



Energy Efficient Transformer Selection Implementing Life Cycle Costs and Environmental Externalities

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Abstract—The goal of this article is to encourage electric utilities and potential investors to purchase and install high-efficiency distribution transformers where they are cost-effective. This paper proposes a methodology that implements the complex economic analyses needed to accurately determine the emission-reduction potential of high-efficiency distribution transformers. This methodology properly introduces the environmental cost into the life cycle cost (total owning cost) calculations implemented by electric utilities, and its results are compared to the classical total owning cost (without environmental cost), indicating the importance of environmental aspects of transformer economy evaluation, which may affect significantly the currently-employed transformer purchasing policy in the near future. Moreover, a sensitivity analysis of the various factors involved in the transformer life cycle cost is implemented, factors such as the transformer loading profile, the specific characteristics of the network where the transformer is installed and the uncertainty of the environmental cost impact on the final energy cost.

Keywords—component; distribution transformers; Total Owning Cost; environmental externalities; sensitivity analysis;

I. INTRODUCTION

The distribution transformer is the most important single piece of electrical equipment installed in electrical distribution networks with a large impact on the network's overall cost, efficiency and reliability. Selection and acquisition of distribution transformers which are optimized for a particular distribution network, the utility's investment strategy, the network's maintenance policies and local service and loading conditions will provide definite benefits (improved financial

and technical performance) for both utilities and their customers [1][2].

Many electrical distribution utilities claim that they purchase distribution transformers using some type of loss evaluation procedure. Over the past 25 years, these purchasing practices have been established, as the utilities have apparently become aware of the range and the value of distribution transformer losses [3]. On the other hand, very few industrial and commercial customers include evaluation of distribution transformer losses in the purchasing process [4][5]. References [6][7] proposed an evaluation technique from the industrial and commercial customers' point of view. Moreover, the expected large increases in energy demand and the need to undertake effective measures to protect the environment could be partially solved by improvements in energy efficiency of distribution transformers. Optimized distribution transformers (cost-effective and highly efficient designs) would provide numerous global benefits to the wider public as well as local benefits to electrical distribution companies, their customers and other users of distribution transformers [8][9][10].

The origin of this work lies in the fact that nowadays there is an increased interest in the protection of the environment from greenhouse gas emissions. In addition, green certificates markets are in operation in various electricity markets all over the world. For an electric utility (Distribution Company) that has numerous distribution transformers in its network, there is an opportunity to install high efficient distribution transformers that have less total energy losses than less efficient transformers, so they pollute the environment less. Bearing all these into mind, the goal of this work is to redefine the Total Owning Cost (*TOC*) method to properly incorporate all the aspects of the transformer life cycle, evaluating not only the

transformer losses but also the environmental externalities. Moreover, the paper deals with current economic evaluation practices adopted by electrical utilities and industrial/commercial customers in selecting distribution transformers. To compare and assess these practices, proper analysis tools are proposed, taking into account environmental economics into the *TOC* equation. Further special characteristics embedded in the proposed analysis reinforce its robustness and novelty, compared to other approaches proposed in the relevant literature. Additional factors which incorporate the reliability cost associated with the loss of load probability due to transformer failures are also included into the *TOC* formula. Section II clearly illustrates the proposed method for the calculation of the environmental cost as well as the *TOC* with and without the environmental cost. Section III shows the different way that the economic evaluation is carried out for commercial/industrial transformer users. Section IV is dedicated to results and discussion. Section V presents sensitivity analysis results when varying various parameters involved in the *TOC* formula. Section VI concludes the paper.

II. ECONOMIC EVALUATION METHOD FOR ELECTRIC UTILITIES

A. Total Owning Cost technique

The most widely used technique for the evaluation of distribution transformers is the *TOC* method [11] that is based on the following formula:

$$TOC = BP + A \cdot NLL + B \cdot LL \quad (1)$$

where *TOC* indicates the Total Owning Cost in €, *BP* refers to the purchasing price of the distribution transformer in €, *A* indicates the equivalent no-load loss cost rate in €/W, *NLL* refers to no-load loss in W, *B* indicates the equivalent load loss cost rate in €/W, and *LL* refers to load loss in W. The optimum transformer is the one with the minimum *TOC*. The *A* and *B* coefficients are computed as follows:

$$A = \frac{LIC + EL \cdot AF \cdot HPY}{CRF} \quad (2)$$

$$B = \frac{LIC + EL \cdot LF \cdot HPY}{CRF} \quad (3)$$

where *LIC* indicates the levelized annual generation and transmission system investment cost in €/W, *EL* refers to the cost of electricity in €/kWh, *AF* represents the transformer availability factor (i.e. the proportion of time that it is predicted to be energized, which may be less than unity due to failures), *HPY* indicates the hours of operation per year (typically 8760 hours), *CRF* refers to the capital recovery factor, and *LF* refers to the loss factor that derives from the load factor l_f (i.e. the mean transformer loading over its lifetime, represented as an equivalent percentage of its nominal power) as follows:

$$LF = 0.15 \cdot l_f + 0.85 \cdot l_f^2 \quad (4)$$

The equation yielding the *CRF* is as follows:

$$CRF = \frac{i \cdot (1+i)^{BL}}{(1+i)^{BL} - 1} \quad (5)$$

where *i* refers to discount rate, and *BL* refers to the number of years of the transformer lifetime.

B. Methodology for the calculation of the proposed environmental cost coefficient

Pollution resulting from electricity generation can be broadly categorized as having local, regional, and global environmental consequences. Regional and global impacts are caused primarily by the emission of atmospheric pollutants that have longer residence times, causing dispersal over large areas. Most important among these gases is CO₂, which is a greenhouse gas and can contribute to global warming [12].

Each kWh has an external cost, i.e. the environmental and health costs to society that are not fully reflected in the price of electricity. These externalities originate in the various types of emissions resulting from the combustion of fossil fuel. In this Section, a methodology for calculating greenhouse gas emissions (carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O)) is applied [13] in order to determine the equivalent emissions corresponding to each MWh of produced energy and yield their environmental cost. These pollutants have become a major concern for most European countries. Therefore, the main goal is to measure these emissions and to illustrate them by an environmental cost coefficient, i.e. a penalty value that will be added to the electricity cost. It may be noted that, although the above environmental costs depend on the generation technology and are not directly linked to distribution transformers, transformer owners should assume these costs as transformer losses correspond to a surplus of energy that must be produced by the existing generation mix of the power system where they are connected. According to the type of fuel (i.e. coal, diesel, natural gas, wind etc), gas emissions are converted into equivalent CO₂ emissions (measured in t_{CO_2} , i.e. tonnes of equivalent CO₂ emissions) in terms of their global warming potential. In order to estimate the emission factor of each fuel type, the following equation is used:

$$GHG_{Fuel_i} = (G_{CO_2} + G_{CH_4} \cdot 21 + G_{N_2O} \cdot 310) \cdot \frac{0.0036}{n_{fuel_i} \cdot (1 - J_{T-D})} \quad (6)$$

where GHG_{Fuel_i} is the emission factor of each fuel type in t_{CO_2} / MWh , G_{CO_2} is the CO₂ emission factor in kg/GJ, G_{CH_4} is the CH₄ emission factor in kg/GJ, G_{N_2O} is the N₂O emission factor in kg/GJ, J_{T-D} represents the transmission and distribution losses in %, and n_{fuel_i} is the fuel conversion efficiency in %. The factor 0.0036 in equation (6) is used so as to convert kg/GJ into t/MWh. It can be seen from equation (6) that CH₄ and N₂O emissions are converted into equivalent CO₂ emissions by multiplying their emission factors with 21 and 310 respectively (these values are provided by the Intergovernmental Panel on Climate Change). CH₄ is thus 21 times more powerful a greenhouse gas than CO₂, and N₂O is 310 times more powerful than CO₂. Taking into consideration

equation (6) and the participation percentage of each fuel type for the electric utility system of Table I, the equivalent tonnes of CO₂ emissions per year is $0.8936 \text{ } t_{CO_2} / MWh (C_{eq})$ for this specific electric utility. The typical range of CO₂ emissions cost factor in the considered electric utility is between 8 and 20 €/t_{CO₂}. Assuming a moderate value of 10 € per t_{CO₂}, the resulting environmental cost coefficient, C , is equal to 8.936 €/MWh.

TABLE I. CALCULATION EXAMPLE OF THE EQUIVALENT CO₂ EMISSION FACTOR C_{eq} ACCORDING TO THE PARTICIPATION OF EACH FUEL TYPE TO THE TOTAL POWER PRODUCTION OF AN ELECTRIC UTILITY SYSTEM.

Fuel type	Coal	Diesel	Hydro	Natural gas	Wind
Fuel participation (%)	69.77	7.6	7.6	15	0.03
G_{CO_2} (kg/GJ)	94.6	74.1	0.0	56.1	0.0
G_{CH_4} (kg/GJ)	0.002	0.002	0.0	0.003	0.0
G_{N_2O} (kg/GJ)	0.003	0.002	0.0	0.001	0.0
n_{fuel} (%)	35	30	100	45	100
J_{T-D} (%)	8	8	8	8	8
GHG_{Fuel} (t _{CO₂} / MWh)	1.069	0.975	0.0	0.491	0.0
$C_{eq} = \frac{69.77}{100} \cdot 1.069 + \frac{7.6}{100} \cdot 0.975 + \frac{15}{100} \cdot 0.491 = 0.8936 \frac{t_{CO_2}}{MWh}$					

C. Proposed TOC methodology including environmental cost

In this Section, a methodology for the calculation of the environmental cost is proposed. Afterwards, the environmental cost is incorporated into the TOC formula. The main aspect of this methodology is to quantify the penalties associated to emissions due to transformer losses, overcoming the difficulty to define the exact contribution of each transformer to these emissions. For that purpose, a reference transformer is selected, i.e. a transformer with reference no-load losses NLL_r and reference load losses LL_r . For any given transformer that has total energy losses less than the total energy losses of the reference transformer, there is no environmental penalty, otherwise, an environmental cost is calculated. The key of computing the aforementioned environmental cost is to find the energy losses that stem from the difference between the total energy losses of the given transformer and the total energy losses of the reference transformer.

Initially, the annual energy losses corresponding to the no-load losses of each given transformer are calculated (E_{NLL_o} in kWh/yr) by multiplying the given no-load losses (NLL_o in kW) by the availability factor (AF) and the total number of hours per year, based on the following equation:

$$E_{NLL_o} = NLL_o \cdot AF \cdot HPY \quad (7)$$

Similarly, the annual energy losses corresponding to the load losses are calculated (E_{LL_o} in kWh/yr) by multiplying the given load losses (LL_o in kW) of each given transformer by the load factor (l_f) and the total number of hours per year:

$$E_{LL_o} = LL_o \cdot l_f^2 \cdot HPY \quad (8)$$

The total annual energy losses (E_{Lo} in kWh/yr) of the given transformer are reached by adding the above-mentioned energy losses, using the equation:

$$E_{Lo} = E_{NLL_o} + E_{LL_o} \quad (9)$$

The same procedure is followed so as to compute the total annual energy losses of the reference transformer (E_{Lr} in kWh/yr), as follows:

$$E_{NLL_r} = NLL_r \cdot AF \cdot HPY \quad (10)$$

$$E_{LL_r} = LL_r \cdot l_f^2 \cdot HPY \quad (11)$$

$$E_{Lr} = E_{NLL_r} + E_{LL_r} \quad (12)$$

where E_{NLL_r} and E_{LL_r} are the annual energy losses due to no-load losses and load losses, respectively, for the reference transformer.

The next step consists of the comparison of the total annual energy losses of each offered transformer with the total annual energy losses of the reference transformer. In particular, if $E_{Lr} < E_{Lo}$, then the surplus of energy losses of each offered transformer is computed, and by multiplying this surplus with the environmental cost coefficient C (calculated in Section II.B), the annual environmental cost of each offered transformer is found. Otherwise, if $E_{Lr} \geq E_{Lo}$, then the corresponding annual environmental cost is considered negative, providing a further incentive for transformer owners to invest to low loss designs. Finally, in order to find the total environmental cost (C_e in €) during the transformer lifespan, the annual environmental cost is multiplied by the transformer book-life (BL), as follows:

$$C_e = \begin{cases} -|E_{Lo} - E_{Lr}| \cdot C \cdot BL, & \text{if } E_{Lr} \geq E_{Lo} \\ |E_{Lo} - E_{Lr}| \cdot C \cdot BL, & \text{if } E_{Lr} < E_{Lo} \end{cases} \quad (13)$$

For the sake of simplicity in the above calculations, C has been considered constant throughout the transformer lifetime.

The total environmental cost is incorporated into the TOC formula of equation (1), resulting in the following equation:

$$TOC_e = BP + A \cdot NLL + B \cdot LL + C_e \quad (14)$$

1) *Example:* It is given that $AF=1$, $l_f=0.5$, $NLL_r=300$ W, $NLL_o=431$ W, $LL_r=2000$ W, $LL_o=2284$ W, $C=8.936$ €/MWh. Using equations (7) to (12) we obtain $E_{NLL_o}=3775.56$ kWh/yr, $E_{LL_o}=5001.96$ kWh/yr, $E_{Lo}=8777.52$ kWh/yr, $E_{NLL_r}=2628$ kWh/yr, $E_{LL_r}=4380$ kWh/yr, $E_{Lr}=7008$ kWh/yr. Next, equation (13) gives that the total environmental cost for the examined distribution transformer during its lifespan is $C_e=395.31$ €.

III. ECONOMIC EVALUATION METHOD FOR INDUSTRIAL AND COMMERCIAL USERS

Commercial and industrial transformer purchasers can use a more simplified but effective approach for evaluating transformer losses [14]. This involves the same formula used by electric utilities, (1), but a different calculation procedure for the coefficients A and B , without taking into account the total environmental cost. The equivalent first cost of no-load losses for any particular transformer can be calculated as follows:

$$A = PW \cdot EL \cdot HPY \quad (15)$$

where PW indicates the present worth of an inflation series for the given transformer life and discount rate, EL indicates the cost of electricity in €/kWh, and HPY indicates the hours of operation per year. The PW is calculated as follows:

$$PW = \frac{1}{(1+i)^{BL}} \quad (16)$$

where i refers to discount rate, and BL refers to the number of years of the transformer lifetime. The equivalent first cost of load losses (factor B) for any particular transformer can be calculated as follows:

$$B = A \cdot P^2 \cdot T \quad (17)$$

where P refers to per unit load (equivalent to the load factor l_j), and T refers to a load loss temperature correction factor to correct specified temperatures, e.g. for liquid-filled transformers the factor T is 1 since efficiency is stated at 55 °C.

In the case of commercial and industrial transformer users, the environmental cost introduction is meaningless since the environmental impact is not included in the electricity price that they have to pay due to the transformer losses. Therefore, in contrast to the electric utilities, which must take into account possible economic burdens due to the environmental impact of their generation units emissions for the economic evaluation of transformer losses, commercial and industrial users may disregard this cost.

IV. RESULTS AND DISCUSSION

A. Transformer models under consideration

To illustrate the impact of the specific operational transformer characteristics on the resulting TOC values, a three-phase oil-immersed distribution transformer, 50 Hz, 160 kVA, is considered, surveying its energy-efficient performance according to the nine different models of Table II (model 1 to model 9 is symbolized as D_1 to D_9). As reference transformer, the transformer with loss category CC' according to CENELEC [15] is selected, which means that $NLL_r=300W$ and $LL_r=2000W$.

B. TOC results for an electric utility

For the case study of the electric utility, it is assumed that $AF=1$, $l_j=0.5$, $i=8\%$, $HPY=8760$ h, $BL=25$ years, $EL=0.054$ €/kWh, $CRF=0.0937$, $LIC=147.54$ €/kW, $C=8.936$ €/MWh. Using equations (2) and (3), it is found that $A=6.63$ €/W and

$B=3.1$ €/W. Then, Table III presents the TOC results for the 9 different models, with and without the introduction of the environmental cost.

TABLE II. NINE DIFFERENT TRANSFORMER MODELS FOR THE 160 kVA DISTRIBUTION TRANSFORMER.

Transformer model	Bid price (€)	No-load losses (W)	Load losses (W)
D ₁	6630	486	2674
D ₂	6750	403	2674
D ₃	7012	344	2697
D ₄	6270	481	3522
D ₅	6390	399	3522
D ₆	6512	345	3475
D ₇	6872	527	2280
D ₈	7030	431	2284
D ₉	7478	342	2247

TABLE III. ELECTRIC UTILITY-BASED TOC RESULTS WITH AND WITHOUT ENVIRONMENTAL COST.

Transformer model	TOC without environmental cost (€)	Total environmental cost (€)	TOC_e with environmental cost (€)	TOC variation (%)
D ₁	18112	693	18806	3.83
D ₂	17682	531	18213	3.00
D ₃	17624	427	18051	2.42
D ₄	20339	1098	21438	5.40
D ₅	19916	938	20854	4.71
D ₆	19535	809	20344	4.14
D ₇	17408	581	17989	3.34
D ₈	16942	395	17338	2.33
D ₉	16686	203	16889	1.22

As it can be observed, although D_9 has the highest bid price (Table II) and it seems the worst investment, in long term, Table III clearly illustrates that D_9 is the most profitable investment, having the lowest TOC value equal to 16686 €. Moreover, the incorporation of the environmental cost results in an increase of the TOC value of up to 5.4%, which is quite considerable in case of investments for purchasing numerous distribution transformers in the electric utility sector. As a general rule, transformers with lower losses, like D_9 , cost more. However, despite its high purchasing cost, this type of transformer is the best investment in the long term, since it has the lowest TOC and TOC_e .

C. TOC results for an industrial / commercial user

For the case study of a commercial / industrial user, it is assumed that $AF=1$, $P=0.5$, $i=8\%$, $BL=25$ years, $T=1$ and $EL=0.07$ €/kWh. Using equations (15), (17), and (16), it is found that $A=7.069$ €/W and $B=1.767$ €/W, and $PW=11.53$. Table IV presents the TOC results for the nine different

models. As mentioned in Section III, in this case, the environmental cost is not taken into account. Once again, the D_9 is proven to be the most energy efficient one, despite its high bid price. Table IV also provides the payback period (in years) of the investment, which is calculated according to the following equation:

$$\text{Payback Period}_{D_i} = \frac{BP_{D_i} - BP_{D_9}}{EL \cdot (E_{Lo}^{D_i} - E_{Lo}^{D_9})} \quad (18)$$

The denominator of equation (18) corresponds to the difference in the cost of energy losses between the considered model and the best model (D_9), while the numerator corresponds to the difference in their purchasing cost.

TABLE IV. TOC RESULTS FOR THE COMMERCIAL / INDUSTRIAL USER.

Transformer model	TOC without Environmental cost (€)	Payback Period (years)
D ₁	14792	5.52
D ₂	14325	7.08
D ₃	14210	6.64
D ₄	15895	4.30
D ₅	15435	4.72
D ₆	15093	5.08
D ₇	14627	5.11
D ₈	14114	7.44
D ₉	13867	-

D. Transformer Efficiency

An alternative approach to the evaluation of a transformer based on its no-load and load losses is to measure its energy efficiency at a specific load or in a given load spectrum. The general expression for efficiency is [14]:

$$E = \frac{100 \cdot P \cdot kVA \cdot 1000}{P \cdot kVA \cdot 1000 + NLL + LL \cdot P^2 \cdot T} \quad (19)$$

where kVA refers to the rated power (in kVA). We have $T=1$ since efficiency is stated at 55 °C. Fig. 1 illustrates the transformer efficiency for the nine different models in a specific load spectrum, i.e. from 10% to 130% loading, using loading step equal to 10%, corresponding to P spectrum [0.1 1.3]. As shown in Fig. 1, D_9 seems the most efficient transformer in comparison with the other models, while D_4 and D_5 seem the least efficient transformers.

V. SENSITIVITY ANALYSIS

In the TOC_e economic analysis, it is helpful to determine how sensitive the TOC_e is to several factors of concern so that proper consideration may be given to them in the decision process. The factors that are selected are: the load factor (l_f), the discount rate (i), the cost of electricity (EL), the levelized annual generation and transmission system investment cost (LIC), the environmental cost coefficient (C), the availability

factor (AF), and the number of years of the transformer lifetime (BL). These components consist the most versatile factors in the equations yielding the A , B and C_e factors of the TOC_e calculation (from the point of view of the electric utility, which is faced with an increased uncertainty in the transformer economic evaluation process, especially during the incorporation of environmental externalities). Before we start vary the above-mentioned components, we should develop a base case of TOC_e , i.e. TOC_e equal to 16889 € (Table III - D_9), which corresponds to $l_f=0.5$, $i=8\%$, $EL=0.054$ €/kWh, $LIC=147.54$ €/kW, and $C=8.936$ €/MWh. Table V and Fig. 2 present the sensitivity parameter analysis results, based on various components values. For example, by changing +10% the component LIC , the TOC_e changes +2.42% in comparison with the TOC_e of the base case. It is noted that in this table, only negative variations of AF are considered, since the availability factor can only be less than unity (the loss of load probability due to transformer failures can result in fewer hours of transformer operation than the total hours per year).

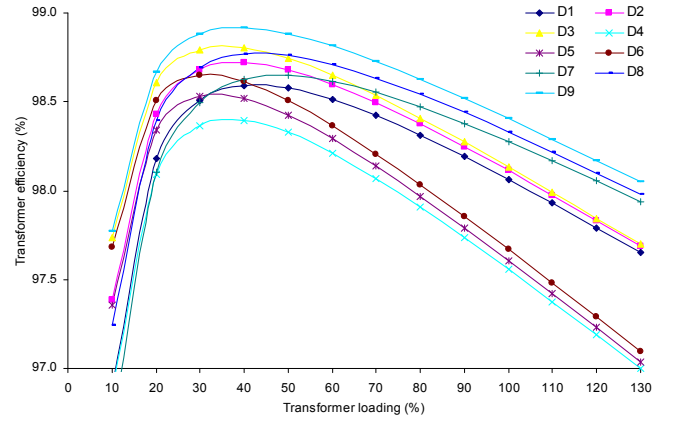


Figure 1. Transformer efficiency for each given model of transformer.

TABLE V. SENSITIVITY PARAMETER ANALYSIS. TOC VARIATION BASED ON VARYING COMPONENTS VALUES

Components variation (%)	TOC _e variation (%) when varying component l_f to BL						
	l_f	i	EL	LIC	C	AF	BL
-20	-6.44	8.36	-6.07	-4.83	-0.24	-0.02	-4.61
-15	-4.93	6.09	-4.55	-3.62	-0.18	-0.05	-3.30
-10	-3.36	3.95	-3.04	-2.41	-0.12	-0.07	-2.10
-5	-1.71	1.92	-1.52	-1.2	-0.06	-0.09	-1.00
5	1.79	-1.81	1.52	1.21	0.06	-	0.92
10	3.65	-3.53	3.04	2.42	0.12	-	1.75
15	5.57	-5.15	4.56	3.62	0.18	-	2.52
20	7.57	-6.69	6.08	4.83	0.24	-	3.22

Fig. 2 shows the sensitivity of the TOC_e to percent deviation changes in each component's best estimate. The other components are assumed to remain at their best estimate values. The relative degree of sensitivity of the TOC_e to each

component is indicated by the slope of the curves (the steeper the slope of a curve, the more sensitive the TOC_e is to the component) [16]. Based on this, as can be observed from Fig. 2, the TOC_e is for all practical purposes insensitive to environmental cost coefficient (C) and availability factor (AF), but quite sensitive to changes in load factor (I_f), the discount rate (i), the cost of electricity (EL), the number of years of the transformer lifetime (BL), and the cost of installing transmission systems (LIC). Finally, Table VI presents in brief the sensitivity results.

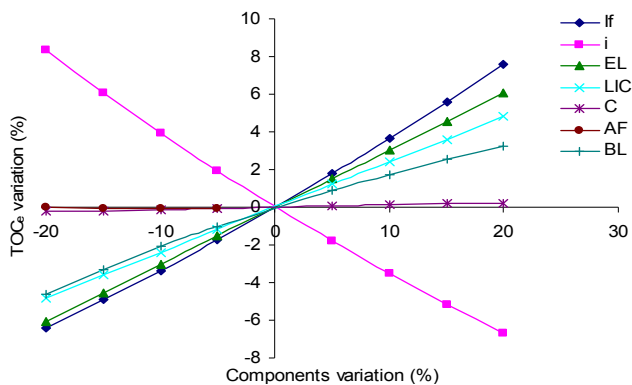


Figure 2. Sensitivity graph of seven components.

The aforementioned non-probabilistic methodology, readily available, provides information about the potential impact of uncertainty in selected factor estimates.

TABLE VI. SENSITIVITY PARAMETER ANALYSIS.

Input parameters	Input variation (%)	Minimum TOC_e variation (%)	Maximum TOC_e variation (%)
I_f	± 20	-6.44	7.57
i	± 20	-6.69	8.36
EL	± 20	-6.07	6.08
LIC	± 20	-4.83	4.83
C	± 20	-0.24	0.24
AF	-20 to -5	-0.02	-0.09
BL	± 20	-4.61	3.22

VI. CONCLUSIONS

In the present paper, a TOC economic analysis with built-in environmental cost was proposed. The differences in assessing a distribution transformer operated by an industrial/commercial owner and a distribution transformer operated by an electric utility were described. The introduction of environmental costs has resulted in a maximum increase of the TOC_e value of 5.4%, which should be considered by electric utilities, as they are already subject to rigorous European and international directives imposed for the global reduction of gas emissions due to electric power production by conventional generating units. Economic assessment adopted by commercial and industrial transformer users yields considerably different TOC

values in comparison with those of electric utilities, partly because of using different formulas for calculating the A and B coefficients, but mainly because of using the electricity price instead of the energy cost and to a lesser extent due to the absence of environmental costs. Alternative calculations of the evaluated transformers efficiency reinforced the results provided by the TOC_e method. Finally, sensitivity analysis was conducted so as to investigate the impact of the TOC_e components variation in the final purchasing decision. According to this analysis, the TOC_e variation is quite sensitive to changes in the transformer loading factor and the discount rate, while changes in the cost of energy, the transmission and generation system investment cost and the transformer lifetime duration affect it less. On the other hand, TOC_e remains practically stable during variations in the availability factor and the environmental cost factor.

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