Utility-based economic assessment of distribution transformers considering specific load characteristics and environmental factors

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Due to the large number of installed distribution transformers in power systems, there is a considerable potential for energy savings through investment in low loss transformers. This paper investigates different methodologies for the economic assessment of distribution transformers taking into account the detailed load characteristics that affect their life cycle cost. The analysis is conducted from the electric utility point of view, using the total owning cost formula and introducing built-in environmental factors.

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1. Introduction

European Commission strategies aim at influencing the scientific and engineering communities, policy makers and key market actors to create, encourage, acquire and apply cleaner, more efficient and more sustainable energy solutions for their own benefit and that of our wider society [1]. The use of energy-efficient technologies is becoming more important in our society because energy resources are expensive and scarce. In the context of the recent global efforts for increases in energy savings, the application of the transformer Total Owning Cost (*TOC*) is common place in the electric utilities and large customers [2]. The *TOC* technique is the most widely used transformer evaluation method for determining the cost-effectiveness of energy-efficient transformers, providing a balance between cost of purchase and cost of energy losses.

Transformer energy losses throughout their life cycle increase significantly their operational costs, resulting to *TOC* values much higher than their purchase price. For the above reason, the decision for what transformer to purchase should not be based only on its purchase price. In general, transformers with the lowest purchase price are also the ones with the highest *TOC*. Therefore, in order to choose the most economical transformer in long term, the *TOC* value during the lifespan of the transformer should be taken into account [1][3][4]. Furthermore, the external environmental costs should be taken into consideration as well, i.e., the costs that are associated with various types of emissions resulting from the combustion of fossil fuels so as to compensate for transformer losses [5].

The *TOC* evaluation method has been developed as a handy tool to reflect the unique financial environment faced by each electric utility (or industrial user) when purchasing distribution transformers. According to this method, the variability of the cost of electric energy, capacity and financing costs is expressed through two evaluation factors developed according to IEEE standard [6] and NEMA standard [7], called *A* and *B* factors, corresponding to the unit cost of no-load and load losses, respectively. The method to define these two factors varies according to the role of the transformer purchaser in the energy market (two major categories can be considered: electric utilities and industrial users) and the depth of the analysis (depending on the accuracy of the representation of the transformer loading characteristics). The industrial customers' distribution transformer cost evaluation model is analysed in [8][9][10], while the simplified implementation of the IEEE standard on the electric utility sector is extensively analysed in [2]. Since the load losses are directly linked to the type of the considered consumer type and the specific details of the network at the transformer installation point, a number of versatile factors should be incorporated in the *TOC* analysis. Such an analysis is performed in depth in [11] and [12], prior to the development of the IEEE standard C57.120 [6], where the authors propose several analytical formulas for the economic evaluation of distribution transformers, incorporating details of the consumer type that they serve and the system where they are connected. Recently, the impact of transformer environmental externalities and the contribution of losses to the greenhouse gas emissions generated by the global power generation mix has been addressed [1][4]. Furthermore, Frau et al. [13] examine the case for using emissions credits to affect life-cycle costs of efficient distribution transformers, studying two 400 kVA rated power distribution transformers with loss category AA′ (as a nonefficient transformer) and loss category CC′ (as an efficient transformer), according to CENELEC (Harmonization Document HD428: 1 S1:1992). As a result, ways to promote the policy to encourage the use of efficient transformers in the Spanish market are proposed, such as introducing incentives to private users and electric utilities, changing Spanish losses regulation, and allowing utilities to participate in the CO_2 emissions market. However, a methodology to quantify the impact of environmental externalities on transformer *TOC* has not yet been developed.

In the present paper, the detailed implementation of the different *TOC* formulas proposed by IEEE standard C57.120 in conjunction to the specific consumer and system characteristics is presented. The goal of this work is to redefine the *TOC* methodology in order to properly incorporate all of the aspects of the transformer life cycle, evaluating not only the transformer losses but also the environmental externalities. For this purpose, the introduction of an appropriate environmental cost factor in the *TOC* formula is proposed. The proposed method is applied to the economic evaluation of three-phase distribution transformers, considering different transformer offers from different manufacturers, and the results of the proposed method are compared to the results of the IEEE standard method [6] indicating the importance of the introduction of built-in environmental factors.

The paper is organized as follows: Section 2 presents the *TOC* technique based on the IEEE Standard C57.120. Section 3 describes the proposed transformer economic evaluation method that introduces an appropriate environmental cost factor in the *TOC* formula of the IEEE Standard C57.120. The transformer economic evaluation results of IEEE Standard C57.120 are compared to the results of the proposed economic evaluation method in Section 4. Sensitivity analysis of the results of Section 4 with respect to various factors influencing the transformer *TOC* are presented in Section 5. Section 6 concludes the paper.

2. Total Owning Cost

The most widely used technique for the evaluation of distribution transformers is the *TOC* method [2] that is based on the following formula:

$$TOC = BP + A \cdot NLL + B \cdot LL \tag{1}$$

where *TOC* indicates the Total Owning Cost in U.S. \$, *BP* refers to the purchasing price of the distribution transformer in U.S. \$, *A* indicates the equivalent no-load loss cost rate in U.S. \$/W, *NLL* refers to no-load loss in W, *B* indicates the equivalent load loss cost rate in U.S. \$/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, [6]:

$$A = \frac{LIC + LECN}{ET \cdot CRF \cdot IF} \tag{2}$$

$$B = \frac{LIC \cdot PRF^2 \cdot PUL^2 + LECL \cdot TLF^2}{ET \cdot CRF \cdot IF} \tag{3}$$

where:

LIC: the levelized annual generation and transmission system investment cost in U.S. \$/kW;
LECN: the levelized annual energy and operating cost of no-load losses in U.S. \$/kW;
ET: the efficiency of transmission;
CRF: the capital recovery factor;
IF: the increase factor (it represents the total money that the user must pay to acquire the transformer, including the purchase price, overhead, fee, and tax);
PRF: the peak responsibility factor, which derives from the comparison of the transformer load curve to the overall load curve of the network where it is connected;
PUL: the peak per unit transformer load;
LECL: the levelized annual energy and operating cost of load losses in U.S. \$/kW;
TLF: the transformer loading factor.

The equation yielding the *CRF* is as follows:

$$CRF = \frac{i \cdot (1+i)^{BL}}{(1+i)^{BL} - 1} \tag{4}$$

where *i* refers to the discount rate, and *BL* refers to the number of years of the transformer lifetime. Furthermore, *LECN* and *LECL* are computed as follows:

$$LECN = CRF \cdot HPY \cdot AF \cdot \sum_{j=0}^{BL-1} CYEC \cdot \frac{(1+EIR)^j}{(1+i)^j} \tag{5}$$

$$LECL = CRF \cdot HPY \cdot \sum_{j=0}^{BL-1} CYEC \cdot \frac{(1+EIR)^j}{(1+i)^j} \tag{6}$$

where *HPY* indicates the hours of transformer operation per year (typically 8760 hours), *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), *CYEC* refers to the current year energy cost (the cost of electricity) in U.S. \$/kW and *EIR* is the energy cost inflation rate per year. Moreover, the *PUL* derives from the following equation:

$$PUL = \frac{\sum_{j=0}^{BL-1} ITL_{TPL} \cdot (1+TPLIF)^j}{BL - 1} \tag{7}$$

where ITL_{TPL} and *TPLIF* indicate the initial transformer load (Transformer Peak Load) and the transformer peak load incremental factor (based on the transformer load curve), respectively. Finally, the factor *TLF* is calculated by:

$$TLF = \sqrt{LF \cdot PUL^2} \qquad (8)$$

where 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, according to the following equation:

$$LF = 0.15 \cdot l_f + 0.85 \cdot l_f^2 \qquad (9)$$

In a nutshell, a variety of calculations are incorporated in the *TOC* formula, representing in detail the transformer load and the network characteristics at the point of its installation. For this purpose, the detailed time characteristic of the load profile (consumer type) is used, incorporating proper coefficients for the long-term prediction of the load growth.

3. Proposed methodology

This Section illustrates the details of the proposed methodology adopted for the evaluation of the transformer Total Owing Cost so as to include the environmental cost, presenting an extension of the IEEE Standard C57.120. This paper proposes the introduction of an additional component into the *TOC* formula, representing the environmental costs that are associated with various types of emissions resulting from the combustion of fossil fuels so as to compensate for transformer losses.

3.1 Reference transformer

One important point of the proposed method is the definition of the reference transformer that has to be part of the transformer specification of the electric utility, i.e., a transformer with reference no-load losses NLL_r and reference load losses LL_r. For any evaluated transformer that has total energy losses less than the total energy losses of the reference transformer, the environmental cost is considered negative, providing a further incentive for transformer owners to invest to low loss designs, otherwise, the environmental cost is considered positive. 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 evaluated transformer and the total energy losses of the reference transformer. The selection of the reference transformer losses is based on the contribution of the transformer energy losses to the total greenhouse gas emissions of the generation system of the considered electric utility and their responsibility to the violation of the maximum values imposed by international standards or protocols concerning each country. The reference transformer must correspond to the maximum permissible losses per kVA rating that do not result to violation of this limit and imposition of environmental penalty to the electric utility.

3.2 Energy losses of the evaluated transformer

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

$$E_{NLLo} = NLL_o \cdot AF \cdot HPY \qquad (10)$$

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

$$E_{LLo} = LL_o \cdot l_f^2 \cdot HPY \qquad (11)$$

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

$$E_{Lo} = E_{NLLo} + E_{LLo} \qquad (12)$$

3.3 Energy losses of the reference transformer

The same (as in Section 3.2) procedure is followed so as to compute the total annual energy losses of the reference transformer (E_{Lr} in kWh/yr), as follows:

$$E_{NLLr} = NLL_r \cdot AF \cdot HPY \qquad (13)$$

$$E_{LLr} = LL_r \cdot l_f^2 \cdot HPY \qquad (14)$$

$$E_{Lr} = E_{NLLr} + E_{LLr} \qquad (15)$$

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

3.4 Environmental cost coefficient

In this Section, a methodology for calculating greenhouse gas emissions (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) is applied [14] in order to determine the equivalent emissions corresponding to each MWh of produced energy and yield their environmental cost. The main goal is to quantify these emissions and to represent them by an environmental cost coefficient. According to the type of fuel (i.e., coal, diesel, natural gas, wind, etc), gas emissions are converted into equivalent CO_2 emissions (expressed in tonnes of equivalent CO_2 emissions, denoted as t_{CO_2}) in terms of their global warming potential. In order to estimate the emission factor of each fuel type, the following equation is used:

$$GHG_{Fuel_i} = \left(G_{CO_2} + G_{CH_4} \cdot 21 + G_{N_2O} \cdot 310\right) \cdot \frac{0.0036}{n_{fuel_i} \cdot (1 - J_{T-D})} \qquad (16)$$

where GHG_{Fuel_i} is the emission factor of each fuel type in t_{CO_2}/MWh, G_{CO_2} is the CO_2 emission factor in kg/GJ, G_{CH_4} is the CH_4 emission factor in kg/GJ, G_{N_2O} is the N_2O emission factor in kg/GJ, $J_{T\text{-}D}$ represents the transmission and distribution losses in %, and n_{fuel_i} is the fuel conversion efficiency in %. The factor 0.0036 in equation (16) is used so as to convert kg/GJ into t_{CO_2}/MWh. It can be seen from equation (16) that CH_4 and N_2O emissions are converted into equivalent CO_2 emissions by multiplying their emission factors with 21 and 310 respectively (these values are provided by the Intergovernmental Panel on Climate Change [15]). CH_4 is thus 21 times more powerful a greenhouse gas than CO_2, and N_2O is 310 times more powerful than CO_2.

The above methodology enables the calculation of an environmental cost coefficient according to the fuel type mix of the generation system of each considered network. As an arithmetic example, let us consider the case of an interconnected transmission system having the energy mix shown in the second row of Table I. Using equation (16) and the data of Table I, it can be easily found that the equivalent CO_2 emissions factor, C_{eq}, is equal to 0.8936 t_{CO_2}/MWh. Taking into account that the typical range of CO_2 emissions cost factor in the considered electric utility is between 10 and 30 \$/t_{CO_2} and assuming a moderate value of 15 \$ per t_{CO_2}, the resulting environmental cost coefficient, C, is equal to 13.4 \$/MWh. As a second arithmetic example, let us consider the case of an isolated network (e.g., an island not interconnected to the mainland grid), considering a fuel mix of 98.4% diesel and 1.6% wind and using the rest of data (for diesel and wind) presented in Table I yield a value of the equivalent CO_2 emissions factor, C_{eq}, equal to 0.96 t_{CO_2}/MWh, and assuming a moderate emissions cost value of 15 \$/t_{CO_2}, the environmental cost coefficient, C, is found to be equal to 14.4 \$/MWh.

3.5 *TOC* including environmental cost

The next step consists of the comparison of the total annual energy losses of each offered transformer

Table 1. Calculation example of the equivalent CO_2 emissions factor, C_{eq}, according to the participation of each fuel type to the total power production of an interconnected transmission 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_i} (%)	35	30	100	45	100
J_{T-D} (%)	8	8	8	8	8
GHG_{Fuel_i} (t_{CO_2}/MWh)	1.069	0.975	0.0	0.491	0.0
$C_{eq}=\frac{69.77}{100}\cdot 1.069+\frac{7.6}{100}\cdot 0.975+\frac{15}{100}\cdot 0.491=0.8936\,\frac{t_{CO_2}}{MWh}$					

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 an environmental cost coefficient C (in U.S. \$/MWh, computed according to the methodology presented in Section 3.4), the annual environmental cost (C_e^{annual}) of each offered transformer is found. Otherwise, if $E_{Lr} \geq E_{Lo}$, the corresponding annual environmental cost is considered equal to $-C_e^{annual}$. The environmental costs (C_e^{annual} or $-C_e^{annual}$, according to the relationship between the energy losses of the evaluated transformer and the reference transformer) are then multiplied by the factors k and m, respectively, yielding the final positive environmental cost value (in case of transformers with energy losses greater than the reference ones) or the negative environmental cost value (in case of transformers with energy losses less than the reference ones). Finally, in order to find the total environmental cost (C_e in U.S. \$) during the transformer lifespan, the annual environmental cost is multiplied by the transformer book-life (BL), as follows:

$$C_e = \begin{cases} -\,|E_{Lo}-E_{Lr}|\cdot k\cdot C\cdot BL, & if\ \ E_{Lr}\geq E_{Lo} \\ |E_{Lo}-E_{Lr}|\cdot m\cdot C\cdot BL, & if\ \ E_{Lr}< E_{Lo} \end{cases} \tag{17}$$

It is important to note that the coefficients k and m define how strong or weak the purchaser's (i.e., the electric utility) motivation is, in terms of investment to energy efficient transformers. This motivation is incorporated in the *TOC* evaluation method as a positive or negative cost, affecting the electric utility purchasing decision among the different manufacturer offers. Therefore, factors k and m reflect the importance accredited to the environmental impact during this decision. For instance, if k=0, then the electric utility does not take into account the environmental impact in the *TOC* formula and does not provide an incentive to the manufacturer to offer transformers with energy losses less than the energy losses of the reference transformer. On the contrary, if k=1, then the electric utility reinforces the purchasing decision by a factor equal to the environmental cost coefficient C. Accordingly, if m=1, the *TOC* value will be increased by a factor equal to the environmental cost coefficient C, affecting negatively the decision to purchase from the considered transformer manufacturer.

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

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

$$TOC_e = BP + A\cdot NLL + B\cdot LL + C_e \tag{18}$$

4. Case studies

This Section presents the economic evaluation of five different transformer offers provided by five different transformer manufacturers. The transformer offers concern the purchase of a three-phase oil-immersed distribution transformer, 50 Hz, 400 kVA. The characteristics of the transformer loading profile are represented in detail. Special consideration is given to the distinction between transformers installed in the interconnected transmission system or in isolated networks (i.e., islands), since this differentiation affects the loading profile, the cost of the produced energy, the load growth rate as well as the environmental costs.

4.1 Transformer offers

The objective is to select a three-phase oil-immersed distribution transformer, 50 Hz, 400 kVA, among five different transformer offers provided by five transformer manufacturers. The technical characteristics of the five different transformer offers are listed in Table II (Manufacturer 1 to Manufacturer 5 is denoted as M_1 to M_5). The calculations are based on a project life of 25 years and the loading profile of four typical electric utility consumers (domestic, industrial, rural and tourist consumers).

Table 2. Five different transformer offers for the 400 kVA distribution transformer.

Offer	*Bid price ($)*	*Load losses (W)*	*No-load losses (W)*
M_1	17081	5020	670
M_2	17529	3900	660
M_3	17835	4610	640
M_4	18676	4570	600
M_5	19921	4170	510

4.2 Calculation of the *A* and *B* coefficients

In this work, four types of transformer consumer are investigated: 1) domestic, 2) industrial, 3) rural, and 4) tourist consumer. For all the consumer types, it is assumed that *AF*=97 %, *IF*=1, *i*=8 %, *HPY* = 8760 h, *BL*=25 years, *LIC*=201.39 U. S. $/kW and *EIR*=2.7.

For the case study of the domestic consumer and based on its specific load characteristics, it is found that *PRF*=0.738, ITL_{TPL}=80%, l_f= 0.678 and *TPLIF*=2.7%. Moreover, the value of *CYEC* is considered equal to 0.074 U. S. $/kWh, corresponding to a typical cost of energy production in the considered interconnected transmission system. Using equations (4)-(9), (2) and (3), it is found that *CRF*=0.0937, *LECN*=855.83 U. S. $/kWh, *LECL*=882.55 U. S. $/kWh, *PUL*=1.122, *TLF*=0.787, *LF*=0.492, *A*=11.88 U. S. $/W and *B*=7.7 U. S. $/W, respectively. The same procedure is followed for the rest consumer types and Table III presents the *A* and *B* factors for each consumer type, as well as the rest of the data used in their calculation. As can be seen in Table III, apart the specific load characteristics of each consumer, the value of energy cost (*CYEC*) is equal for the first three types of consumers (domestic, industrial and rural), which are considered to be connected to the mainland grid (interconnected transmission system). On the other hand, in the case of the tourist consumer, the installation is located on an isolated island grid, where the value of energy cost is higher (due to the fact that the main fuel type used in the considered isolated networks is diesel).

Table 3. Computation of A and B coefficients of TOC formula for the four different consumers by applying the methodology of IEEE Standard C57.120 presented in Section 2.

Parameter	*Domestic consumer*	*Industrial consumer*	*Rural consumer*	*Tourist consumer*
CYEC ($/kWh)	0.074	0.074	0.074	0.110
PRF	0.738	0.699	0.800	0.552
ITL_{TPL}	0.8	0.8	0.8	0.8
l_f	0.678	0.461	0.709	0.382
TPLIF	0.027	0.027	0.027	0.027
CRF	0.0937	0.0937	0.0937	0.0937
LECN ($/kWh)	855.8	855.9	855.9	1268.0
LECL ($/kWh)	882.5	882.4	882.4	1307.2
PUL	1.122	1.122	1.122	1.122
TLF	0.787	0.561	0.819	0.478
LF	0.492	0.250	0.534	0.181
A ($/W)	11.88	11.88	11.87	16.51
B ($/W)	7.70	4.51	8.48	4.22

Fig. 1 presents the daily load curves corresponding to the four types of consumers (for the first year of the study period, expressed in per unit of the transformer rated power), which are taken into account for the calculation of the parameters of Table III. The peak daily load curve of the year is considered, corresponding to a winter working day in the case of domestic and industrial consumer, a summer working day in the case of the rural consumer and a summer weekend day in the case of the tourist consumer. Fig. 1 illustrates the diversity of the considered consumer type variation, which is reflected to the different values of load factors (l_f), loss factors (*LF*) and transformer load factors (*TLF*) of Table 3.

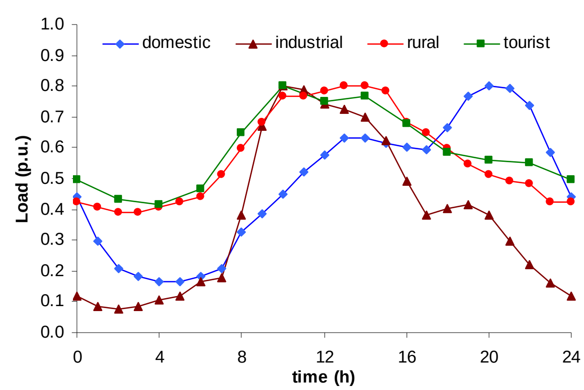

Fig. 1. Typical daily load curves corresponding to the four types of transformer consumers.

4.3 *TOC* results without the environmental cost

Table IV presents the *TOC* results for the 5 different offers of Table II, without the introduction of the environmental cost, based on the *A* and *B* coefficients of Table III and the bid price as well as the losses of each transformer offer (Table II).

Table 4. Electric utility-based TOC without environmental cost for all consumer types.

Offer	*TOC without environmental cost ($)*			
	Domestic consumer	***Industrial consumer***	***Rural consumer***	***Tourist consumer***
M_1	63674	47674	67618	49328
M_2	55384	42954	58448	44884
M_3	60916	46223	64538	47856
M_4	60974	46408	64564	47868
M_5	58071	44781	61347	45939

Despite the fact that the transformer offered by M_1 is the cheapest one concerning the bid price (as can be seen from the second column of Table II), Table IV shows that, in long term, the transformer offered by M_1 is the worst investment since it has the highest total owning cost and this result exists for the four different consumer types. In contrast, it is clear that the transformer offer of M_2 is the best investment in long term, in all cases of the considered consumers, since it has the lowest total owning cost. The domestic and rural consumers correspond to relatively higher *TOC* values in Table IV, compared to the other consumers, due to their higher load factor. The comparison of the results appearing in Table IV illustrates the importance of the detailed representation of the consumer characteristics to the accurate evaluation of the total owning cost: although the selection of M_2 is verified in all cases, a difference of up to 16656 U. S. $ in the *TOC* value of transformers of the same loss category, according to the consumer category can be observed, which is quite considerable in case of investments for purchasing numerous distribution transformers by the same electric utility.

4.4 *TOC* results with the environmental cost

Table V presents the TOC_e results for the 5 different offers of Table II, with the introduction of the environmental cost, based on the *A* and *B* coefficients of the Table III, the coefficient *C* (*C*=13.4 $/MWh for domestic, industrial and rural consumer, while *C*=14.4 $/MWh for the tourist consumer, as calculated in Section 3.4) as well as *k* and *m* equal to 1.

For the calculation of environmental costs, a reference transformer with NLL_r=590W and LL_r=4460W is selected, in the case of the three first consumer types, located in the interconnected utility grid. These values correspond to the maximum permissible losses of a 400 kVA transformer in order to maintain the total greenhouse gas emissions of the considered electric utility system below the imposed national limit. The values were calculated based on the total number of installed 400 kVA transformers in the utility network and their overall contribution to the total energy losses of this network. In the case of the tourist consumer, the reference values are equal to NLL_r=570W and LL_r=4320W.

Table 5. Electric utility-based TOC_e with environmental cost for all consumer types, using k=1 and m=1.

Offer	*TOC with environmental cost ($)*			
	Domestic consumer	***Industrial consumer***	***Rural consumer***	***Tourist consumer***
M_1	64657	48251	68672	49913
M_2	54827	42804	57821	44961
M_3	61260	46459	64901	48180
M_4	61151	46505	64755	48060
M_5	57452	44372	60692	45704

As can be observed in the results of Table V, the offer of M_2 remains the most profitable one. Due to the introduction of the environmental cost, the difference between the rest of the offers is now higher, resulting to values up to 15.8% (difference in the TOC_e value between M_1 and M_2, in the case of the rural consumer, Table V). The respective maximum difference in the case of transformer evaluation without environmental cost is 13.6% (difference in the *TOC* value between M_1 and M_2, in the case of the rural consumer, Table IV).

Table VI and Table VII present the results for the TOC_e including environmental factors for different k and m values, namely *k*=1 and *m*=0.6, and *k*=0 and *m*=1, respectively. In both cases, the difference between the TOC_e of M_2 and the TOC_e of other offers is now lower than the one of Table V, due to the decrease of the environmental cost penalty (through the decrease of factor *m* in the calculations of Table VI) or the reduction of the environmental reward of low loss transformer offers (through the reduction of factor *k* in the calculations of Table VII).

Table 6. Electric utility-based TOC_e with environmental cost for all consumer types, using k=1 and m=0.6.

Offer	*TOC with environmental cost ($)*			
	Domestic consumer	*Industrial consumer*	*Rural consumer*	*Tourist consumer*
M_1	64264	48020	68250	49679
M_2	54827	42804	57821	44930
M_3	61123	46364	64756	48050
M_4	61080	46466	64678	47983
M_5	57452	44372	60692	45704

Table 7. Electric utility-based TOC_e with environmental cost for all consumer type, using k=0 and m=1.

Offer	*TOC with environmental cost ($)*			
	Domestic consumer	*Industrial consumer*	*Rural consumer*	*Tourist consumer*
M_1	64657	48251	68672	49913
M_2	55384	42954	58448	44961
M_3	61260	46459	64901	48180
M_4	61151	46505	64755	48060
M_5	58071	44781	61347	45939

5. Sensitivity analysis

In the *TOC* 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 parameters that are selected are: the discount rate (*i*), the cost of electricity (*CYEC*), the levelized annual generation and transmission system investment cost (*LIC*), the environmental cost coefficient (*C*), the coefficient *k* from equation (17), and the number of years of the transformer lifetime (*BL*). These parameters 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 parameters, we should develop a base case of TOC_e, i.e., TOC_e equal to 54827 U.S. $ (Table V – (Domestic consumer) M_2), which corresponds to *k*=1, *m*=1, *i*=8 %, *CYEC*=0.074 U.S. $/kWh, *LIC*= 201.43 U.S. $/kW, and *C*=13.4 U.S. $/MWh. Table VIII and Fig. 2 present the sensitivity parameter analysis results, based on various parameter values. For example, by changing + 10% the discount rate (parameter *i*), the TOC_e changes -3.66% in comparison with the TOC_e of the base case.

Table 8. Sensitivity parameter analysis. TOC_e variation based on varying parameters values.

Parameters variation (%)	*TOC_e variation (%) when varying parameter i to BL*					
	i	*CYEC*	*LIC*	*C*	*k*	*BL*
-20	8.72	-11.06	-2.75	0.20	0.2	-12.86
-15	6.34	-8.29	-2.06	0.15	0.15	-10.38
-10	4.1	-5.53	-1.38	0.10	0.1	-7.86
-5	1.99	-2.76	-0.69	0.05	0.05	-2.65
5	-1.88	2.76	0.69	-0.05	0.05	1.03
10	-3.66	5.53	1.38	-0.10	0.10	2.97
15	-5.34	8.29	2.06	-0.15	0.15	3.85
20	-6.93	11.06	2.75	-0.20	0.20	4.68
Minimum	-6.93	-11.06	-2.75	-0.2	0.05	-12.86
Maximum	8.72	11.06	2.75	0.2	0.2	4.68

Fig. 2 shows the sensitivity of the TOC_e to percent deviation changes in each parameter's best estimate. The other parameters are assumed to remain at their best estimate values. The relative degree of sensitivity of the TOC_e to each parameter is indicated by the slope of the curves (the steeper the slope of a curve, the more sensitive the TOC_e is to the parameter) [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 the coefficient *k*, but quite sensitive to changes in the discount rate (*i*), the cost of electricity (*CYEC*), the number of years of the transformer lifetime (*BL*), and the cost of installing transmission systems (*LIC*).

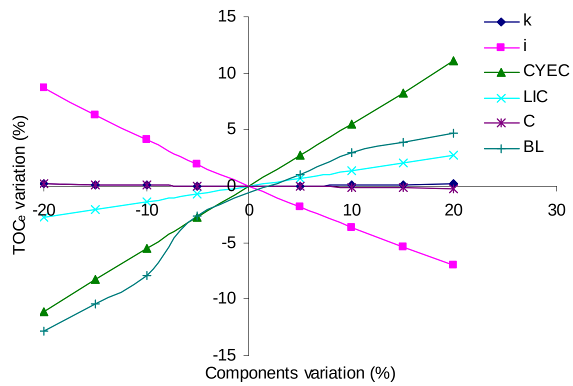

Fig. 2. Sensitivity graph of six parameters.

7. Conclusion

In the present paper, the electric utility-based economic assessment of distribution transformers, taking into account their specific loading characteristics, the power system parameters and the environmental impact of losses was presented. The analysis was based on the guidelines provided by the IEEE Standard C57.120, introducing the incorporation of environmental costs to the *TOC* formula, yielding the TOC_e formula. The method was employed for the economic evaluation of a 400kVA three-phase oil-immersed distribution transformer, serving different kind of consumers, installed either on an interconnected transmission system or an isolated network. The results of the calculations indicated that the incorporation of specific consumer and system characteristics results to significant differences in the *TOC* values, which must be taken into account by electric utilities. The introduction of environmental costs is quite substantial, as it reinforces the optimal transformer choice, resulting to more significant difference in the TOC_e values, compared to the values based on the classical *TOC* formula. Finally, sensitivity analysis was conducted so as to investigate the impact of the TOC_e parameters variation in the final purchasing decision. According to this analysis, the TOC_e variation is quite sensitive to changes in the discount rate and the estimated cost of energy, while changes in the transmission and generation system investment cost and the transformer lifetime duration affect it less. On the other hand, TOC_e remains practically stable in variation of in the environmental cost factor.

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