Economical Profits in Medium Voltage Networks Obtained by Rearrangement of Installed Transformers

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Abstract - **This paper presents a study on gains with relocation of medium voltage monophase transformers, based on load profile data measured for 69 transformers belonging to the electrical rural network of a Brazilian utility – AES Sul. The main purposes of this analysis are the verification of possible benefits to the distribution network and reduction of total loss by relocation of the transformers. The study was conducted considering comparisons among three groups . The first group is composed by the 69 transformers as they are installed on the power system. The second group uses the same 69 transformers, but they are rearranged and organized on the power system according to the pre-defined load conditions. The third group considers the organization of the transformers according to the load conditions and also allows the utilization of stored unities for rearrangement. The study was based on two methodologies: time supplying maximum power according to probability distributions and according to reference load profiles. It was achieved that the relocation is a reasonable procedure that contributes do increase the efficiency of distribution networks.**

Keywords-component; load profile; power efficiency; power transformers; rearrangement.

I. INTRODUCTION

Medium voltage transformers are among the components of distribution systems that are responsible for major losses, around 33% of total losses, being surpassed only by transmission lines [1]. A viable option that might bring a reduction in such losses is the replacement of the transformers installed in the distribution system [4].

This paper analyzes the importance of the reallocation and replacement of medium voltage transformers and the reduction of costs intrinsic to the losses in the distribution system. A statistical analysis was carried out including demand data measured for 69 medium voltage transformers, single phase, that belong to AES Sul Distribuidora Gaúcha de Energia S.A, a Brazilian distribution utility.

The transformers were separated into three groups. Group 1 contains the 69 transformers as they are placed in the network, according to their rated power. For Group 2, the transformers are organized according to a rearrangement made among them, according to their actual load profile. Therefore, this group considers that electricity distributor will not use transformers from the stock to perform the rearrangement, that is, the rearrangement will be carried out only with the transformers that are already running.

Group 3 corresponds to the transformers rearranged among them and also replaced by brand new unities according to their load profiles, avoiding their utilization underloaded or overloaded. Therefore, this group considers that the electricity distributor will use transformers from the stock to carry out the rearrangement if necessary.

The TSMP (Time Supplying Maximum Power) and the Maximum Demand were the main factors considered in the analysis. The TSMP shows the total time during the day (24 hours) that a transformer running in full load needs to display the losses that occur in a normal cycle with average load [5]. The value of the TSMP can be obtained from Equation 1.

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

Where,

S_i – is the instantaneous power in Watts;

S_n – is the rated power in Watts;

n_d - is the number of time intervals used to discriminate the daily load.

Figure 1 shows the behavior of the TSMP calculated from the load curve. By definition, it can be checked that the area below the blue curve is equal to the value of the TSMP. The analysis was performed through the comparison between of the results of the TSMPs obtained before and after the rearrangement of the transformers. This transformers present the powers of 5 kVA, 10 kVA , and 15 kVA.

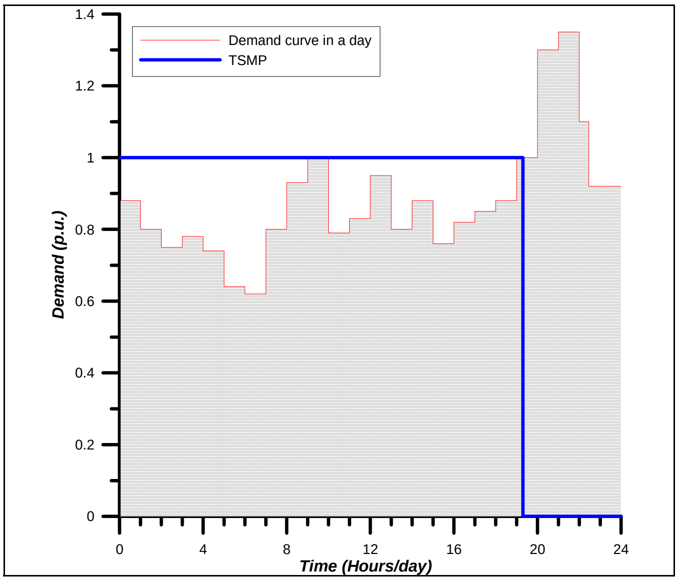

Figure1. TSMP calculated from the load curve.

The study of the transformers in Groups 1, 2 and 3 was performed based on two methods: analysis of TSMPs obtained from the probability distribution of load profiles, and TSMPs obtained from the average load profiles.

II. Development

A. Conditions Establisheds for the Rearrangement of Transformers

Groups 1, 2 and 3 were obtained using maximum weekly demand considering a maximum loading of 85%. The conditions for the rearrangement of the transformers according to their power are stated below:

- Transformers with a weekly maximum demand equal to or below 4.25 kVA were included in the group of transformers of 5 kVA;
- Transformers with a weekly maximum demand above 4.25 kVA or below 8.5 kVA were included in the group of transformers of 10 kVA;
- Transformers with a weekly maximum demand above 8.5 kVA were included in the group of transformers of 15 kVA.

B. Rearrangement of Transformers

Table I presents the amount of transformers organized according to each group.

TABLE I - AMOUNT OF TRANSFORMERS FOR EACH GROUP

Groups	5 kVA	10 kVA	15 kVA
	Amount of transformers	*Amount of transformers*	*Amount of transformers*
Group 1	10	30	29
Group 2	10	30	29
Group 3	22	36	11

Tables II and III show how Group 2 and Group 3 were created and organized according to the following statements:

- The transformers 5 I to 5 V are running at a weekly maximum demand between 4.25 kVA and 8.5 kVA, and therefore have to be replaced by 10 kVA transformers;
- The transformers 10 I to 10 XI and 15 I to 15 VI are running at a weekly maximum demand equal to or below 4.25 kVA and, therefore, need to be replaced by 5 kVA transformers;
- The transformer 10 XII is running at a weekly maximum demand above 8.5 kVA and needs to be replaced by a 15 kVA transformer;
- The transformers 15 VII to 15 XIX are running at a weekly maximum demand between 4.25 kVA and 8.5 kVA and, therefore, should be replaced by 10 kVA transformers.

In Table II, only the transformers tagged in bold characters were interchanged, since the Group 2 does not use transformers in stock.

Table II shows the rearrangement process for the Group 1 resulting in Group 2. The rearrangement is carried out only using transformers that are operating in the system, this case, only the transformers represented in the Table II in bold should be replaced. Transformers 5 I, 5 II, 5 III, 5 IV, and 5 V were over weekly maximum demands between 4.25 kVA and 8.5 kVA, and therefore, were replaced by transformers 10 I, 10 II, 10 III, 10 IV, and 10 V, as they were running at a demands below 4.25 kVA.

The choice of transformers 10 I to 10 V, shows a better adjustment to the 5 kVA power when compared to other transformers that showed a weekly maximum demand below 4.25 kVA. It has to be mentioned that other transformers at 10 kVA and 15 kVA, Group 1, are running at weekly maximum demands below 4.25 kVA. These transformers should not be replaced because only five 5 kVA transformers that belong to the Group 1 need rearrangement, and there are not 5 kVA transformers available.

It was noted that only one 10 kVA transformer (10 XII) that belongs to the Group 1 was running at overload. Through the analysis of the 15 kVA transformers in the Group 1 it was found that the transformer that supplied the load that was best adjusted to 10 kVA was number 15 VIII, therefore both pieces of equipment were rearranged, that is, number 10 XII was installed replacing number 15 VII, and number 15 VII was installed replacing number 10 XII. It must be noted that, after the rearrangement, twelve 15 kVA transformers started running at a weekly maximum demand between 4.25 kVA and 8.5 kVA.

TABLE II – GROUP 2

5 kVA					
Fit load	5-VI	5-VII	5-VIII	5-IX	5-X
Over load	**5-I**	**5-II**	**5-III**	**5-IV**	**5-V**

10 kVA					
Under Load	**10-I**	**10-II**	**10-III**	**10-IV**	**10-V**
	10-VI	10-VII	10-VIII	10-IX	10-X
	10-XI				
Fit Load	10-XIII	10-XIV	10-XV	10-XVI	10-XVII
	10-XVIII	10-XIX	10-XX	10-XX1	10-XXII
	10-XXIII	10-XXIV	10-XXV	10-XXVI	10-XXVII
	10-XXVIII	10-XXIX	10-XXX		
Over load	**10-XII**				

15 kVA					
Under load	15-I	15-II	15-III	15-IV	15-V
	15-VI	**15-VII**	15-VIII	15-IX	15-X
	15-XI	15-XII	15-XIII	15-XIV	15-XV
	15-XVII	15-XVIII	15-XIX		
Fit load	15-XX	15-XXI	15-XXII	15-XXIII	15-XXIV
	15-XXV	15-XXVI	15-XXVII	15-XXVIII	15-XIX

Table III shows the rearrangement process for the Group 1 that brings as a result the Group 3 (the rearrangement is carried out using transformers that are operating in the system and transformers of stock). This group has its origins in Group 2 where it was seen that, even after the rearrangement process, under loaded transformers continued to exist.

These transformers were rearranged considering the utilization of brand new stocked ones, with their rated power chosen accordingly to real load conditions of the network. Therefore, twelve 5kVA transformers were used to replace transformers 10 VI to 10 XI and 15 I to 15 VI. The six 10 kVA transformers (10 VI to 10 XI) replaced by other 5 kVA transformers were used to replace the six 15 kVA transformers (15 VIII a 15 XIII), but those still running at a weekly maximum demand between 4.25kVA and 8.5kVA (15 XIV to 15 XIX) were replaced by others from stock.

TABLE III – GROUP 3

5 kVA					
Fit load	5-VI	5-VII	5-VIII	5-IX	5-X
Over load	5-I	5-II	5-III	5-IV	5-V

10 kVA					
Under Load	10-I	10-II	10-III	10-IV	10-V
	10-VI	10-VII	10-VIII	10-IX	10-X
	10-XI				
Fit Load	10-XIII	10-XIV	10-XV	10-XVI	10-XVII
	10-XVIII	10-XIX	10-XX	10-XX1	10-XXII
	10-XXIII	10-XXIV	10-XXV	10-XXVI	10-XXVII
	10-XXVIII	10-XXIX	10-XXX		
Over load	10-XII				

15 kVA					
Under load	15-I	15-II	15-III	15-IV	15-V
	15-VI	15-VII	15-VIII	15-IX	15-X
	15-XI	15-XII	15-XIII	15-XIV	15-XV
	15-XVII	15-XVIII	15-XIX		
Fit load	15-XX	15-XXI	15-XXII	15-XXIII	15-XXIV
	15-XXV	15-XXVI	15-XXVII	15-XXVIII	15-XIX

C. Analsis of TSMPs obtained from probability distributions

After the rearrangement of the transformers and using Equation 1, the TSMPs for each day of the week were calculated for all the transformers analyzed and that belonged to Groups 1, 2 and 3. The daily load collected from in-field measurements was recorded in time intervals of 5 minutes during the five working days of the week.

With the values of the TSMPs, statistical analyses were carried out in the three groups of transformers using the Statistical Software MINITAB 14®. With this Software, it was possible to build statistical models based on the use of probability distributions that better represented the data collected. The models were selected according to the Anderson-Darling criterion.

The data collected from the curves of probability were entered on tables IV, V and VI. Nevertheless, only data in relation to probabilities from 1, 5, 50, 95, and 99% were collected because these were enough to include all the pieces of information needed for an appropriate conclusion.

Table IV introduces possible values for TSMPs related to three groups considering a 5 kVA power. A probability of 50% is considered as the most probable value. In this case this most probable value presented a significant reduction after the rearrangement of transformers. This behavior results from the amount of overloaded transformers that were replaced by transformers that were operating underloaded conditions. As for Group 2, it was found that five of the ten 5 kVA transformers included in the group were running at a power below 2 kVA. Whereas for Group 3 nine of the twenty-two transformers were running at a power below 2.5 kVA.

TABLE IV. TSMPS IN HOURS/DAY AT 5 KVA POWER

Probability	**TMSP**		
	Group 1	***Group 2***	***Group 3***
1%	0.001	0.000	0.001
5%	0.014	0.000	0.007
50%	1.174	0.009	0.144
95%	9.092	0.324	0.820
99%	15.495	0.671	1.366

On Table V, possible values of TSMPs related to the 10 kVA power for the three groups in the study are displayed. A TSMP increase was found after the transformers rearrangement.

Six transformers were replaced in Group 2, of which 5 were running underloaded and one, overloaded. But for the creation of Group 3, eighteen transformers were replaced to this group, five of them were running overloaded and belonged originally to the 5 kVA power, and thirteen were running underloaded, belonging originally to the 15 kVA power. Therefore, the Group 2 showed a load profile that provided the most significant TSMP value when compared to the other groups.

TABLE V. TSMPS IN HOURS/DAY AT 10 KVA POWER

Probability	TSMP		
	Group 1	*Group 2*	*Group 3*
1%	0.001	0.025	0.058
5%	0.005	0.075	0.107
50%	0.196	0.523	0.467
95%	1.204	3.645	2.037
99%	1.974	10.829	3.750

Table VI shows TSMPs possible values for Groups 1, 2 and 3 for 15kVA. A significant TSMP increase was noted in Group 3 when compared to the other groups of transformers. The increase happened due to the replacement of eighteen transformers to powers of 5 kVA and 10 kVA, and one replacement for 10 kVA power.

Such replacements happened because 18 transformers showed a demand below 8.5 kVA, and one showed a weekly maximum demand above 8.5 kVA. Therefore, the 11 transformers found in Group 3 related to 15kVA are running at a demand above 8.5 kVA, showing TSMPs higher than in the other groups.

TABLE VI. TSMPS IN HOURS/DAY AT 15 KVA POWER.

Probability	TSMP		
	Group 1	*Group 2*	*Group 3*
1%	0.006	0.004	0.051
5%	0.024	0.020	0.142
50%	0.305	0.317	0.899
95%	3.897	4.920	5.692
99%	16.246	22.866	16.014

D. Analysis of TSMPs obtained from characteristic curves

The average load profiles were created according to the demands measured every 5 minutes in a period of 24 hours during working days for the 69 analyzed transformers.

With such demands, it was possible to carry out 288 distributions of probability, each one related to a specific period of 5 minutes during the 24 hours of a typical day. TSMPs were calculated using Equation 1. These calculations were performed in the three groups of transformers that were analyzed. On Table VII, only the values of TSMPs with a 50% probability are found and they provide enough information for a conclusion of this analysis.

TABLE VII - TSMPS VALUES OBTAINED FROM CHARACTERISTIC CURVES

	TSMP		
	Group 1	*Group 2*	*Group 3*
5 kVA	1.622	0.119	0.392
10 kVA	0.339	0.341	0.473
15 kVA	0.375	0.404	0.821

TSMP results obtained from the characteristic curves exceed those obtained from the characteristics of probability. Nevertheless, TSMPs data obtained from the characteristic curves are not calculated from actual, instantaneous demand data. This happens because instantaneous demand peaks are eliminated after data statistical treatment, that is, data are only the most probable values of those demands calculated at every 5 minutes and, therefore, do not represent the actual daily load of transformers. This also turns into a load factor much above to the one actually obtained during measurement.

E. Analysis of the total losses costs for transformers

To be able to check gains obtained due to a reduction in total losses in transformers, resulting from their rearrangement, an analysis of Group 1, Group 2 and Group 3 was carried out. This analysis was based on the TSMPs calculated according to both methodologies used: TSMPs obtained from the distributions of probability, and TSMPs obtained from the average load profiles.

With the aid of equations 2, 3, 4, 5, and 6, the total losses costs in transformers will be calculated. These costs will be compared to check the feasibility of proceeding with the rearrangements.

$$C_{WO} = T_{WO} \times W_N \tag{2}$$

$$C_{WL} = T_{WL} \times W_L \tag{3}$$

$$T_{WO} = 8{,}76 \times C_{EE} \tag{4}$$

$$T_{WL} = 0{,}365 \times C_{EE} \times TSMP \tag{5}$$

$$C_{WT} = C_{W0} + C_{WL} \tag{6}$$

Where:

T_{W0} – is the rate for core losses in US$/kW;

T_{WL} – is the rate for load losses in US$/kW;

W_N – are core losses in kW;

W_L – are load losses in W;

TSMP – is Time Supplying Maximum Power;

C_{EE} – Cost of Power US$/kWh;

C_{WT} – Cost of total losses.

Tables VII and VIII show the TSMPs that result from both methodologies used in this study, where Table VII introduces the TSMPs obtained through the distributions of probability, and Table VIII introduces the TSMPs obtained from the average curves. To analyze the costs of total losses in transformers, only TSMPs obtained from 50% probability were deployed .

The TSMPs related to the three groups of transformers are found in each table. They have been organized according to their respective power: 5 kVA, 10 kVA, or 15 kVA.

TABLE VIII. TSMPS VALUES IN HOURS/DAY OBTAINED FROM PROBABILITY DISTRIBTIONS

	Group 1	Group 2	Group 3
5 kVA	1.174	0.009	0.144
10 kVA	0.196	0.523	0.467
15 kVA	0.305	0.317	0.899

With the TSMPs introduced on tables VII and VIII, and deploying equations 2, 3, 4, 5, and 6, it was possible to calculate the costs due to total losses in transformers for each of the groups analyzed. The cost of power used for the calculations was 0.06 US$/kWh. The results are shown on tables IX and X, where table IX introduces the TSMPs obtained from the distributions of probability, and table X introduces the TSMPs obtained from the characteristic curves.

TABLE IX. COSTS IN DOLLAR DUE TO TOTAL LOSSES OBTAINED FROM DISTRIBUTIONS OF PROBABILITY.

	Group 1	Group 2	Group 3
5 kVA	315.03	284.65	632.25
10 kVA	1,051.76	1,098.28	1,308.36
15 kVA	1,458.77	1,461.01	594.47
Total costs	2,825.56	2,843.93	2,532.89

TABLE X. COSTS IN DOLLAR DUE TO TOTAL LOSSES OBTAINED FROM CHARACTERISTIC CURVES.

	Group 1	Group 2	Group 3
5 kVA	326.32	287.18	647.45
10 kVA	1,070.87	1,071.15	1,307.88
15 kVA	1,470.06	1,475.44	588.97
Total costs	2,867.25	2,833.78	2,544.30

The costs a possible acquisition of new transformers were not considered in the analysis.

III. RESULTS

According to the analyses carried out, it was possible to find, when analyzing 5 kVA powers that the TSMPs of the Groups 2 and 3 are significantly below those from the Group 1, which shows the existence of an imbalance between the distribution of the Group 1 and the load supplied. This implies in the existence of a large set of 10 kVA and 15 kVA transformers running underloaded, associated to an also reasonable set of 5 kVA transformers, overloaded.

Group 3 showed 9 out of the 22 transformers with a maximum demand below 2.5kVA, that is, 40.91% of the transformers in this group show maximum demands relatively small and, therefore, relatively low TSMPs. If this becomes a problem for the 5 kVA set of transformers, it is much more serious for transformers with higher power.

The results found in the research of the groups of transformers showed that for the 10 kVA power the rearrangement brought a significant increase in TSMPs. The six replacements that took place in Group 1 brought an increase in TSMP because it was found that 5 of these replacements had their origin in overloaded transformers. As for the Group 3, the TSMP increased because the group showed a data sample that included 36 maximum demands with values exceeding expectations and a lower dispersion when compared to Group 1. Therefore, after rearrangement, demands showed a better adjustment to the 10 kVA power, thus obtaining more significant values for the TSMP.

Similarly, this was also observed for the 15 kVA transformers that after rearrangement showed increase in TSMPs. No significant increase was found in Group 2 because only one replacement took place. Nevertheless, this happened in this group because of the rearrangement of transformers previously considered as 15 kVA transformers but running at a demand below 8.5 kVA. Therefore, the transformers with low demand are replaced, and average probability increased.

All the results presented in this conclusion were based on TSMP values obtained from the distributions of probability because these introduce the real behavior of the load supplied by the transformers. No TSMP values obtained from average curves were used because this tends to overestimate the profits and under estimate the losses leading to mistaken economic decisions. This behavior does not include the appropriate result of the analysis mainly because it does not show the actual behavior of the load because of the elimination of the instantaneous peaks resulting from the instantaneous analysis performed every 5 minutes.

With the calculations of the TSMPs, it was possible to carry out an analysis including the costs of total losses in transformers. It was found that within the set of 69 transformers used in the research, the rearrangement performed without the use of transformers from the stock, Group 2, showed an increase of US $18.35 in the annual cost of total losses. In this sense, it is possible to understand that the rearrangement of only part of transformers in the group only brings good results in terms of the increase of the life-cycle of the pieces of equipment because they are used more efficiently.

When it comes to the rearrangement deploying transformers from the stock, Group 3, a reduction of US $292.67 in the annual cost of total losses in the transformers was found. Therefore, these results show that the rearrangement of medium voltage transformers provide a technical and economic use of electrical power, and it is possible to optimize the use of the assets of the companies that distribute electrical power.

IV. CONCLUSIONS

This study made it possible to verify that transformers rearrangement without the use of brand new equipments from stock does not bring significant economic gains but results in life-cycle increase for the transformers. Nevertheless, when rearrangement is performed using transformers from the stock, or that are purchased, it is possible to obtain not only an increase in the pieces of equipment life-cycle but also a reduction on investments through the purchase of pieces of equipment with a rated power below the current standard deployed by the company.

Adding to this study, some papers were performed to check extremely important points in the project of single phase transformers, i.e., the relationship between the maximum demand supplied, the percent impedance and the voltage decrease as well as, secondarily, the level of short circuit in low voltage.

Finally, once the calculations of TSMP obtained from average curves tend to overestimate the profits and under estimate the losses, as shown in this paper, it is not advisable the use of load average characteristics for the evaluation of losses and costs capitalized in transformers.

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