV.

Projects	Copper Losses (W)	Core Losses (W)	Total Losses (W)	Percent Impedance
ABNT [4]	-	60	260	2,5
Standard Project	202,72	61,82	264,54	2,35
Project_11	262,23	34,18	296,41	3,88
Project_12	257,86	35,48	293,33	3,81
Project_13	253,49	36,87	290,36	3,74

If core's section is kept constant, the flux density is reduced, implicating in the decrease of the core losses.

Table 2 shows some data obtained for the designed transformers: quantity of copper and silicon steel used in each project, percent impedance and manufacture cost.

TABLE II. INFLUENCE OF THE PERCENT IMPEDANCE IN THE COPPER AND SILICON STEEL WEIGHT AND INDUCTION.

Projects	LV turns	Induction in the column (Gauss)	Copper Total Weight (kg)	Total Weight of Silicon Steel (kg)	Percent Impedance
Standard Project	51,33	16750,00	10,94	27,52	2,35
Project_01	61,59	13958,33	14,11	26,67	3,88
Project_02	60,57	14194,92	13,88	26,50	3,81
Project_03	59,54	14439,66	13,64	26,34	3,74

As shown in Table 2, increasing the percent impedance results in increasing also the copper's volume used in the project, as the increase of percent resistance is obtained using windings composed by a greater turn's number. Although it implies in higher losses in the windings, under the conditions of low loading these losses are reduced, so that, the total losses in operation may be smaller than the standardized values [6]. This is demonstrated by the lower total cost observed in the Table 5. In contrast to the increased resistance, the quantity of silicon steel used is reduced where compared to the used in the standard transformer, implying a fall in the manufacturing price.

AMORPHOUS CORE

Transformers with amorphous core technology present reduced no load losses, compared to the transformer with conventional silicon steel core. Thus, transformers with this type of core have advantages when used in areas with low demand, rural areas, whereas in regions like this, the no load losses predominate. Thus, some projects were developed to be a comparison between the percent impedance methodology, and amorphous core technology. Tables 3 and 4 show details of the projects developed with amorphous core. For projects with amorphous core was also used the methodology of percent impedance, so that its influence in a transformer with amorphous core could be verified.

TABLE III. TRANSFORMERS DESIGNED FOR THE POWER OF 10 KVA AND INSULATION CLASS OF 15 KV.

Projects	Copper Losses (W)	Core Losses (W)	Total Losses (W)	Percent Impedance
Project_01	231,86	12,10	296,41	2,70
Project_02	239,21	10,30	293,33	2,79
Project_03	226,02	12,55	290,36	2,63

TABLE IV. INFLUENCE IN THE PERCENT IMPEDANCE IN THE COPPER AND SILICON STEEL WEIGHT AND MANUFACTURING PRICE.

Projects	LV turns	Induction in the column (Gauss)	Copper Total Weight (kg)	Total Weight of core (kg)	Percent Impedance
Project_01	61,59	15861,74	12,50	25,98	2,70
Project_02	60,57	14194,92	12,90	29,76	2,79
Project_03	59,54	16044,06	12,19	26,20	2,63

In the tables above, one can see that the no load losses of transformers with amorphous core are quite low compared to developed projects with the technique of percent impedance. The decision on which technology to adopt, can be obtained with a technical evaluation followed by an economic analysis.

FINANCIAL ANALYSIS OF THE DESIGNED TRANSFORMERS

A financial analysis was conducted after development of the designs to estimate the cost of each one of them. Manufacturing costs and total costs were presented based on values for a fictitious plant. However, these costs represent feasible values estimated in the market for percent impedance. For transformers with amorphous core technology, it was used an estimated cost by manufacturing partners.

The manufacturing costs are the costs to purchase the efficient transformer at the supplier. In these costs are included the costs with silicon steel, copper, tank, hand labor, other transformers components miscellaneous, expenses with manufacturing equipment, taxes and profit.
The total cost represents the transformer manufacturing cost added to the present value of losses costs [5]. To the attainment of this cost, it was considered the equipment life time as 20 years and amortization of transformer costs over its life time, (which can be cause for some discussions [7,8]), analysis time of 10 years, interest rate of 8% per year and TSMP equal to 1 hour/day .
The costs of the designed efficient transformers and also the cost of the standard transformer can be seen in the Table 5 for percent impedance methodology, and in the Table 6 for amorphous core technology. It was performed a conversion of Brazilian currency to U.S. dollars in January 10, 2010.

TABLE V. MANUFACTURING COST AND TOTAL COST FOR METHODOLOGY OF THE PERCENT IMPEDANCE

Projects	Manufacturing Price (US$)	Total Cost (Capitalized Losses) (US$)
Standard Project	641,23	706,58
Project_11	664,02	626,08
Project_12	660,82	628,15
Project_13	657,63	630,59

TABLE VI. MANUFACTURING COST AND TOTAL COST FOR AMORPHOUS CORE TECHNOLOGY

Projects	Manufacturing Price ($)	Total Cost (Capitalized Losses) (US$)
Project_01	784,81	623,13
Project_02	819,73	641,03
Project_03	783,67	623,18

In Tables 5 and 6, one can see that the manufacturing cost of transformers with amorphous core technology have higher manufacturing cost if compared with transformers with impedance percent methodology. However, the total cost of transformers with amorphous core come to be compatible with transformers with a technique of percent impedance. For both solutions, the capitalization of the losses offsets the initial investment made viable solutions Thus, it is necessary to perform a technical / economical evaluation, according to the need of the company that intends to acquire such equipment.

CONCLUSIONS

A previous study realized for AES Sul by LAT-EFEI indicated that efficient transformers, developed to replace the standard transformers in AES Sul rural areas, needed to present reduced the core losses, considering the reduced loading characteristics of these areas.
Through consultations with manufacturers, it was verified that actually, there are three feasible solutions in the market, for reduction of core losses. One solution would be the use of efficient transformers within the standards currently normalized in silicon steel, aiming specifically at reduction of no load losses [12]. This solution presents a high cost, considering that it uses a larger amount of silicon steel when compared to a standard transformer.
Other option, described in this paper, would be use transformers with amorphous core, but, typically, equipment with core obtained from such technology presents high costs if compared to a conventional standard transformer with silicon steel core. By comparison, the transformer with amorphous core, despite presenting relatively low no load losses, they present higher costs when compared with efficient transformers with conventional core of silicon steel.
The third solution also presented in this paper, regarding the manipulation of the percent impedance through optimization, raising it. As shown, the increase of the impedance can result in an efficient transformer to application in rural areas with clients of low loading profile, and still can present lower cost to the manufacturing cost of standard transformer. Thus, unless the relative changes in the manufacturing costs, the transformers with highest percent impedance, are shown as feasible, and can be represent the best solution among the three possible ones, due to present a simpler manufacturing process, as well as a reduced manufacturing cost, low no load losses and reduced total cost, so, this solution presents technical / economic feasibility.
Some transformers designed according to the study developed in this paper are being purchased. These transformers will be installed in AES Sul concession network so that the proposed solutions can be evaluated.

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