Economical Analysis for Efficient Transformers Projects

Hermes R. P. M. de Oliveira
Edson L. Batista
AES Sul Distribuidora Gaúcha de Energia S.A.
Porto Alegre, Brazil
hermes.oliveira@aes.com
edson.batista@aes.com

Diego L. Coriolano
Manuel L. B. Martinez
Estácio T. Wanderley Neto
Arimatéa A. Nunes
Aellfclêniton M. M. Diniz
High Voltage Laboratory – LAT-EFEI
Federal University of Itajubá
Itajubá, Brazil
diego@lat-efei.org.br
martinez@lat-efei.org.br

Abstract—**This paper presents results for the economical analysis of efficient monophase transformers when used instead of standard transformers made at the High Voltage Laboratory if Federal University of Itajubá (LAT-EFEI). The analysis was made using capitalization rules based into two wages cycles, as recommended by Brazilian Electrical Energy Agency - ANEEL. In addition, it is also discussed, briefly, a comparison made with the traditional method using the present value of transformer losses costs. Finally, authors propose a methodology to study the application of efficient transformers to replace the ones standardized by Brazilian normative association, ABNT.**

Keywords-loading; Economical viability analysis, payback, energy factor, energy efficiency, transformers.

I. INTRODUCTION

Distribution transformers are equipments that present a high performance, about 99%. Although, when used in electrical networks, considering different voltage levels, the total amount of losses can be considerably high.

When an efficiency increase is desired, it is necessary to decrease the load and no load losses. Therefore, increasing the efficiency depends on the dimensions, quality and quantity of materials used for the transformer's core and windings and no additional technological innovation is necessary.

No load losses are related to the core project. If silicon steel is used, the core must present larger dimensions, so that the magnetic flow can be reduced. Load losses are related to the windings design so that, when the conductors section is increased the current density is decreased, reducing the load losses.

In general, transformers must be designed according to losses levels established in technical standards. Actually, there is no common definition about high efficiency transformers. Each standard and each country define their own limits taking into account losses, costs or the production of transformers over a certain period.

An economical viability study for a transformer design indicates is the design is feasible or not, considering its costs. This paper presents a study based on data supplied by AES Sul, a Brazilian power distribution company, using the rules imposed by Brazilian Electrical Energy Agency – ANEEL for investment analysis.

Previous studies [1] using the PHOPHET Method indicate that this kind of studies may result in feasible projects with a payback time smaller than 5 years.

II. INVESTIMENT CALCULATION

Using ANEEL rules, the payback for the investment in transformers, for tariffs adjustment, are calculated using five years cycles. For AES Sul, the last cycle for tariff adjustment begun in 2008. According to ANEEL's methodology, the profits with losses reduction by the replacement of equipments are calculated only in the period for the first cycle after the tariffs adjustment and do not depend on the year the investment was made. As a consequence, the capitalization period range from five to zero years. After finishing the first period, the investment is calculated according to the return on assets. The economical analysis presented in this paper includes a period of 10 years.

A. Profits for the First Period of Tariff Adjustment

According to ANEEL regulation, the profits for the first period of tariff adjustment are due to the losses reduction obtained with the replacement of standard transformers by efficient ones.

At first place, it is necessary to consider the investment with the transformers replacement, represented by ΔC_{TR} - Costs Difference between standard and efficient transformers. This difference is remunerated by costs of load and no load losses during the analysis time. Costs for maintenance and installation are not considered in this study.

Costs for no load and load losses, based on the rated losses of transformers, are calculated by expressions in (1) and (2), values using Brazilian currency (R$):

$$C_{WO} = T_{WO} . W_N \tag{1}$$

$$C_{WL} = T_{WL}.W_L \qquad (2)$$

where T_{W0} is the tax for no load losses, R$/kW; T_{WL} is the tax for load losses, R$/kW; W_N is the no load losses, W; and W_L is the load losses, W.

For the taxes:

$$T_{WO} = 8{,}76.C_{EE} \qquad (3)$$

$$T_{WL} = 0{,}365.C_{EE}.FE \qquad (4)$$

where C_{EE} is the Electrical energy cost, R$/kWh; and FE is the Consumed energy factor, Hours/Day.

The FE (Consumed Energy Factor) or TSMP (Time Supplying Maximum Power) defined by (5), indicates the total time, in one day, for which the transformer, working at full load, needs to present the series losses for a daily average duty cycle.

$$FE = \frac{24}{n_d}\sum_{i=1}^{n_d}\left(\frac{kVA_i}{kVA_N}\right)^2 \qquad (5)$$

where n_d is the number of time intervals used to discretize the daily load profile.

The profits obtained with the losses - ΔC_E due to the replacement of standard equipments, for the first cycle, as shown in (6), is constant for all the years that compose the cycle. Considering that the unities are acquired in a year "t" (before the next tariff adjustment - T_{RT}) the profits with the first adjustment comprise the years between "t - T_{RT}". For AES Sul, the T_{RT}, year for the next tariff adjustment, is 2013.

$$\Delta C_{E\rightarrow P} = (C_{WO} + C_{WL})_P - (C_{WO} + C_{WL})_E \qquad (6)$$

A comparison between the profit actual value with the initial investment must can be made if the profits are converted to the present value. So that the net interest (discounting the inflation for the period) – jk (minimum attractive rate), used for investment analysis must be calculated as shown in equation (7).

$$j_k = \frac{1 + WACC_k}{1 + i_k} - 1 \qquad (7)$$

where $WACC_K$ is the Average weighted capital cost for AES Sul during the k^{th} period of tariff adjustment; i_k is the Average inflation rate during the k^{th} period of tariff adjustment.

Figure 1 depicts an example of the profits obtained with losses reduction.

Equation (8) is used to calculate the present value of the profits for the first period of tariff's adjustment.

$$V_{P1^o{}_{P\rightarrow RT}} = \Delta C_E.\left(\frac{(1+j_1)^n - 1}{(1+j_1)^{p+n}.j_1}\right) \qquad (8)$$

where ΔC_E is the profits with losses reduction; j_1 is the Minimum attractive rate for the first period of tariff's adjustment; n is the Time, in years, between the investment date and the next period of tariff's adjustment; and p is the Time, in years, between the investment date and the current date.

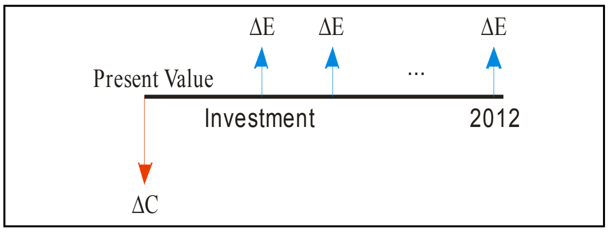

Figure 1. Profits obtained with reduction of transformer's losses.

B. *Profits for the Period Following the Tariff's Adjustment*

According to ANEEL regulation, capital profits during 2nd and 3rd periods of tariff's adjustment are due to the return on assets, considering cumulated inflation and depreciation in the period. The depreciation for a transformer is of 4% per year, considering a 25 years lifetime.

The depreciation for the difference of assets (costs difference between standard and efficient transformers) after the first and following periods for tariff's adjustment – ΔC_{TRDK} is calculated by equation (9).

$$\Delta C_{TR_{D_k}} = \Delta C_{TR}\frac{1 - [n + 5.(k-2)].D}{(1+j_1)^p} \qquad (9)$$

where ΔC_{TR} is the Difference between transformers' costs, R$; D is the Yearly depreciation value, p.u.; k is the Tariff's adjustment period.

The value for the difference between investments in transformers, deprecated, must be corrected using the inflation of previous years, according to equation (10):

$$\Delta C_{TR_{D_k\rightarrow C}} = \Delta C_{TR\,D_k}(1+i)^{n+5.(k-2)}\text{, or,}$$

$$\Delta C_{TR_{D_k\rightarrow C}} = \Delta C_{TR}\frac{(1+i)^{n+5.(k-2)}\{1 - [n + 5.(k-2)].D\}}{(1+j_1)^p} \qquad (10)$$

where *i* is the Average inflation rate during the analysis time.

To calculate the profits due to the return on assets - G_{RAk} in the k^{th} period after the tariff's adjustment, after deprecating and correcting the transformers' costs difference, it is used the WACC for the corresponding period, according to (11).

$$G_{RA_K} = \Delta C_{TR_{D_k\rightarrow C}} WACC_k \qquad (11)$$

To calculate the present value of the second period after the tariff's adjustment, the minimum attractiveness tax of the two cycles, obtained individually with equations (7) and (12), must be used.

$$V_{P2^o{}_{P\rightarrow RT}} = G_{RA_2}.\left(\frac{(1+j_2)^5 - 1}{(1+j_2)^5.j_2}\right).\frac{1}{(1+j_1)^{p+n}} \qquad (12)$$

where G_{RA_2} is the profits due to return on assets in the second cycle; and j_2 is the Minimum attractiveness tax for the company during the second period of tariff's adjustment.

To calculate the present value of the second period after the tariff's adjustment, the minimum attractive tax of the three cycles must be used, obtained with equations (7) and (13).

$$V_{P3^o_{P\rightarrow RT}} = G_{RA_3} \cdot \frac{(1+j_3)^{5-n} - 1}{(1+j_3)^{5-n} \cdot j_3} \cdot \frac{1}{(1+j_2)^5} \cdot \frac{1}{(1+j_1)^{p+n}} \quad (13)$$

where G_{RA_3} is the Profits due to return on assets in the third cycle; and j_3 is the Minimum attractiveness tax for the company during the third period of tariff's adjustment.

The total present value of the profits that ANEEL allows is given by the sum of equations (8), (12) and (13), as indicated by (14).

$$V_P = V_{P1^o_{P\rightarrow RT}} + V_{P2^o_{P\rightarrow RT}} + V_{P3^o_{P\rightarrow RT}} \quad (14)$$

III. Economical Analysis

This economical analysis was developed based on the data supplied by AES Sul, as indicated in Table 1. It is seen that some values come from the respective standards and the transformers depreciation is of 4% per year.

TABLE I. PARAMETERS FOR THE INVESTMENT ECONOMICAL ANALYSIS.

Parameters	Valor	Unity
Costs difference (Efficient-Standard) - ΔC_{TR}	1,000	R$
Energy Costs - C_{EE}	0.115	R$/kWh
No Load Losses (Standard) - W_{0P}	220	W
Load Losses (Standard) - W_{LP}	780	W
No Load Losses (Efficient) - W_{0E} #	190	W
Load Losses (Efficient) - W_{LE} #	650	W
Energy Factor - FE	10	h/day
Minimum Attractiveness Tax 1st Cycle - j_1	10.12	%
Minimum Attractiveness Tax 2nd Cycle - j_2	6.82	%
Minimum Attractiveness Tax 3rd Cycle - j_3	5.41	%
Depreciation of transformer, per year - D	4	%
Inflation - i	4.5	%
WACC – 1st Cycle	15.08	%
WACC – 2nd Cycle	11.63	%
WACC – 3rd Cycle	10.15	%

Nota- # Values assumed by company.

A. *Sensibility Analysis – year 2009*

In order to evaluate the sensibility of the achieved results, some studies were conducted considering variations in FE, difference of costs between efficient and standard transformers and investment date, using 2009 as basis year. Results are shown in Table 2.

It can be seen, in Table 2, that a positive cash flow can be obtained, with a payback time of 10 years, if a high value of FE and a small costs difference is used. It is also possible to see that, for a fixed payback time, decreases in the FE result in reduction in the manufacturing costs.

TABLE II. CASH FLOW FOR YEAR 2009.

$\Delta C_{E\rightarrow P}$ (R$)	FE	Present Value (R$)
1,000.00	**5**	-447.11
	10	-360.85
	15	-274.60
500.00	**5**	-132.66
	10	-46.40
	15	39.85
Costs difference for Present Value = 0 #		
426.22	**10**	**0.00**
563.37	**15**	**0.00**
FE for Present Value = 0 ##		
500.00	12.69	**0.00**
750.00	21.80	**0.00**

Nota- # Costs difference considering FE = 10 and 15 and a 10 years payback and analysis time.
FE difference considering costs difference equal to R$ 500.00 and R$ 750.00 and payback and analysis time of 10 years.

Table 3 shows some aspects related to "the best year to initiate the investments" in efficient transformers. Payback and analysis time were considered constant and equal do 10 years. Present values are referred to year 2009 and the FE is also constant and equal do 12. It means that load losses during a daily cycle match with the operation of transformers using rated power during half a day.

TABLE III. PARAMETERS FOR THE INVESTMENT ECONOMICAL ANALYSIS.

Beginning of investment	$\Delta C_{E\rightarrow P}$ (R$)	Present value (R$)
2009	**1.000,00**	-326,35
2010		-314,80
2011		-309,64
2012		-309,84
2009	**500,00**	-11,90
2010		-49,58
2011		-86,45
2012		-122,38

Considering investment values and energy factor – FE presented, independently of the year for the beginning of investment, the projects are economically feasible as the present values are always negative. Analyzing data in Table 3, there is no straight relation linking the year for the beginning of investment and present value. Anyway, in cases where the investment is considered high, there is a tendency to reduce economical losses (increase in profits) as the time for the beginning of investment is closer to the end of the tariff's adjustment cycle, implying in a larger weight for the return on assets. On the other hand, if the cases with a small investment are considered, there is a tendency to reduce economical losses as the beginning of investment is close to the beginning of tariff's adjustment cycle, implying in a larger weight for the present value of losses costs, assumed as constant.

Figure 2 depicts this tendency for several investment difference values, FE equal to 12 and losses and energy costs according to Table 1. For each economical data and losses set there is a difference between transformers costs that updates the present value to a fixed value. For this example, this costs difference is equal to R$ 900.00. Smaller values indicate that it is more opportune to invest in the beginning of the first cycle of tariff's adjustment. On the other hand, larger values make it more appropriate to invest in the end of the first cycle of adjustment. From the exposed data, it is possible to verify that only differences in transformers costs below R$ 200.00 result in positive present values.

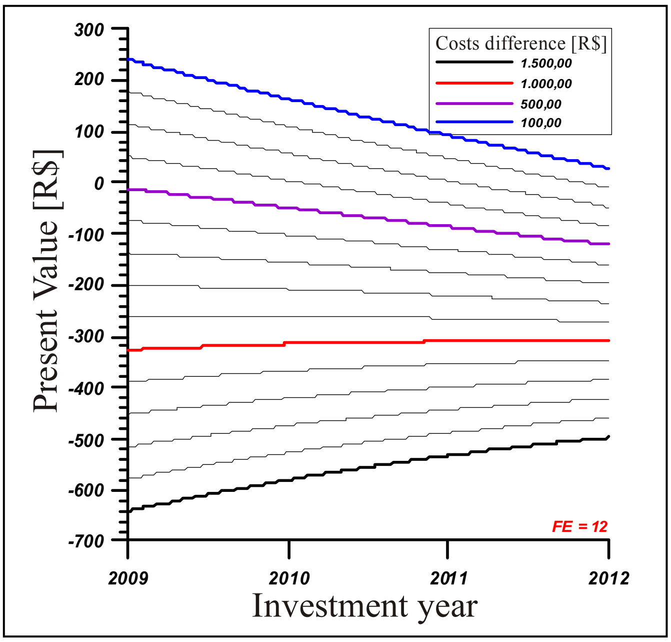

Figure 2. Present Value versus Investment Year – FE = 12.

Figure 3 depicts the influence of the reduction of spent energy factor. According to this figure, reductions in energy factor imply in modifications for the characteristics "Present Value x Investment Year". It is possible to notice a displacement, with no tendency, of the transformers' costs difference bringing the present value to a constant cost. Taking technical limitations of this study into account, for FE = 3, it is possible to notice a tendency to define a cost difference between standard and efficient transformers about R$ 100.00 to R$ 150.00.

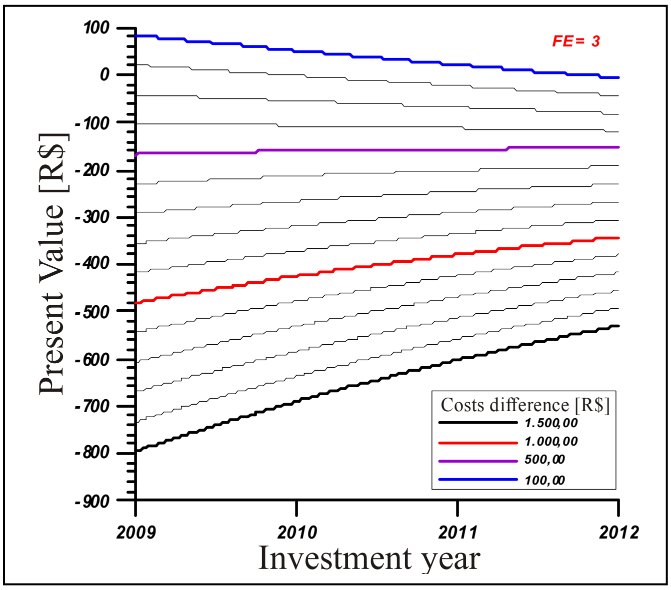

Figure 3. Present value versus Investment Year – FE = 3.

Table 4 presents variations for the investment year and transformers' cost difference so that it is possible to find an energy factor to make the cash flow equal to zero. This is important information, as it is related with the minimum load to make the efficient transformer project become feasible, according to adopted technical and economical limitations.

TABLE IV. FE VALUES FOR A NULL CASH FLOW CONSIDERING A PERIOD OF 10 YEARS.

Beginning of investment	**$\Delta C_{E\rightarrow P}$ (R$)**	**Spent Energy Factor - FE**
2009	**750.00**	21.80
2010		- #
2011		- #
2012		- #
2009	**500.00**	12.69
2010		16.03
2011		23.08
2012		- #
2009	**250.00**	3.58
2010		5.25
2011		8.77
2012		19.72

Note- # Values above 24 hours.

B. Present Value of Losses Costs

Equation (15) represents the usual model to calculate de benefits associated to the use of efficient transformers, based in the conception of present value of losses costs.

$$V_{P1^o} = \frac{\Delta C_E}{(1+j_1)^{p+n}} \cdot \left(\frac{(1+j_1)^n - 1}{j_1} \right)$$

$$V_{P2^o} = \frac{\Delta C_E}{(1+j_1)^{p+n}} \cdot \left(\frac{(1+j_2)^5 - 1}{(1+j_2)^5 . j_2} \right)$$

$$V_{P3^{o}} = \frac{\Delta C_E}{(1+j_1)^{p+n}} \cdot \frac{(1+j_3)^{5-n} - 1}{(1+j_3)^{5-n} . j_3} \cdot \frac{1}{(1+j_2)^5}$$

$$V_P = V_{P1^{o}} + V_{P2^{o}} + V_{P3^{o}} \qquad (15)$$

where J_k is the Minimum attractiveness rate during the k^{th} period of tariff's adjustment.

Figure 4 shows the influence of energy factor in this procedure.

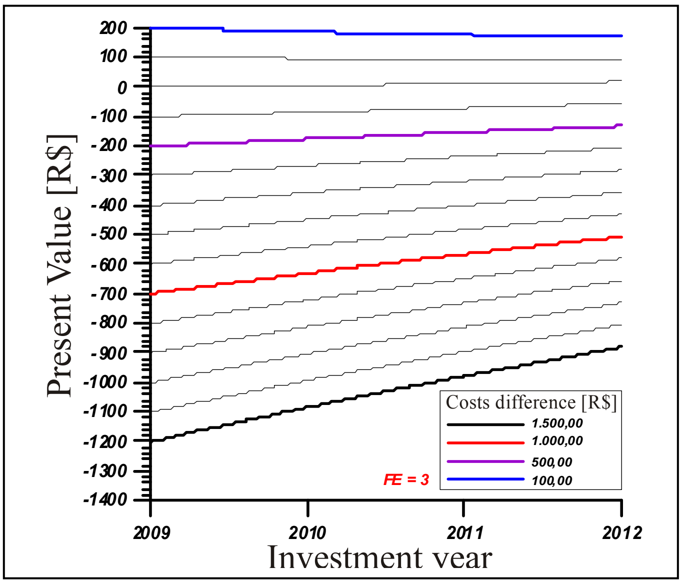

Figure 4. Present Value versus Investment Year – FE = 3 – Losses Costs.

Comparing information from figures 3 and 4, it is possible to conclude that for high differences in costs, ANEEL's capitalization method presents outstanding advantages. In these cases, as an example, for FE = 3, basis year and investment year 2009, costs differences equal to R$ 1,200.00, and an analysis time of 10 years, ANEEL's method presents a present value of R$ - 607.39, against R$ - 900.59. On the other hand, considering a cost difference of only R$ 200.00, ANEEL's method presents a present value of R$ 21.51 against R$ 99.41. For high investment costs (see figures 2 and 3), the assets amortization is predominant. In cases where the investment costs are small, the present value of losses costs is predominant for the return on assets.

IV. Conclusion

The results presented in this paper reproduce distinctive conditions of winding and core losses in transformers obtained from manufacturers. A reduction of these losses was considered to calculate hypothetical costs to be paid, as though as its reflections on the investment payback. In the used examples, a difference for the core losses of about 30 W (reduction of 13.6%) and winding losses of 130 W (reduction of 16.7%) presents a difference for the investment costs in the range of R$ 100.00 to R$ 1,500.00. Some technical aspects were not taken into account, as the hypothesis that larger costs differences must result in smaller losses.

As noticed in table 2, considering the limits indicated above, large differences for the investment costs request large spent energy factors, above 12 hours a day in full load. On the other hand, small energy factors, around 3 hours a day in full load, implies in the necessity of smaller costs differences, around R$ 200.00 (Figure 4).

It is not possible to indicate directly which the best methodology for investment payback is. It seems that, for each pattern of losses reduction, there is an investment that results approximately in the same present value, considering the same period of analysis. This value depicts boundaries between the regions where the return on assets or the present value of losses costs are predominant. Consequently, considering the possibility of small investments, considering energy factors below 5 hours per day at full load, it is possible to deal with maximum investment differences in the order of R$ 400.00.

Finally, the usage of efficient transformers needs to consider the models for investment payback, losses profits and assets amortization, as proposed by ANEEL, so that it can become economically feasible. The variables that take part in this process present strong correlations and each case must be studied in particular. Calculation procedures must take into account load measurements, as indicated by the consumed energy factor (FE), which is related to the transformer thermal model and its time constants. To make the whole process reasonable, i.e., smaller costs to result in larger profits with losses reduction, the model for investment payback according to present value of losses costs must be considered. After the attainment of the most appropriate losses configuration and presentation of the final transformer project to manufacturers, the values for losses and costs must be reassessed according to ANEEL's proposal for return on assets.

References

[1] Picanço, Alessandra, F. (2006). *Avaliação econômica de transformadores de distribuição com base no carregamento e eficiência energética*. Master's Thesis. Universidade Federal de Itajubá - UNIFEI.

[2] Cardoso, Bruno, P. (2005) *Eficiência de transformadores de distribuição*. Master's Thesis. Universidade Federal de Itajubá - UNIFEI.

[3] Leonardo Energy (2004). *Global Energy Savings Potencial from High Efficiency Distribution Transformers*. European Copper Institute.

[4] NBR 5440 (1999): *Transformadores para Redes Aéreas de Distribuição. Características Elétricas e Mecânicas – Padronização*. ABNT.

[5] Picanço, A.F., de Salles, C., Martinez, M.L.B. de Oliveira, H.R.P.M. e de Jesus, N.C. (2006). *Avaliação Econômica de Transformadores de Distribuição de Alta Eficiência*. Simpósio Brasileiro de Sistemas Elétricos – SBSE.