Core Losses Profit in Rural Monophase Transformers by Means of Percent Impedance Optimization

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Abstract—**This paper presents a study aiming the project of efficient monophase distribution transformers to be used in regions of low energy demand. In these regions, due to the clients profile, no load losses are more expressive than losses in copper. The study necessary for the realization of this work was based on a survey accomplished by AES Sul - Distribuidora Gaúcha de Energia in partnership with the High Voltage Laboratory of Federal University of Itajubá - LAT-EFEI. Through this study, it was found that most of the transformers in rural area operate with low demand, not exceeding, in some cases, the limit of 0,3 p.u.. In these conditions, it is necessary to prioritize the reduction of no load losses so that the transformer can operate efficiently. This work introduces an analysis based on optimization of the percent impedance of the monophase distribution transformer aiming the reduction of losses in the core, indicating that on contrary to common sense, the increase of the percent impedance can result in a transformer with low costs and low no load losses, presenting reduced total losses if used under indicated loading conditions.**

Keywords-loading; demand; Energy Efficiency; percent impedance; distribution transformers.

I. 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 if 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.

An 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.

II. Application of Transformers in Rural Areas

Monophase 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 no load 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).

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

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.

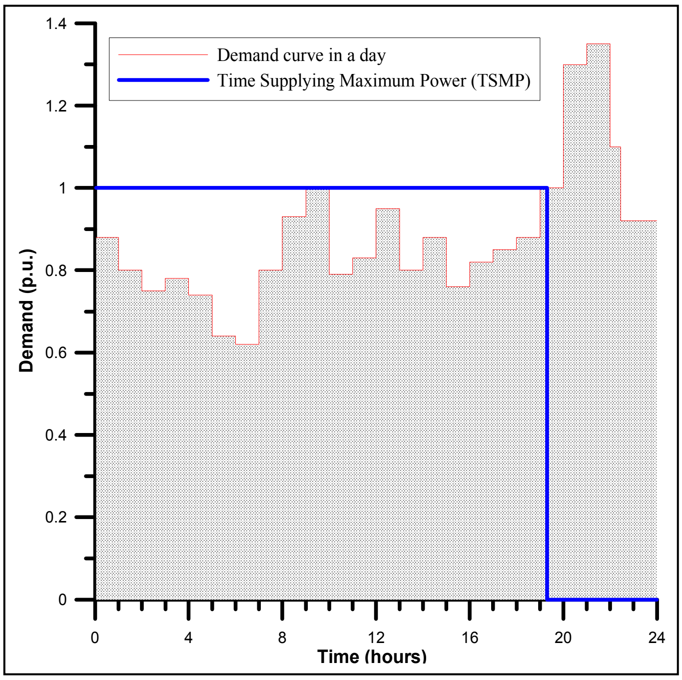

Figure 1. Graph with example of the demand curve and equivapent TSMP curve.

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.

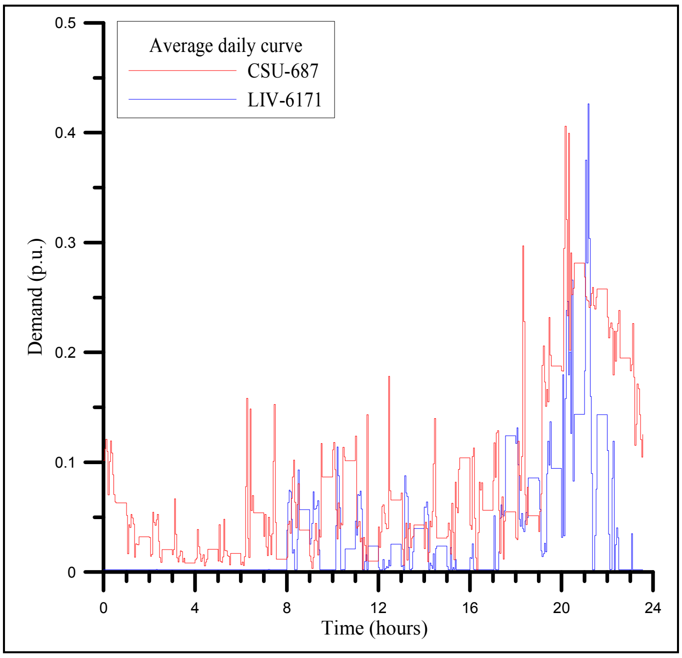

Figure 2. Graph of the demand curve for company's concession network transformers.

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 design, 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).

Starting from the standard transformer, 21 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 21 developed designs can be seen in tables 1 and 2. These designs can be divided in 2 groups, based in a parameter: number of LV layers. The first group is composing by the projects numbered from 1 to 10 and presenting 2 layers in the LV coil. The other group is composed by remainders projects, presenting 3 layers in the LV coil. As consequence, project 1 is similar, in terms of algorithm input parameters, to project 11, differing only in the LV and HV layers number. Project 2 is similar to the project

12, and so on, with project 21 been similar to the standard project, but now with 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_1	243,27	40,10	283,37	2,84
Project_2	239,21	41,56	280,77	2,79
Project_3	235,16	43,13	278,29	2,74
Project_4	231,10	44,83	275,94	2,69
Project_5	227,05	46,67	273,72	2,64
Project_6	223,00	48,67	271,67	2,60
Project_7	218,94	50,85	269,79	2,55
Project_8	214,89	53,23	268,11	2,50
Project_9	210,83	55,83	266,66	2,45
Project_10	206,78	58,68	265,46	2,40

TABLE II. 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
Project_14	249,12	38,38	287,49	3,67
Project_15	244,75	40,01	284,76	3,60
Project_16	240,38	41,79	282,16	3,54
Project_17	236,00	43,72	279,73	3,47
Project_18	231,63	45,83	277,47	3,40
Project_19	227,26	48,14	275,41	3,33
Project_20	222,89	50,68	273,57	3,26
Project_21	218,52	53,47	271,99	3,19

III. FINALCIAL 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.

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 capitalized losses costs [5]. To the attainment of this cost, it was considered a 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 Tables 3 and 4. It was performed a conversion of Brazilian currency to U.S. dollars in may 13, 2010.

TABLE III. MANUFACTURING COST AND TOTAL COST OF THE TRANSFORMERS

Projects	Manufacturing Price ($)	Total Cost (Capitalized Losses) ($)
Standard Project	641,23	706,58
Project_1	677,17	654,66
Project_2	673,58	657,13
Project_3	669,98	660,03
Project_4	666,39	663,42
Project_5	662,80	667,36
Project_6	659,20	671,90
Project_7	655,60	677,11
Project_8	652,01	683,08
Project_9	648,42	689,91
Project_10	644,82	697,69

IV. PERCENT IMPEDANCE

The percent impedance, also called of 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 monophase distribution transformers located in rural areas, 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.

TABLE IV. MANUFACTURING COST AND TOTAL COST OF THE TRANSFORMERS

Projects	Manufacturing Price ($)	Total Cost (Capitalized Losses) ($)
Standard Project	641,23	706,58
Project_11	664,02	626,08
Project_12	660,82	628,15
Project_13	657,63	630,59
Project_14	654,43	633,47
Project_15	651,24	636,84
Project_16	648,04	640,74
Project_17	644,85	645,25
Project_18	641,66	650,42
Project_19	638,46	656,37
Project_20	635,27	663,17

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).

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

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

If core's section is kept constant, the flux density is reduced, implicating in the decrease of the core losses, as can be seen in the Table 5 and 6.

Figure 3 shows the influence in the total cost and the manufacturing cost according of the variations of percent impedance. This graph was produced using data from 121 transformers design of 10 kVA/15 kV. In this case, it is realized that increasing the percent impedance causes a reduction is in the manufacturing cost.

TABLE V. INFLUENCE OF THE PARAMETERS MANIPULATED IN THE PERCENT IMPEDANCE

Projects	LV turns	Core Losses (W)	Induction in the column (Gauss)	Percent Resistance	Percent Impedance
Standard Project	51,33	61,82	16750,00	2,03	2,35
Project_1	61,59	40,10	13958,33	2,43	2,84
Project_2	60,57	41,56	14194,92	2,39	2,79
Project_3	59,54	43,13	14439,66	2,35	2,74
Project_4	58,52	44,83	14692,98	2,31	2,69
Project_5	57,49	46,67	14955,36	2,27	2,64
Project_6	56,46	48,67	15227,27	2,23	2,60
Project_7	55,44	50,85	15509,26	2,19	2,55
Project_8	54,41	53,23	15801,89	2,15	2,50
Project_9	53,38	55,83	16105,77	2,11	2,45
Project_10	52,36	58,68	16421,57	2,07	2,40

TABLE VI. INFLUENCE OF THE PARAMETERS MANIPULATED IN THE PERCENT IMPEDANCE

Projects	LV turns	Core Losses (W)	Induction in the column (Gauss)	Percent Resistance	Percent Impedance
Standard Project	51,33	61,82	16750,00	2,03	2,35
Project_11	61,59	34,18	13958,33	2,62	3,88
Project_12	60,57	35,48	14194,92	2,58	3,81
Project_13	59,54	36,87	14439,66	2,53	3,74
Project_14	58,52	38,38	14692,98	2,49	3,67
Project_15	57,49	40,01	14955,36	2,45	3,60
Project_16	56,46	41,79	15227,27	2,40	3,54
Project_17	55,44	43,72	15509,26	2,36	3,47
Project_18	54,41	45,83	15801,89	2,32	3,40
Project_19	53,38	48,14	16105,77	2,27	3,33
Project_20	52,36	50,68	16421,57	2,23	3,26
Project_21	51,33	53,47	16750,00	2,19	3,19

A similar procedure was used to obtain Figure 4, showing variations of losses in the copper and no load losses according of the percent impedance. It is noticed that by increasing the percent impedance, reductions in the values of the core losses are obtained.

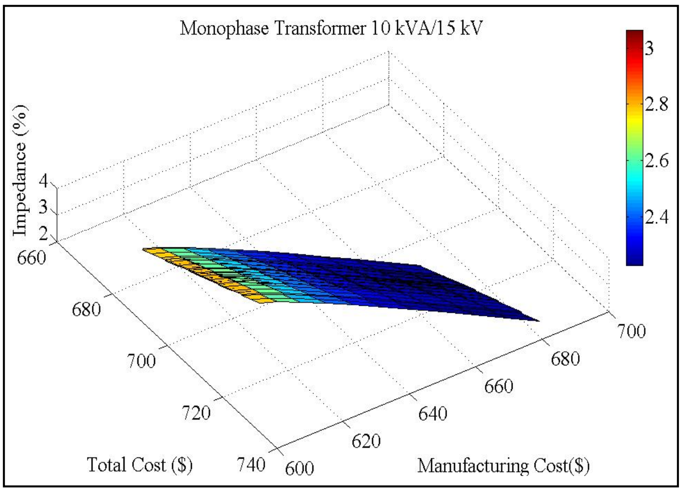

Figure 3. Percent Impedance, Total Cost and Manufacturing Cost for Transformers of 10 kVA/15 kV

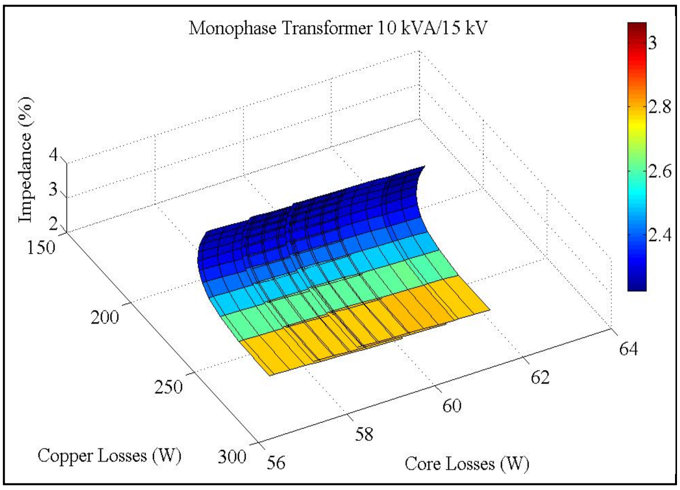

Figure 4. Percent Impedance, Core Losses and Copper Losses for Transformers of 10 kVA/15 kV

Tables 7 and 8 show some data obtained for the designed transformers: quantity of copper and silicon steel used in each project, percent impedance and manufacture cost.

As shown in Tables 7 and 8, 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 turns 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 normalized values [6]. This is demonstrated by the lower total cost observed in the Tables 3 and 4. 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 price of manufacturing.

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

Projects	**Copper Total Weight (kg)**	**Total Weight of Silicon Steel (Kg)**	**Percent Impedance**	**Manufac. Price ($)**
Standard Project	10,94	27,52	2,35	641,23
Project_1	13,12	30,01	2,84	677,17
Project_2	12,90	29,76	2,79	673,58
Project_3	12,69	29,51	2,74	669,98
Project_4	12,47	29,26	2,69	666,39
Project_5	12,25	29,01	2,64	662,80
Project_6	12,03	28,76	2,60	659,20
Project_7	11,81	28,51	2,55	655,60
Project_8	11,59	28,27	2,50	652,01
Project_9	11,37	28,02	2,45	648,42
Project_10	11,15	27,77	2,40	644,82

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

Projects	**Copper Total Weight (kg)**	**Total Weight of Silicon Steel (kg)**	**Percent Impedance**	**Manufac. Price ($)**
Standard Project	10,94	27,52	2,35	641,23
Project_11	14,11	26,67	3,88	664,02
Project_12	13,88	26,50	3,81	660,82
Project_13	13,64	26,34	3,74	657,63
Project_14	13,41	26,17	3,67	654,43
Project_15	13,17	26,00	3,60	651,24
Project_16	12,94	25,84	3,54	648,04
Project_17	12,70	25,67	3,47	644,85
Project_18	12,47	25,51	3,40	641,66
Project_19	12,23	25,34	3,33	638,46
Project_20	12,00	25,17	3,26	635,27
Project_21	11,76	25,01	3,19	632,07

V. 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 the no load losses [12]. This solution present a high cost, considering that it uses a larger amount of silicon steel when compared to a standard transformer.

Other option 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 they present relatively low no load losses, they present higher costs when compared with efficient transformers with conventional core of silicon steel.

The third solution is presented and discussed in this work, 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 represent the best solution among the three possible ones, considering that they present reduced no load losses and efficiency according to load type, associated to attractive manufactures prices. 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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