Environmental Cost of Transformer Losses for Industrial and Commercial Users of Transformers

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***Abstract*— Improvements in energy efficiency of electrical equipment reduce the greenhouse gas (GHG) emissions and contribute to the protection of the environment. This paper proposes a simplified model that quantifies the environmental cost of transformer losses and incorporates it into the economic evaluation of distribution transformers for industrial and commercial users of transformers. This environmental cost is coming from the cost to buy GHG emission credits because of the GHG emissions associated with supplying transformer losses throughout the transformer lifetime. Application results indicate that the environmental cost of transformer losses can reach on average 35% of transformer purchasing price for high-loss transformers. That is why it is important to incorporate the environmental cost of transformer losses into the economic evaluation of distribution transformers.**

I. INTRODUCTION

Nowadays the reduction of greenhouse gas (GHG) emissions is becoming a topical issue due to the growing concern for global warming and climate change. GHG emissions trading scheme is a mechanism that allows participating countries to establish limits on pollution in a form of allowances [1]. These allowances can then be either used or traded in emissions markets. It means that similar to the cost of energy, GHG emissions are also assigned a price by the energy markets [1]. The price of GHG emissions varies as a function of supply and demand [1]. In the GHG emissions markets, those companies that do not use all their GHG emission credits can sell them to those companies that surpass them.

The most effective measures to reduce GHG emissions are energy efficiency and renewable energy sources [1]. Existing international policy instruments supporting energy efficiency of distribution transformers are summarized in [2]. Among these instruments, efficiency standards and labels are the most effective tools that foster the development and dissemination of energy efficient distribution transformers [2].

Energy efficient transformers have reduced losses, so they reduce energy consumption and consequently reduce the generation of electrical energy and greenhouse gas emissions [3]. In deregulated electricity markets, as the price of electrical energy varies every hour, so does the cost of transformer losses. European Copper Institute studies indicated that improving energy efficiency of existing European stock of transformers by 40% would result in about 22 TWh annual energy savings equivalent to annual reduction in greenhouse gas emissions of about 9 million tonnes of CO_2 equivalent [4].

This paper quantifies and analyzes the impact of the environmental cost of transformer losses on the economic evaluation of distribution transformers for industrial and commercial users of transformers. This environmental cost is coming from the cost to buy GHG emission credits because of the GHG emissions associated with supplying transformer losses throughout the transformer lifetime. The extensive analysis in conjunction with the use of actual data (transformer specifications, transformer prices) and the derivation of general conclusions make the work presented in this paper very useful for industrial and commercial users of transformers as well as for transformer manufacturers.

II. Capacity and Energy Cost of Transformer Losses

The cost of transformer losses for industrial and commercial users requires an assessment of the electricity prices they pay to the electric utility. More specifically, the transformer total owning cost, *TOC*, throughout the transformer lifetime is computed by [3], [5], [6]:

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

where [5], [6]:

$$A = C \times HPY \times \frac{\left[(1+d)^{BL} - 1\right]}{d \times (1+d)^{BL}} \times 10^{-6} \tag{2}$$

$$B = A \times L^2 \tag{3}$$

where *BP* ($) is the transformer bid price, *A* is the no-load loss cost rate ($/W), *NLL* is the no-load loss (W) of the evaluated transformer, *B* is the load loss cost rate ($/W), *LL* is the load loss (W) of the evaluated transformer, *d* is the interest rate, *C* is the electricity price ($/MWh), *HPY* is the hours of transformer operation per year (typically *HPY*=8760), *L* is the transformer loading (in per unit of the transformer rated load), and *BL* is the transformer lifetime.

It is concluded from the above that for the computation of *TOC*, the values of the following eight parameters are needed: *BP*, *NLL*, *LL*, *C*, *HPY*, *d*, *L*, and *BL*.

The capacity and energy cost of transformer losses, *CL*, throughout the transformer lifetime is computed as follows:

$$CL = A \times NLL + B \times LL \tag{4}$$

In (4), the term $A \times NLL$ expresses the cost of transformer no-load losses and the term $B \times LL$ expresses the cost of transformer load losses throughout the transformer lifetime.

III. Environmental Cost of Transformer Losses

The computation of the environmental cost of distribution transformer losses for industrial and commercial users of transformers is based on an extension of a recently developed model [7], [8], [9] for electric utilities that have generation, transmission, and distribution facilities.

The transformer total owning cost including the environmental cost of transformer losses, TOC_e, throughout the transformer lifetime is computed as follows [7], [8]:

$$TOC_e = TOC + A_e \times (NLL - NLL_r) + B_e \times (LL - LL_r) \tag{5}$$

where this paper proposes that A_e and B_e are computed by:

$$A_e = C_e \times HPY \times \frac{\left[(1+d)^{BL} - 1\right]}{d \times (1+d)^{BL}} \times 10^{-6} \tag{6}$$

$$B_e = A_e \times L^2 \tag{7}$$

where *TOC* is the total owning cost excluding the environmental cost {*TOC* is computed by (1)}, A_e the no-load loss environmental factor ($/W), *NLL* the no-load loss (W) of the evaluated transformer, NLL_r the no-load loss (W) of a reference transformer, B_e the load loss environmental factor ($/W), *LL* the load loss (W) of the evaluated transformer, LL_r the load loss (W) of a reference transformer, C_e the greenhouse gas emission cost penalty ($/MWh), *HPY* the hours of transformer operation per year, *L* the transformer loading (in per unit of the transformer rated load), *BL* the transformer lifetime, and *d* the interest rate. It should be noted that the losses of the reference transformer (NLL_r and LL_r) are determined in such a way that the reference transformer is charged exactly zero dollars for GHG emission credits.

It should be noted that the greenhouse gas emission cost penalty, C_e, depends on market structure. Moreover, if a vertically integrated utility owns a larger penetration of renewable then it might have a lower C_e compared to other utilities in the same market.

It is concluded from the above that for the computation of TOC_e, the values of the following eleven parameters are needed: *BP*, *NLL*, *LL*, NLL_r, LL_r, *C*, C_e, *HPY*, *d*, *L*, and *BL*.

The environmental cost of transformer losses, *EC*, throughout the transformer lifetime is computed as follows:

$$EC = A_e \times (NLL - NLL_r) + B_e \times (LL - LL_r) \tag{8}$$

It should be noted that in (5) and (8):

- The term $A_e \times (NLL - NLL_r)$ expresses the environmental cost of transformer no-load losses throughout the transformer lifetime. This formulation shows that the environmental cost of transformer no-load losses can be positive or negative. For example, the transformer user has to pay GHG emission penalties due to transformer no-load loss only if $NLL - NLL_r > 0$.
- The term $B_e \times (LL - LL_r)$ expresses the environmental cost of transformer load losses throughout the transformer lifetime. This formulation shows that the environmental cost of transformer load losses can be positive or negative. For example, the transformer user has to pay GHG emission penalties due to transformer load loss only if $LL - LL_r > 0$.

TABLE I. Data for two Competing Transformer Offers

Parameter	Offer D1	Offer D2
Rated power (kVA)	1600	1600
No-load losses, *NLL* (W)	2600	1700
Load losses, *LL* (W)	20,000	14,000
EN 50464-1 loss category	E_0D_k	C_0B_k
EN 50464-1 loss level	High	Low
Bid price, *BP* ($)	27,000	31,300

TABLE II. Total Owning Cost (With Environmental Cost) for the two Offers of Table I.

Parameter	Offer D1	Offer D2
Bid price, *BP* ($)	27,000	31,300
Cost of no-load losses ($)	30,758	20,111
Cost of load losses ($)	59,200	41,440
Cost of losses, *CL* ($)	89,958	61,551
Total owning cost without *EC*, *TOC* ($)	116,958	92,851
Environmental cost of no-load losses ($)	4437	0
Environmental cost of load losses ($)	3690	-3690
Environmental cost of losses, *EC* ($)	8127	-3690
Total owning cost with *EC*, TOC_e ($)	125,085	89,161
EC / TOC_e (%)	6.5	-4.1
TOC / TOC_e (%)	93.5	104.1
EC / BP (%)	30.1	-11.8

TABLE III. LIST OF NINE SCENARIOS CONSIDERED.

Scenario	Input parameters: C and C_e				Computed parameters				Offer D1	Offer D2
	C level	C (\$/MWh)	C_e level	C_e (\$/MWh)	A (\$/W)	B (\$/W)	A_e (\$/W)	B_e (\$/W)	TOC_e (\$)	TOC_e (\$)
1	Medium	120	Medium	50	11.83	2.96	4.93	1.23	125,085	89,161
2	Medium	120	Low	25	11.83	2.96	2.47	0.62	122,871	90,991
3	Medium	120	High	100	11.83	2.96	9.86	2.47	129,522	85,441
4	Low	80	Medium	50	7.89	1.97	4.93	1.23	95,041	68,603
5	Low	80	Low	25	7.89	1.97	2.47	0.62	92,827	70,433
6	Low	80	High	100	7.89	1.97	9.86	2.47	99,478	64,883
7	High	160	Medium	50	15.78	3.95	4.93	1.23	155,155	109,736
8	High	160	Low	25	15.78	3.95	2.47	0.62	152,941	111,566
9	High	160	High	100	15.78	3.95	9.86	2.47	159,592	106,016

IV. RESULTS AND DISCUSSION

A. Data

Table I shows two competing transformer offers for three-phase, oil-immersed, power transformers, with loss categories as defined by EN 50464-1 standardization [10]. The offer D1 corresponds to a high-loss transformer, while the offer D2 corresponds to a low-loss transformer. Let us suppose that $C = 120\ \$/\text{MWh}$, $C_e = 50\ \$/\text{MWh}$, $d = 0.08$, $L = 0.5$, $BL = 30$, $HPY = 8760$, while the reference transformer has $NLL_r = 1700\ \text{W}$ and $LL_r = 17{,}000\ \text{W}$.

B. Calculation of *A*, *B*, A_e, and B_e Loss Factors

The A and B loss factors are computed by (2) and (3), respectively:

$$A = 120 \times 8760 \times \frac{\left[1.08^{30} - 1\right]}{0.08 \times 1.08^{30}} \times 10^{-6} \Rightarrow A = 11.83\ \frac{\$}{\text{W}}$$

$$B = 11.83 \times 0.5^2 \Rightarrow B = 2.96\ \frac{\$}{\text{W}}$$

The A_e and B_e loss factors are computed by (6) and (7), respectively:

$$A_e = 50 \times 8760 \times \frac{\left[1.08^{30} - 1\right]}{0.08 \times 1.08^{30}} \times 10^{-6} \Rightarrow A_e = 4.93\ \frac{\$}{\text{W}}$$

$$B_e = 4.93 \times 0.5^2 \Rightarrow B_e = 1.23\ \frac{\$}{\text{W}}$$

C. Calculation of *TOC* and TOC_e

The *TOC* and TOC_e for the offer D1 are computed by (1) and (5), respectively:

$$TOC_{D1} = 27{,}000 + 11.83 \times 2600 + 2.96 \times 20{,}000 \Rightarrow TOC_{D1} = \$\,116{,}958$$

$$TOC_{e,D1} = 116{,}958 + 4.93 \times (2600 - 1700) + 1.23 \times (20{,}000 - 17{,}000) \Rightarrow TOC_{e,D1} = \$\,125{,}085$$

Table II presents the total owning cost *including* the environmental cost of transformer losses, TOC_e, for the offers D1 and D2 of Table I.

D. Transformer Selection

If the criterion is the minimum *TOC*, then the offer D2 has to be selected, because its *TOC* is lower than that of offer D1, as Table II shows.

If the criterion is the minimum TOC_e, then again the offer D2 has to be selected, because its TOC_e is lower than that of offer D1, as Table II shows.

Based on Table II, the following conclusions are drawn:

1. The best investment is the transformer of offer D2 since it has the lowest *TOC* as well as the lowest TOC_e.
2. Although the transformer of offer D2 is the most expensive concerning the bid price, it is the best investment, since it has the lowest TOC_e. This happens because the transformer of offer D2 is the most energy-efficient and consequently it has the lowest cost of losses (*CL*) as well as the lowest environmental cost of losses (*EC*) during the transformer lifetime.
3. As can be seen from the last row of Table II, in case of offer D1, the environmental cost of losses, *EC*, is 30.1% of transformer bid price, *BP*. That is why it is important to incorporate the environmental cost of transformer losses into the economic evaluation of distribution transformers. This very important indicator, i.e., the indicator *EC*/*BP* will be used in Section IV.E for further evaluating the environmental cost of transformer losses.

E. Sensitivity Analysis

Two very important parameters that influence the TOC_e and the environmental cost of transformer losses are the following:

1. The electricity price, C (\$/MWh). When C increases, the loss factors A and B also increase, which implies increase of *TOC* and TOC_e.
2. The greenhouse gas emission cost penalty, C_e (\$/MWh). When C_e increases, the environmental loss

factors (A_e and B_e) also increase, which implies increase or decrease of the environmental cost of transformer losses (*EC*), depending on the losses of the evaluated transformer in relation with the losses of the reference transformer.

Due to the above reasons, the parameters C and C_e have been selected for creating alternative scenarios as follows:

1. Three different values have been assigned to C, i.e.., 80, 120, and 160 \$/MWh, corresponding to low, medium, and high C, respectively.
2. Three different values have been assigned to C_e, i.e.., 25, 50, and 100 \$/MWh, corresponding to low, medium, and high C_e, respectively.

All the combinations of C and C_e values have been considered, thus the nine scenarios of Table III are studied. The values of all the other input parameters remain unchanged, having the values given in Section IV.A. Under these assumptions, for each one of the nine scenarios, the values of A, B, A_e, and B_e, which are computed based on (2), (3), (6), and (7), are also given in Table III. It can be observed from Table III that the values of A, B, A_e, and B_e for scenario 1 are the same with the ones computed in Sections IV.B, because scenario 1 has the same data (including C and C_e) with Section IV.A.

Fig. 1 shows the TOC_e of the offer D1 (high-loss transformer) for each one of the nine scenarios of Table III. The best is scenario 5 because it implies the lowest TOC_e value among the nine scenarios, as Fig. 1 shows, which is due to the fact that scenario 5 corresponds to low value for both C and C_e, as Table III shows. However, for the same scenario, the offer D2 has always lower TOC_e in comparison with offer D1, as Table III shows.

Fig. 2 shows the values of *EC*/*BP* indicator of the offer D1 (high-loss transformer) for each one of the nine scenarios of Table III. As can be seen from Fig. 2, the *EC*/*BP* indicator ranges from 15.1% to 60.3% with 35.2% average value.

More details about the environmental cost of transformer losses, the economic evaluation and the selection of transformers can be found in Chapter 8 of book [7].

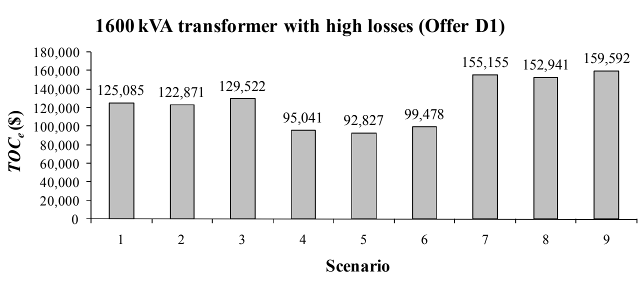

Figure 1. TOC_e of the 1600 kVA transformer with high losses (Offer D1 of Table I) for each one of the nine scenarios of Table III.

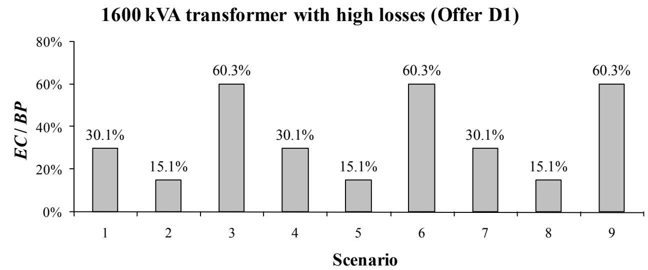

Figure 2. *EC*/*BP* of the 1600 kVA transformer with high losses (Offer D1 of Table I) for each one of the nine scenarios of Table III.

V. Conclusion

This paper quantifies and analyzes the impact of the environmental cost of transformer losses on the economic evaluation of distribution transformers for industrial and commercial users of transformers. Actual data (transformer specifications, electricity prices, transformer prices) is used. Sensitivity analysis has been also carried out. It has been found that the environmental cost of transformer losses can reach on average 35% of transformer purchasing price for high-loss transformers. That is why it is important to incorporate the environmental cost of transformer losses into the economic evaluation of distribution transformers.

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