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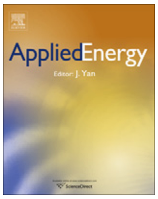

Environmental cost of distribution transformer losses

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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. Moreover, as system investment and energy costs continue to increase, electric utilities are increasingly interested in installing energy-efficient transformers at their distribution networks. This paper analyzes the impact of the environmental cost of transformer losses on the economic evaluation of distribution transformers. This environmental cost is coming form the cost to buy GHG emission credits because of the GHG emissions associated with supplying transformer losses throughout the transformer lifetime. Application results on the Hellenic power system for 21 transformer offers under 9 different scenarios indicate that the environmental cost of transformer losses can reach on average 34% and 8% of transformer purchasing price for high loss and medium loss transformers, respectively. That is why it is important to incorporate the environmental cost of transformer losses into the economic evaluation of distribution transformers.

1. 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 [2]. 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 [3]. Existing international policy instruments supporting energy efficiency of distribution transformers are summarized in [4]. Among these instruments, efficiency standards and labels are the most effective tools that foster the development and dissemination of energy efficient distribution transformers [4].

Distribution transformers have a significant impact on the losses of a utility's transmission and distribution system [5]. Based on a study conducted at the United States, distribution transformers contributed: (a) about 40% of the losses for non-generating public utilities, and (b) over 16% of the losses for investor-owned utilities [5]. 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 [6].

Energy-efficient transformers have reduced total losses, i.e., reduced load and no-load losses. Energy-efficient transformers reduce energy consumption and consequently reduce the generation of electrical energy and greenhouse gas emissions. In deregulated electricity markets, as the price of electrical energy varies every hour, so does the cost of transformer losses. The seasonal load variations also increase the benefits associated with efficient transformers, particularly if the season of maximum load is coincident with the maximum energy prices. As the system investment and energy costs continue to increase, electric utilities are more and more interested in installing energy-efficient transformers at their distribution networks. The transformer manufacturers have developed new manufacturing techniques and new types of core materials to provide cost-effective and energy-efficient transformers to the transformer users [5,7–13].

Energy-efficient transformers cost more but use less energy than low efficiency transformers. The decision as to whether to purchase a low cost, inefficient transformer or a more expensive, energy-efficient transformer, is primarily an economic one. The common practice used by the electric utilities for determining the cost-effectiveness of distribution transformers is based on the total owning cost (*TOC*) method, where *TOC* is equal to the sum of transformer purchasing price plus the cost of transformer losses throughout the transformer lifetime [5]. The basic concept of the *TOC* method is that the evaluation for each type of transformer loss

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(no-load, load) is the sum of the demand part and the energy part [14]. The demand part is the cost of installing system capacity. The energy part is the present value of the energy that will be used to supply transformer losses throughout the transformer lifetime. The *TOC* method for the electric utility can be found in [5,14–16]. The *TOC* method for the industrial and commercial transformer user can be found in [17,18]. Transformer users apply *TOC* method to determine the relative economic benefit of a high-first-cost, low-loss unit versus one with a lower first cost and higher losses [19,20]. Transformer manufacturers use *TOC* method to optimize the design and provide the most economical transformer to bid and manufacture [21,22].

This paper analyzes the impact of the environmental cost of transformer losses on the economic evaluation of distribution transformers. This environmental cost is coming form the cost to buy GHG emission credits because of the GHG emissions associated with supplying transformer losses throughout the transformer lifetime. The computation of the environmental cost of distribution transformer losses is based on a recently developed model [23,24]. A wide range of representative distribution transformer offers, ranging from 100 to 1600 kVA, is collected and evaluated for the Hellenic power system. Moreover, alternative scenarios regarding key input parameters of transformer environmental cost are analyzed. In addition, a key performance indicator is introduced, which measures the impact of the environmental cost on transformer purchasing decision. This indicator is analyzed for various transformer offers and alternative scenarios. The extensive analysis in conjunction with the use of actual data (transformer specifications, transformer prices, electric utility data) and the derivation of general conclusions make the work presented in this paper very useful for electric utilities and transformer manufacturers.

The paper is organized as follows. Section 2 briefly discusses transformer losses and efficiency. Section 3 computes the capacity and energy cost of transformer losses. Section 4 is focused on the calculation of the environmental cost of transformer losses. Sections 5 to 7 compute the environmental cost of distribution transformer losses for the Hellenic power system. In particular, Section 5 presents economic evaluation results for three distribution transformers by excluding the environmental cost of transformer losses. Section 6 discusses economic evaluation results for the three distribution transformers of Section 5 by including the environmental cost of transformer losses. Section 7 presents a detailed analysis of the environmental cost for a wide range of distribution transformers and for different scenarios. Section 8 concludes the paper.

2. Transformer losses and efficiency

A transformer is an electromagnetic device that transmits electrical power from one alternating voltage level to another without changing the frequency. It has two or more windings of wire wrapped around a ferromagnetic core. These windings are magnetically coupled, i.e., the only connection between the windings is the magnetic flux present within the core. The transformer is the most efficient of electrical machines, with efficiencies typically higher than 95%. Nevertheless, the cost of losses is an important factor in specifying and selecting transformers. The transformer losses are divided into two components: no-load losses and load losses.

2.1. No-load losses

No-load losses occur in the transformer core 24 h a day 365 days a year when a voltage is applied to the transformer regardless of load, hence the term no-load losses. They are constant and occur even when the transformer secondary is open-circuited.

The no-load losses can be divided into five components:

1. Hysteresis losses in the core laminations.
2. Eddy current losses in the core laminations.
3. $I^2 \cdot R$ losses due to no-load current.
4. Stray eddy current losses in core clamps, bolts, and other core components.
5. Dielectric losses.

Hysteresis losses and eddy current losses contribute over 99% of the no-load losses, while $I^2 \cdot R$ losses due to no-load current, stray eddy current, and dielectric losses are small and consequently often neglected. The hysteresis loss is the biggest contributor to no-load losses.

2.2. Load losses

Load losses are losses that vary according to the loading on the transformer. They consist of heat losses in the conductor caused by the load current and eddy currents in the conductor. These losses increase as the temperature increases because the resistance in the conductor is increased with temperature. It is often difficult to determine load losses because of the difficulty of knowing the load. This requires knowing the peak load as well as the load factor. The most significant load losses are $I^2 \cdot R$ or copper losses, i.e., the heat losses in the conductor caused by the load current.

2.3. Efficiency

The transformer efficiency, n, is computed as follows:

$$n = \frac{L \cdot S_n \cdot \cos\phi}{L \cdot S_n \cdot \cos\phi + NLL + LL \cdot L^2} \quad (1)$$

where S_n is the rated power (VA), L is the per-unit load, $\cos\phi$ is the power factor, NLL is the no-load loss (W), and LL is the load loss (W) of transformer. In (1), the term $NLL + LL \cdot L^2$ denotes the transformer total loss (W) at per-unit load L, while the term $L \cdot S_n \cdot \cos\phi$ denotes the transformer output power (W) at per-unit load L.

As can be seen from (1), transformer efficiency is increased by reducing transformer losses.

3. Capacity and energy cost of transformer losses

The cost of transformer losses is important to the purchaser of a transformer. If the purchaser assumes a high cost for transformer losses, he or she will purchase more efficient transformers. On the other hand, if the purchaser assumes a low cost of transformer losses, he or she will purchase less efficient transformers.

The perspective of the electric utility is different from the perspective of the industrial and commercial users of transformers. The cost of transformer losses for the electric utility involves understanding and assessing the total cost of generating, transmitting and distributing transformer losses. On the other hand, the cost of transformer losses for industrial and commercial users requires an understanding and assessment of the electric rates they pay to the electric utility. The rest of this article is focused on the perspective of the electric utility.

The cost of transformer loss is the cost to produce, transmit, and distribute each kilowatt of transformer loss. The electric utility must add capacity to its generation, transmission and distribution system in order to deliver each additional kilowatt required to supply and deliver all losses, including transformer losses. In addition to the cost of generating, transmitting and distributing capacity for transformer losses, there is the cost of generating, transmitting and distributing the electrical energy. Both capacity and energy have to be dealt with individually.

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

$$CL = A \cdot NLL + B \cdot LL \tag{2}$$

where *A* is the no-load loss cost rate ($/W), *NLL* is the no-load loss (W), *B* is the load loss cost rate ($/W), and *LL* is the load loss (W) of transformer. The formulas for computing the *A* and *B* factors can be found in Appendix A.2. In (2), the term $A{\cdot}NLL$ denotes the cost of no-load loss ($), while the term $B \cdot LL$ denotes the cost of load loss ($) throughout the transformer lifetime.

The no-load loss cost rate, *A*, remains constant throughout the life of the transformer. Its value is determined by the capacity and energy required to generate, transmit, and distribute the no-load losses of transformer. Because no-load losses are constant, the power to serve transformer no-load losses comes from the utility's base load demand. It is concerned with the incremental cost of that base load demand. The difficulty comes in assigning a value over the let say 30-year typical life of the transformer. This means that there is a need to project the cost of no-load losses by predicting how the cost of generation, transmission, and distribution will change in the future.

The load loss cost rate, *B*, remains constant throughout the life of the transformer. Its value is determined by the capacity and energy required to generate, transmit, and distribute the load losses of the transformer.

The total owning cost, *TOC*, of the transformer lifetime is:

$$TOC = BP + CL \tag{3}$$

where *BP* ($) is the transformer bid price and *CL* ($) is the cost of transformer losses that is computed by (2). Among various transformer offers, the optimum transformer is the one with the minimum total owning cost.

4. Environmental cost of transformer losses

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

$$EC = A_e \cdot (NLL - NLL_r) + B_e \cdot (LL - LL_r) \tag{4}$$

where A_e is the no-load loss environmental factor ($/W), *NLL* is the no-load loss (W) of the evaluated transformer, NLL_r is the no-load loss (W) of a reference transformer, B_e is the load loss environmental factor ($/W), *LL* is the load loss (W) of evaluated transformer, and LL_r is the load loss (W) of a reference transformer. The formulas for computing the A_e and B_e factors can be found in Appendix A.3.

It should be noted that in (4):

- The term $A_e{\cdot}(NLL - NLL_r)$ 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 electric utility has to pay GHG emission penalties due to transformer no-load loss only if $NLL - NLL_r > 0$.
- The term $B_e{\cdot}(LL - LL_r)$ 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 electric utility has to pay GHG emission penalties due to transformer load loss only in case that $LL - LL_r > 0$.

Incorporating the environmental cost of transformer losses into the total owning cost yields the following formula:

$$TOC_e = TOC + EC \tag{5}$$

where TOC_e ($) is the total owning cost including the environmental cost, *TOC* ($) is the total owning cost excluding the environmental cost, and *EC* ($) is the environmental cost of transformer losses throughout the transformer lifetime. Among various transformer offers, the optimum transformer is the one with the minimum TOC_e (total owning cost including the environmental cost).

5. Results excluding environmental cost

5.1. Electric utility input data

The method is applied for the economic evaluation of distribution transformers for the Hellenic power system. The first step in the application of the method is to collect the data for the 14 input parameters (Appendix A.2) that are involved in the calculation of the *A* and *B* loss factors. In case of the Hellenic Public Power Corporation (PPC), the following values correspond to the 14 input parameters of Appendix A.2: $AF = 0.97$, $BL = 30$ yr, $CYEC = 0.084$ $/kW h, $d = 0.07$, $EIR = 0.027$, $ET = 0.95$, $FCR = 0.10$, $g = 0.025$, $HPY = 8760$ h/yr, $IF = 1$, $IP = 0.48$, $LDF = 0.678$, $LIC = 270$ $/kW yr, and $PRF = 0.443$. It should be noted that the previously mentioned values of *g*, *IP*, and *LDF* correspond to the typical load profile for residential low voltage consumers of PPC power system.

5.2. Calculation of A and B loss factors

Using the data of Section 5.1 and applying successively the formulas (A.1)–(A.6) of Appendix A.2, the following results are obtained: $CRF = 0.0806$, $LECN = 972.44$ $/kW yr, $LECL = 1002.51$ $/kW yr, $PUL = 0.6359$, $LSF = 0.4924$, and $TLF = 0.4463$. It should be noted that these results have been rounded for presentation purposes. Finally, using formulas (A.7) and (A.8), it is found that $A = 13.08$ $/W and $B = 2.33$ $/W.

5.3. Transformer offers

Let us consider that PPC has defined in its transformer specification that the transformer selection will be based on minimum *TOC* with the following loss cost rates: $A = 13.08$ $/W and $B = 2.33$ $/W, as computed in Section 5.2 considering a transformer lifetime of 30 years. It is considered that the electric utility receives the three competing offers of Table 1 for a 1000 kVA, three-phase, oil-immersed distribution transformer. The losses of the transformers of Table 1 are standardized according to EN 50464-1 [25]. It should be noted that the transformer bid price data of Table 1 was provided by a transformer manufacturer.

5.4. Transformer efficiency curves

Figs. 1 and 2 present the transformer total loss and the transformer efficiency, respectively, for the three offers of Table 1 for unity power factor and per-unit load ranging from 0.1 to 1.0 with step 0.1.

It can be seen from Fig. 2 that the most energy-efficient transformer is the one of offer D3 for the whole range of per-unit load. This happens because the transformer of offer D3 has the lowest total losses for the whole range of per-unit load, as Fig. 1 shows.

5.5. Transformer selection

Table 2 presents the total owning cost without environmental cost, *TOC*, for the three offers of Table 1. Based on Table 2, the following conclusions are drawn:

Table 1
Three competing transformer offers.

Offer code	Rated power, S_n (kVA)	EN 50464-1 loss category	Loss level	No-load loss, *NLL* (W)	Load loss, *LL* (W)	Bid price, *BP* ($)
D1	1000	E_0D_k	High	1700	13,000	20,450
D2	1000	D_0C_k	Medium	1400	10,500	22,250
D3	1000	C_0B_k	Low	1100	9000	25,800

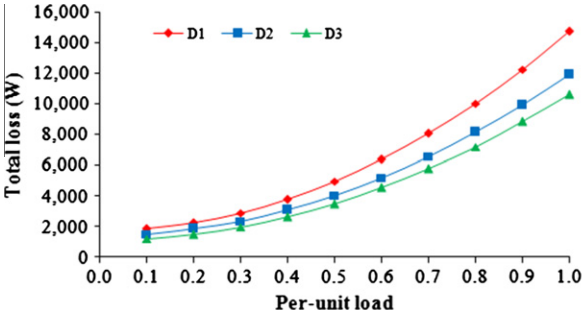

Fig. 1. Transformer total loss curves for the three offers of Table 1 at unity power factor.

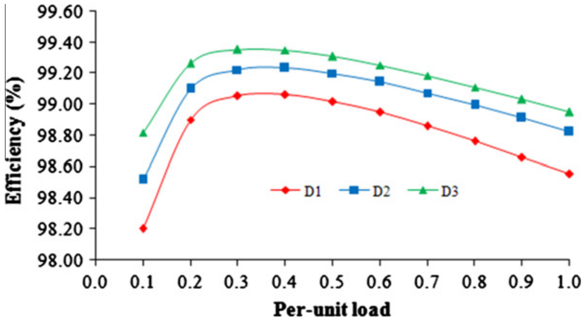

Fig. 2. Transformer efficiency curves for the three offers of Table 1 at unity power factor. The most energy-efficient transformer is the one of offer D3 for the whole range of per-unit load.

Table 2
Total owning cost (without environmental cost) for the three offers of Table 1.

Parameter	Offer D1	Offer D2	Offer D3
Bid price, *BP* ($)	20,450	22,250	25,800
Cost of no-load loss ($)	22,236	18,312	14,388
Cost of load loss ($)	30,290	24,465	20,970
Cost of losses, *CL* ($)	52,526	42,777	35,358
Total owning cost without *EC*, *TOC* ($)	72,976	65,027	61,158
BP/*TOC* (%)	28.0	34.2	42.2
CL/*TOC* (%)	72.0	65.8	57.8

1. Despite the fact that the transformer of offer D1 is the cheapest one concerning the bid price, it is the worst investment, since it has the highest *TOC*. This happens because the transformer of offer D1 is the less efficient (as can be seen in Fig. 2) and consequently it has the highest cost of losses during the transformer lifetime. More specifically, in the offer D1, the cost of losses is 72.0% of the *TOC* and the remaining 28.0% of the *TOC* is the bid price for offer D1.
2. Although the transformer of offer D3 is the most expensive concerning the bid price, it is the best investment, since it has the lowest *TOC*. This happens because the transformer of offer D3 is the most energy-efficient (as can be seen in Fig. 2) and consequently it has the lowest cost of losses during the transformer lifetime. Particularly, in the offer D3, the cost of losses is 57.8% of the *TOC* and the remaining 42.2% of the *TOC* is the bid price for offer D3.

Table 3
Electric utility electricity mix and greenhouse gas emission data.

Fuel type	Coal	Diesel	Hydro	Natural gas	Wind
Indicator of fuel type, *i*	1	2	3	4	5
f_i (%)	69.77	7.6	7.6	15	0.03
n_i (%)	35	30	100	45	100
λ_i (%)	8	8	8	8	8
$e_{\mathrm{CO}_2,i}$ (kg/GJ)	94.6	74.1	0	56.1	0
$e_{\mathrm{CH}_4,i}$ (kg/GJ)	0.002	0.002	0	0.003	0
$e_{\mathrm{N}_2\mathrm{O},i}$ (kg/GJ)	0.003	0.002	0	0.001	0

3. Although the bid price of D1 is 20.7% cheaper than the bid price of D3, the *TOC* of D1 is 19.3% more expensive than the *TOC* of D3 throughout the 30 years of transformer lifetime. The above-mentioned difference in *TOC* of D1 and D3 is attributed to the difference in the cost of losses of D1 and D3, as Table 2 shows. That is why it is very important to incorporate the cost of losses into the economic evaluation of distribution transformers.
4. The offer D3 has to be selected, since it has the minimum *TOC*, namely $61158.

6. Results including environmental cost

6.1. Electric utility additional input data

In addition to the data given in Section 5.1, the data of nine more input parameters (Appendix A.3), which are involved in the calculation of the A_e and B_e loss factors, have to be defined. In case of PPC electric utility, the following values correspond to the three input parameters of Appendix A.3: $C_{cy} = 50\$/t_{\mathrm{CO}_2}$, $EIR_e = 0.035$, and $N = 5$, while the values of the rest six parameters ($e_{\mathrm{CH}_4,i}, e_{\mathrm{CO}_2,i}, e_{\mathrm{N}_2\mathrm{O},i}$, f_i, n_i, and λ_i, $\forall\, i = 1,\ldots,N$) of Appendix A.3 are shown in Table 3.

6.2. Calculation of A_e and B_e loss factors

Using the data of Sections 5.1 and 6.1 and applying successively the formulas (A.9)–(A.12) of Appendix A.3, the following results are obtained: e_1 = 1.0685 $/MW h (similarly e_2, e_3, e_4, and e_5 are also computed from (A.9) formula), C = 44.66 $/MW h, $LECN_e$ = 570.89 $/kW yr, and $LECL_e$ = 588.54 $/kW yr. Finally, using formulas (A.13) and (A.14), it is found that A_e = 6.01 $/W and B_e = 1.23 $/W.

6.3. Comparison of three competing offers

Let us consider that PPC electric utility has defined in its transformer specification that the transformer selection will be based on minimum TOC_e (i.e., *TOC* including environmental cost) with the following loss cost rates: A = 13.08 $/W, B = 2.33 $/W, A_e = 6.01 $/W, B_e = 1.23 $/W, which have been computed in Sections 5.2 and 6.2, respectively. It is also given in the transformer specification that the reference transformer has NLL_r = 1100 W and LL_r = 10,500 W. It is considered that PPC receives the three competing

Table 4
Total owning cost (with environmental cost) for the three offers of Table 1.

Parameter	Offer D1	Offer D2	Offer D3
Bid price, *BP* ($)	20,450	22,250	25,800
Cost of no-load loss ($)	22,236	18,312	14,388
Cost of load loss ($)	30,290	24,465	20,970
Cost of losses, *CL* ($)	52,526	42,777	35,358
Total owning cost without *EC*, *TOC* ($)	72,976	65,027	61,158
Environmental cost of no-load loss ($)	3606	1803	0
Environmental cost of load loss ($)	3075	0	−1845
Environmental cost of losses, *EC* ($)	6681	1803	−1845
Total owning cost with *EC*, TOC_e ($)	79,657	66,830	59,313
EC/TOC_e (%)	8.4	2.7	−3.1
TOC/TOC_e (%)	91.6	97.3	103.1
EC/BP (%)	32.7	8.1	−7.2

offers of Table 1 for a 1000 kVA, three-phase, oil-immersed distribution transformer.

Table 4 presents the total owning cost with environmental cost, TOC_e, for the three offers of Table 1. Based on Table 4, the following conclusions are drawn:

1. The best investment is the transformer of offer D3 since it has the lowest *TOC* as well as the lowest TOC_e.
2. As can be seen from the last row of Table 4, in case of offer D1, the environmental cost of losses, *EC*, is 32.7% 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 7 for further evaluating the environmental cost of transformer losses.

7. Environmental cost of transformer losses for transformers ranging from 100 to 1600 kVA

7.1. Overview

The evaluation of the environmental cost of distribution transformer losses and the extraction of general conclusions require the consideration of representative transformer offers (Section 7.2), the analysis of alternative scenarios regarding key input parameters of the transformer environmental cost (Section 7.3), the introduction of a key performance indicator measuring the impact of the environmental cost on transformer purchasing decision (Section 7.4) and the analysis of this indicator for various transformer offers and alternative scenarios (Section 7.5).

7.2. Transformer offers

The transformer offers have to be as representative as possible. That is why seven different transformer ratings have been considered, ranging from 100 to 1600 kVA. Moreover, for each transformer rating, three loss levels are studied: high, medium, and low losses. In particular, EN 50464-1 standardization [25] of loss levels is used and the transformer losses are classified as follows in this paper:

1. *High loss transformer*: loss category E_0D_k [25]. In this paper, E_0D_k transformer offer is coded as kVA-D1, where kVA is the transformer rating.
2. *Medium loss transformer*: loss category D_0C_k. The transformer offer is coded as kVA-D2.
3. *Low loss transformer*: loss category C_0B_k. The transformer offer is coded as kVA-D3.

Table 5 presents the list of 21 transformer offers received for three-phase, oil-immersed distribution transformers. Moreover, in this table, the reference losses (NLL_r and LL_r) are also provided, which will be used for the computation of TOC_e. The transformer bid price data of Table 5 was provided by a transformer manufacturer.

7.3. Scenarios

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

1. The number of years of transformer lifetime, *BL*. When *BL* increases, all the loss factors (*A*, *B*, A_e, and B_e) also increase, which implies increase of the cost of losses (*CL*), and increase (decrease) of the environmental cost of transformer losses in case that the losses of the evaluated transformer are higher (lower) than the losses of the reference transformer as equation (4) shows.

Table 5
List of 21 transformer offers. Seven transformer ratings are considered, ranging from 100 to 1600 kVA. For each transformer rating, three competing offers are listed, corresponding to high, medium and low losses.

Offer code	S_n (kVA)	EN 50464-1 category	Loss level	*NLL* (W)	*LL* (W)	*BP* ($)	Reference losses for *EC* calculation (utility data)
100-D1	100	E_0D_k	High	320	2150	6000	NLL_r = 210 W, LL_r = 1750 W
100-D2	100	D_0C_k	Medium	260	1750	6400	NLL_r = 210 W, LL_r = 1750 W
100-D3	100	C_0B_k	Low	210	1475	7850	NLL_r = 210 W, LL_r = 1750 W
160-D1	160	E_0D_k	High	460	3100	6650	NLL_r = 300 W, LL_r = 2350 W
160-D2	160	D_0C_k	Medium	375	2350	7200	NLL_r = 300 W, LL_r = 2350 W
160-D3	160	C_0B_k	Low	300	2000	9550	NLL_r = 300 W, LL_r = 2350 W
250-D1	250	E_0D_k	High	650	4200	8450	NLL_r = 425 W, LL_r = 3250 W
250-D2	250	D_0C_k	Medium	530	3250	9350	NLL_r = 425 W, LL_r = 3250 W
250-D3	250	C_0B_k	Low	425	2750	11,000	NLL_r = 425 W, LL_r = 3250 W
400-D1	400	E_0D_k	High	930	6000	11,500	NLL_r = 610 W, LL_r = 4600 W
400-D2	400	D_0C_k	Medium	750	4600	12,500	NLL_r = 610 W, LL_r = 4600 W
400-D3	400	C_0B_k	Low	610	3850	15,100	NLL_r = 610 W, LL_r = 4600 W
630-D1	630	E_0D_k	High	1200	8700	16,000	NLL_r = 800 W, LL_r = 6750 W
630-D2	630	D_0C_k	Medium	940	6750	18,850	NLL_r = 800 W, LL_r = 6750 W
630-D3	630	C_0B_k	Low	800	5600	21,250	NLL_r = 800 W, LL_r = 6750 W
1000-D1	1000	E_0D_k	High	1700	13,000	20,450	NLL_r = 1100 W, LL_r = 10,500 W
1000-D2	1000	D_0C_k	Medium	1400	10,500	22,250	NLL_r = 1100 W, LL_r = 10,500 W
1000-D3	1000	C_0B_k	Low	1100	9000	25,800	NLL_r = 1100 W, LL_r = 10,500 W
1600-D1	1600	E_0D_k	High	2600	20,000	27,000	NLL_r = 1700 W, LL_r = 17,000 W
1600-D2	1600	D_0C_k	Medium	2200	17,000	29,000	NLL_r = 1700 W, LL_r = 17,000 W
1600-D3	1600	C_0B_k	Low	1700	14,000	31,300	NLL_r = 1700 W, LL_r = 17,000 W

Table 6

List of nine scenarios considered. These scenarios are defined by the values of the two input parameters *BL* and C_{cy}, each taking three discrete values: high, medium and low.

Scenario	Input parameters: *BL* and C_{cy}				Computed parameters			
	BL level	*BL* (yr)	C_{cy} level	C_{cy} (\$/t_{CO_2})	*A* (\$/W)	*B* (\$/W)	A_e (\$/W)	B_e (\$/W)
1	Medium	30	Medium	50	13.08	2.33	6.01	1.23
2	Medium	30	Low	25	13.08	2.33	3.00	0.62
3	Medium	30	High	100	13.08	2.33	12.02	2.47
4	Low	20	Medium	50	12.32	1.85	5.42	0.95
5	Low	20	Low	25	12.32	1.85	2.71	0.47
6	Low	20	High	100	12.32	1.85	10.83	1.89
7	High	40	Medium	50	13.69	2.81	6.52	1.53
8	High	40	Low	25	13.69	2.81	3.26	0.77
9	High	40	High	100	13.69	2.81	13.04	3.06

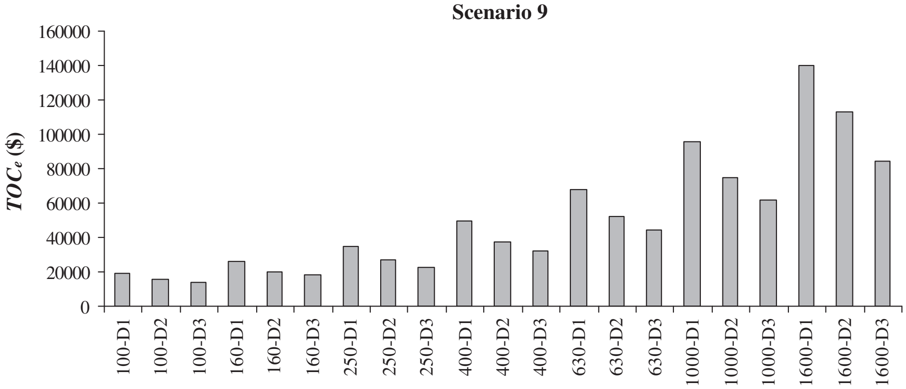

Fig. 3. TOC_e of scenario 9 for the 21 transformer offers of Table 5.

2. The current year (initial year or year zero of study) greenhouse gas emission cost value, C_{cy}. When C_{cy} 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 *BL* and C_{cy} have been selected for creating alternative scenarios as follows:

1. Three different values have been assigned to *BL*, i.e., 20, 30, and 40 years, corresponding to low, medium, and high *BL*, respectively.
2. Three different values have been assigned to C_{cy}, i.e., 25, 50, and 100 \$/t_{CO_2}, corresponding to low, medium, and high C_{cy}, respectively.

All the combinations of *BL* and C_{cy} values have been considered, thus the nine scenarios of Table 6 are studied. The values of all the other input parameters remain unchanged, having the values given in Sections 5.1 and 6.1. 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 the formulas of Appendix A, are also given in Table 6. It can be observed from Table 6 that the values of *A*, *B*, A_e, and B_e for scenario 1 are the same with the ones computed in Sections 5.2 and 6.2, because scenario 1 has the same data (including *BL* and C_{cy}) with Sections 5 and 6.

7.4. Performance indicator

The most important indicators in the transformer purchasing decision are the *TOC* and TOC_e, as already mentioned in Sections 3 and 4, respectively.

As an additional measure of the impact of the environmental cost on transformer purchasing decision, this paper introduces the indicator *EC*/*BP*, i.e., the ratio of the environmental cost of transformer losses over the transformer bid price. *BP* is given in the transformer offer, while *EC* is computed using (4). An application example of *EC*/*BP* is presented in Table 4, where it is observed that the *EC*/*BP* indicator can take positive or negative values. For example, a value of 0.3 for *EC*/*BP* means that the environmental cost of transformer losses is 30% of the transformer bid price. On the other hand, a value of −0.1 for *EC*/*BP* means that during the transformer lifetime a revenue equal to 10% of transformer bid price is produced for the transformer user due to the emission credits thanks to the reduced losses of the transformer in relation to the losses of the reference transformer.

7.5. Results and discussion

Fig. 3 shows the TOC_e of scenario 9 for the 21 transformer offers of Table 5. The main conclusion from this figure is that always the lowest TOC_e corresponds to the low loss transformer offer coded as kVA-D3, so this transformer has to be purchased according to the TOC_e criterion. For example, among 160-D1, 160-D2, and 160-D3, the lowest TOC_e corresponds to 160-D3, as Fig. 3 shows. Although not presented here due to space limitations, the same conclusion also applies to all the nine scenarios, i.e., almost always the best investment is the low loss transformer, with only the following exceptions:

1. Transformer offer 100-D2 for scenario 5. This result is due to the low values for all the loss factors (Table 6), which implies that the cost of losses (*CL*) of 100-D2 is \$1125 higher than 100-D3, the environmental cost of losses (*CL*) of 100-D2 is \$265 higher than 100-D3, but since the bid price (*BP*) of 100-D2 is \$1450 lower than 100-D3, finally, the TOC_e of 100-D2 is just \$60 lower than 100-D3, that is why 100-D2 is marginally the best investment for scenario 5.
2. Transformer offer 160-D2 for scenarios 2, 4, 5, and 8.

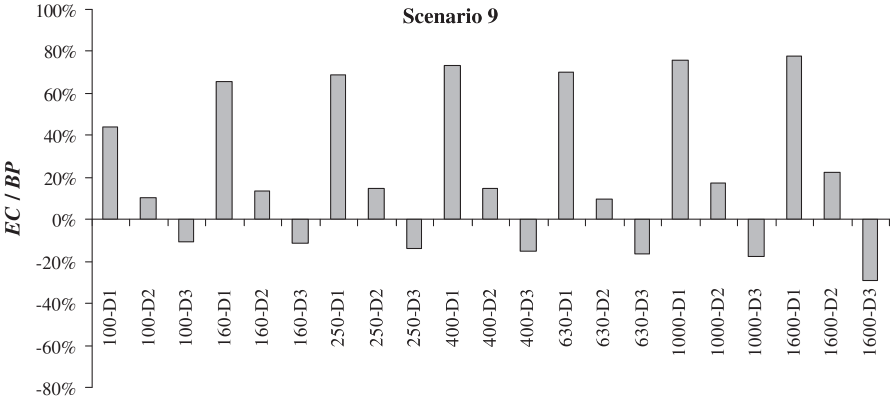

Fig. 4. *EC/BP* of scenario 9 for the 21 transformer offers of Table 5.

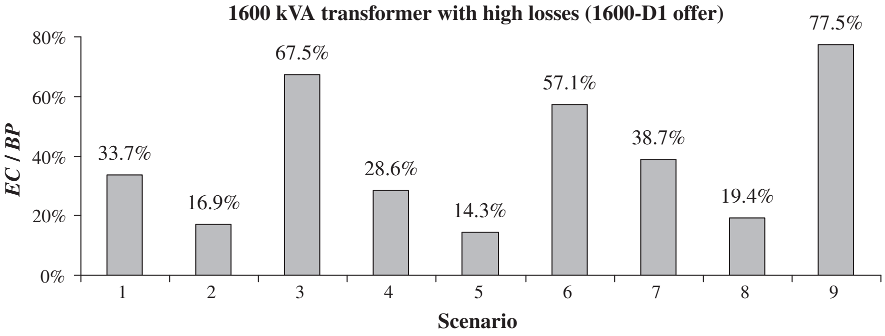

Fig. 5. *EC/BP* of the 1600 kVA transformer with high losses (1600-D1 offer of Table 5) for each one of the nine scenarios of Table 6.

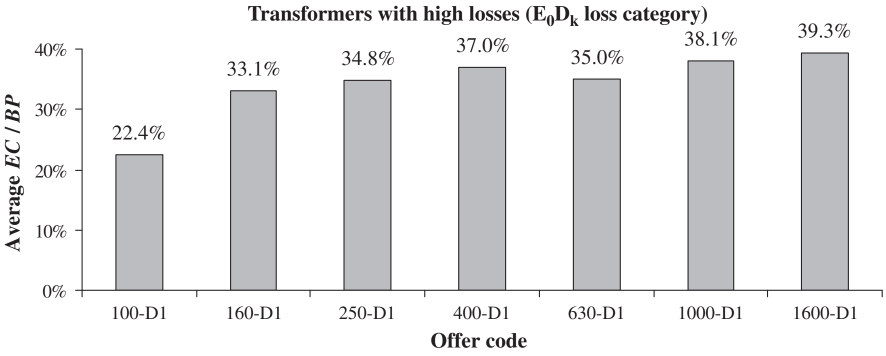

Fig. 6. Average *EC/BP* of the nine scenarios of Table 6 for the seven transformers with high losses (E_0D_k loss category) of Table 5.

Fig. 4 shows the values of *EC/BP* indicator of scenario 9 for the 21 transformer offers of Table 5. As can be seen from Fig. 4, the *EC/BP* indicator takes positive values for high loss and medium loss transformers, while it takes negative values for low loss transformers. This means that the negative environmental cost of low loss transformers makes these transformers economically more attractive, however, the final decision is based on the minimum TOC_e criterion.

Fig. 5 shows the values of *EC/BP* indicator for the 1600 kVA transformer with high losses for each one of the nine scenarios of Table 6. As can be seen from Fig. 5, the *EC/BP* indicator ranges from 14.3% to 77.5% with 39.3% average value. Fig. 6 shows the average *EC/BP* of the nine scenarios of Table 6 for the seven transformers with high losses of Table 5. As can be seen from Fig. 6, the average *EC/BP* indicator ranges from 22.4% to 39.3% with 34.2% average value.

Fig. 7 shows that for the case of 1600 kVA transformer with medium losses, the *EC/BP* indicator ranges from 4.7% to 22.5% with 12.0% average value. This variation is much smaller in comparison with the one encountered for the case of 1600 kVA high loss transformer (Fig. 5). Fig. 8 shows that for the case of medium loss transformers, the *EC/BP* indicator ranges from 5.2% to 12.0% with 7.9% average value. Again, this variation is much smaller in comparison with the one encountered for the case of high loss transformers (Fig. 6).

Fig. 9 shows that for the case of 1600 kVA transformer with low losses, the *EC/BP* indicator ranges from −29.3% to −4.5% with −13.8% average value. Fig. 10 shows that for the case of low loss transformers, the *EC/BP* indicator ranges from −13.8% to −5.1% with −7.7% average value. This negative environmental cost of low loss transformers makes them economically more attractive, however, the final decision is based on the minimum TOC_e.

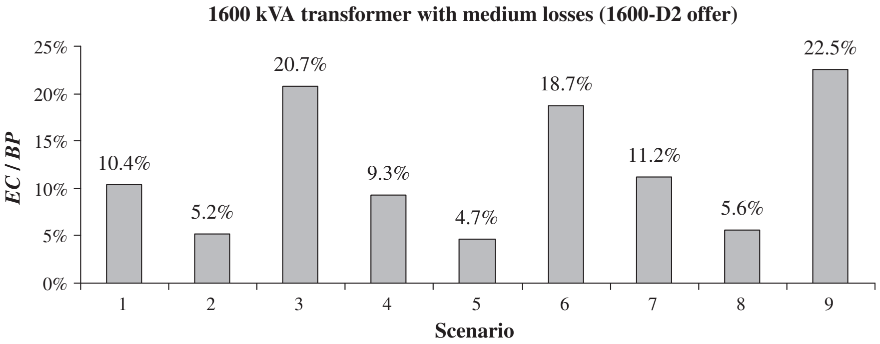

Fig. 7. *EC/BP* of the 1600 kVA transformer with medium losses (1600-D2 offer of Table 5) for each one of the nine scenarios of Table 6.

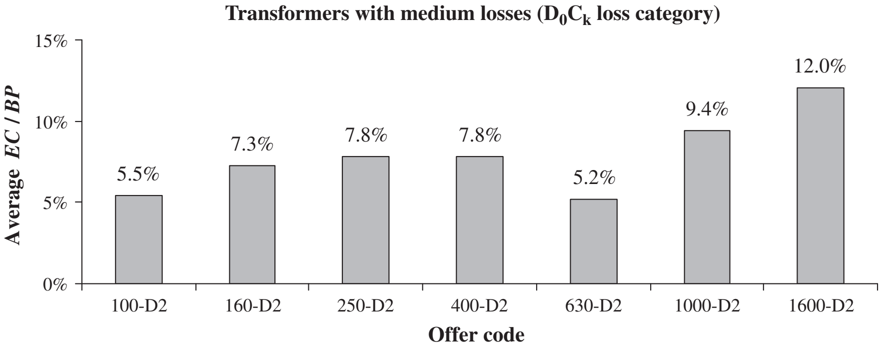

Fig. 8. Average *EC/BP* of the nine scenarios of Table 6 for the seven transformers with medium losses (D_0C_k loss category) of Table 5.

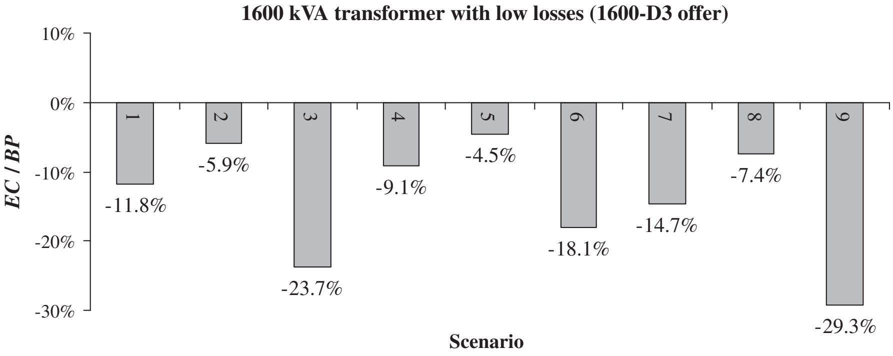

Fig. 9. *EC/BP* of the 1600 kVA transformer with low losses (1600-D3 offer of Table 5) for each one of the nine scenarios of Table 6.

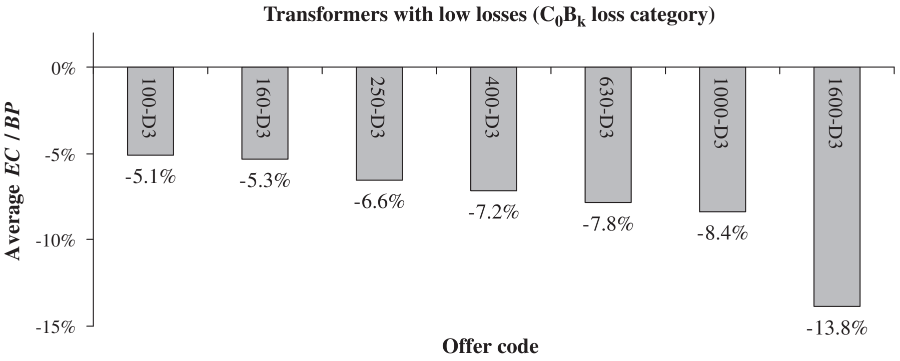

Fig. 10. Average *EC/BP* of the nine scenarios of Table 6 for the seven transformers with low losses (C_0B_k loss category) of Table 5.

8. Conclusions

This paper analyzes the impact of the environmental cost of transformer losses on the economic evaluation of distribution 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. Actual data (transformer specifications, transformer prices, electric utility data) is used. In particular, 21 transformer offers under 9 different scenarios are evaluated and their environmental cost of losses is computed. The offers correspond to high, medium and low loss transformers that are evaluated for the Hellenic power system. It has been found that the environmental cost of transformer losses can reach on average 34% and 8% of transformer purchasing price for high loss and medium loss transformers, respectively. That is why it is important to incorporate the environmental cost of transformer losses into the economic evaluation of distribution transformers.

Acknowledgements

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Appendix A. Calculation method for *A*, *B*, *A_e*, and *B_e* factors

A.1. Nomenclature

A.1.1. Input variables

AF	Transformer availability factor
BL	Number of years of transformer lifetime
C_{cy}	Current year (initial year or year zero of study) greenhouse gas emission cost value ($/$t_{CO_2}$), where t_{CO_2} denotes the tonnes of equivalent CO_2 emissions
CYEC	Current year energy cost ($/kWh)
d	Annual discount (interest) rate (%)
$e_{CH_4,i}$	CH_4 emission factor for fuel *i* (kg/GJ)
$e_{CO_2,i}$	CO_2 emission factor for fuel *i* (kg/GJ)
EIR	Annual escalation rate of the electricity cost (%)
EIR_e	Annual escalation rate of the current year greenhouse gas emission cost value C_{cy} (%)
$e_{N_2O,i}$	N_2O emission factor for fuel *i* (kg/GJ)
ET	Efficiency of transmission
FCR	Fixed charge rate
f_i	Fraction of end-use electricity coming from fuel *i* (%)
g	Levelized annual compound peak load growth rate (%)
HPY	Hours of transformer operation per year
IF	Increase factor
IP	Current year transformer annual peak load as a percentage of transformer rated power
LDF	Load factor, i.e., mean transformer loading throughout its lifetime
LIC	Levelized annual generation and transmission system investment cost ($/kW yr)
N	Number of fuels in the electricity mix
n_i	Conversion efficiency for fuel *i* (%)
PRF	Peak responsibility factor
λ_i	Fraction of electricity lost in transmission and distribution for fuel *i* (%)

A.1.2. Computed variables

A	No-load loss factor ($/kW)
A_e	No-load loss environmental factor ($/kW)
B	Load loss factor ($/kW)
B_e	Load loss environmental factor ($/kW)
C	Current year greenhouse gas emission cost factor ($/MW h)
CRF	Capital recovery factor
e_i	Emission factor for fuel *i* (%)
LECL	Levelized annual energy and operating cost of transformer load loss ($/kW yr)
$LECL_e$	Levelized annual environmental cost of transformer load loss ($/kW yr)
LECN	Levelized annual energy and operating cost of transformer no-load loss ($/kW yr)
$LECN_e$	Levelized annual environmental cost of transformer no-load loss ($/kW yr)
LSF	Loss factor
PUL	Peak per-unit load
TLF	Transformer loading factor

A.2. Calculation of A and B factors

The following equations are successively used to compute the *A* and *B* factors [14,23]:

$$CRF = \frac{d\cdot(1+d)^{BL}}{(1+d)^{BL}-1} \tag{A.1}$$

$$LECN = CRF\cdot HPY\cdot AF\cdot CYEC\cdot\left(\frac{1+EIR}{d-EIR}\right)\cdot\left[1-\left(\frac{1+EIR}{1+d}\right)^{BL}\right] \tag{A.2}$$

$$LECL = \frac{LECN}{AF} \tag{A.3}$$

$$PUL = IP\cdot\sqrt{\left[\frac{(1+g)^{2\cdot BL}-(1+d)^{BL}}{(1+g)^2-(1+d)}\right]\cdot\left[\frac{d}{(1+d)^{BL}-1}\right]} \tag{A.4}$$

$$LSF = 0.15\cdot LDF + 0.85\cdot LDF^2 \tag{A.5}$$

$$TLF = PUL\cdot\sqrt{LSF} \tag{A.6}$$

$$A = \frac{LIC + LECN}{ET\cdot FCR\cdot IF} \tag{A.7}$$

$$B = \frac{LIC\cdot PRF^2\cdot PUL^2 + LECL\cdot TLF^2}{ET\cdot FCR\cdot IF} \tag{A.8}$$

It is concluded from the above that for the calculation of the *A* and *B* loss factors, the following 14 input parameters are involved: *AF*, *BL*, *CYEC*, *d*, *EIR*, *ET*, *FCR*, *g*, *HPY*, *IF*, *IP*, *LDF*, *LIC*, and *PRF*. More details for these parameters can be found in [5,14–16].

A.3. Calculation of A_e and B_e factors

The following equations are successively used to compute the A_e and B_e factors [23,24]:

$$e_i = (e_{CO_2,i} + e_{CH_4,i}\cdot 21 + e_{N_2O,i}\cdot 310)\cdot\frac{0.0036}{n_i\cdot(1-\lambda_i)},\quad \forall\, i = 1,\ldots,N \tag{A.9}$$

$$C = C_{cy} \cdot \sum_{i=1}^{N} f_i \cdot e_i \tag{A.10}$$

$$LECN_e = CRF \cdot HPY \cdot AF \cdot C \cdot \left(\frac{1 + EIR_e}{d - EIR_e}\right) \cdot \left[1 - \left(\frac{1 + EIR_e}{1 + d}\right)^{BL}\right] \tag{A.11}$$

$$LECL_e = \frac{LECN_e}{AF} \tag{A.12}$$

$$A_e = \frac{LECN_e}{ET \cdot FCR \cdot IF} \tag{A.13}$$

$$B_e = \frac{LECL_e \cdot TLF^2}{ET \cdot FCR \cdot IF} \tag{A.14}$$

It is concluded from the above that for the calculation of the A_e and B_e loss factors, the following 9 input parameters are involved: C_{cy}, EIR_e, N, $e_{CH_{4,i}}$, $e_{CO_{2,i}}$, $e_{N_2O_{,i}}$, f_i, n_i, and λ_i, where the last six parameters have to be set $\forall\ i = 1, \ldots, N$. More details for these 9 parameters can be found in [23,24]. It should be noted that CRF and TLF, which are involved in the calculation of A_e and B_e, are computed by (A.1) and (A.6), respectively. Obviously, all the input parameters, which are common for the computation of the A and B as well as the A_e and B_e loss factors, share the same data.

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