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Economic Evaluation of Transformer Selection in Distribution Systems

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Abstract— This paper presents an approach to determine the total owning cost (TOC) of transformers. Different assumptions are introduced by discounting the transformer cost and/or the losses cost, using either A and B loss coefficients or the idea of annuity factor. Moreover, the paper presents a comparative study between different cases under different presumptions to evaluate the transformer's TOC. The obtained results confirm that the proposed approach equips the decision-maker with valuable and trustable criteria to select the proper transformer(s) based on the proposed practical cost criteria. The presumptions of the proposed cost criteria influence economic evaluation. The TOC of the transformer is also illustrated. Finally, the proposed approach cost criteria were illustrated through a numerical example. The obtained results have been summarized and discussed.

Keywords—Losses coefficients, total owning cost, transformer economics, transformer losses.

I. INTRODUCTION

The main purpose of power generation, transmission, and distribution is to provide electrical energy to the end users. However, the flow of the electrical current in the power system equipment causes several types of power losses and a decrease in power efficiency. Accordingly, the maximum power efficiency can be obtained when all equipment in the power system is working at its maximum efficiency. Thus, the proper selection of the power system equipment will enhance system efficiency and reduce the overall cost. Transformers are regarded as static equipment; and they are usually designed for a lifetime of 20 years or more. Their efficiencies are varying in the range of 96% to 99.2% or more. The huge numbers of transformers used in power systems make their influence to be significant. Accordingly, the proper selection of the transformer in terms of its type, capacity and technical parameters with regard to the investment cost is considered an important issue. Different types of materials and processes are used to optimize the energy loss cost and the overall transformer cost. The transformer core material and windings are usually the main components which cause electrical losses. Windings are mostly made of copper (Cu) though the aluminum (Al) price is lower than Cu, which is the reason why Al is sometimes used. The required Al cross-section area is around 1.6 times more than Cu to carry the same current. This feature is utilized to use Al instead of Cu and avoid breaking of the wires during the winding process when a thin wire of Cu is used.

Several approaches have been used recently to find the total owing cost (TOC) of the transformers. They are mainly categorized into three methods: discounting the transformer cost in a simple way with or without considering the cost of losses [1], [2]; providing the idea of A and B loss coefficients [3]; and discounting all the values that have an effect on TOC of the transformer by providing the idea of annuity factor [4], [5]. The other used methods are usually a combination of these above-mentioned methods.

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The proposed method in this paper differs from the previous work in term of the fact that the introduced transformer economic evaluation method does not neglect any coefficients that could take place or Affect the processes of the transformer economic evaluation. Moreover, the presented approach is easy to follow because it does not need special mathematical tools or programs to be applied. The usage of different presumptions (cases) is a very helpful indicator for which a presumption is suitable to be applied in order to obtain an acceptable result. Hence, the failure in taking an appropriate decision when selecting the proper transformer could cause a defect in the whole investment, which could continue for the operation lifetime and cause a continuous loss of money over the whole transformer lifespan. The advantage and disadvantage of each presumption are outlined.

The rest of the paper is organized as follows: In section II, problem formulation is presented. The economic evaluation is introduced in section III. In section IV, a numerical example is given to demonstrate the implementation of the proposed approach. Finally, the results and conclusions are presented in section V.

II. PROBLEM FORMULATION

To minimize the cost associated with the electrical energy loss and the investment cost of the transformer, the objective function can be mathematically formulated as follows:

find:

$$\text{Min. } \{C_{\text{Tr.i}}\} \tag{1}$$

subject to:

$$S_{\text{Tr.}} \geq S_{\text{D}} \tag{2}$$

and

$$C_{\text{Tr.i}} = C_{\text{c.Tr.}} + C_{\text{losses}} + C_{\text{availability}} \tag{3}$$

where $C_{\text{c.Tr.}}$- capital cost of the transformer [$/year]; $C_{\text{Tr.i}}$- total owning cost of the *i^{th}* transformer [$/year]; C_{losses}- losses cost of the transformer [$/year]; $C_{\text{availability}}$- availability cost [$/year]; S_{D}- designed capacity of the transformer [kVA]; and $S_{\text{Tr.}}$- transformer capacity, [kVA].

The availability cost or economic cost in relation to the interruptions of the power supply could have a harmful effect if the old (in service) transformer is going to be replaced by a new one. An interruption in the production may occur then. However, if the old transformer is replaced during the design stage or the annual shutdown period, then there will be no effect of such a cost which can be saved. For the simplicity of the forthcoming calculations, the availability cost in (3) will be neglected; and the objective function becomes as in (4):

$$C_{\text{Tr.i}} = C_{\text{c.Tr.}} + C_{\text{losses}} \tag{4}$$

The capital cost of the transformer includes the price of the transformer, transportation cost, supervision, erection, testing and commissioning. However, the yearly discounted cost includes the cost of maintenance. The total losses cost of the transformer is the sum of the no-load and load losses as expressed in (5):

$$C_{\text{losses}} = C_{\Delta P_{\text{NLL}}} + C_{\Delta P_{\text{LL}}} \tag{5}$$

where $C_{\Delta P_{NLL}}$ - costs of the no-load losses [\$/year]; and $C_{\Delta P_{LL}}$ - costs of the load losses [\$/year].

A) Transformer Losses

The connection of the transformer to the power supply causes the flow of a no-load current, even if the secondary winding of the transformer is not connected to the load. The main types of losses that have a place in the transformer are as follows:

1) Power Losses: The active power losses caused by the flow of the current are mainly related to the losses generated in the core sheets by the main flux of the transformer. They are called the iron losses or the no-load losses; hysterics losses and eddy current losses. These types of losses are independent from the load current. The second type of transformer losses is generated by the flow of the load current in the transformer's windings. They are called the copper losses or load losses. The active power loss is a sum of the losses caused by the flow of the active and reactive power as follows:

$$\Delta P = \Delta P_p + \Delta P_q \tag{6}$$

The active power losses due to the flow of no-load and load current can be expressed as:

$$\Delta P_p = \Delta P_{Fe} + \Delta P_{Cu} \cdot \left(\frac{S_L}{S_n}\right)^2 \tag{7}$$

The values of the no-load and load losses are usually given in the manufacturer's technical data sheet for a certain type of transformers.

Similarly, the flows of the reactive power cause reactive power losses in the transformer in term of no-load and load as:

$$\Delta Q = \Delta Q_o + \Delta Q_L \cdot \left(\frac{S_L}{S_n}\right)^2 \tag{8}$$

where ΔQ_o and ΔQ_L can be expressed as in (9) and (10), respectively:

$$\Delta Q_o = \frac{I_{o\%}}{100} \cdot S_n \tag{9}$$

$$\Delta Q_L = \frac{\Delta V_{x\%}}{100} \cdot S_n \tag{10}$$

The active power losses caused by the flow of the reactive power can be represented by an equivalent coefficient (k_e) as:

$$\Delta P_q = k_e \cdot \Delta Q \tag{11}$$

Substituting (7) and (8) with (6) considering (11) yields the total power losses formula which is given by (12):

$$\Delta P = \Delta P_{Fe} + \Delta P_{Cu} \cdot \left(\frac{S_L}{S_n}\right)^2 + k_e \cdot [\Delta Q_o + \Delta Q_L \cdot \left(\frac{S_L}{S_n}\right)^2] \tag{12}$$

However, if the relation between the maximum loading of the transformer and the rated capacity is signified by (β), and substituted with (12), formula (13) will be obtained:

$$\Delta P = (\Delta P_{Fe} + k_e \cdot \frac{I_{o\%}}{100} \cdot S_n) + \left(\Delta P_{Cu} + k_e \cdot \frac{\Delta V_{x\%}}{100} \cdot S_n\right) \cdot \beta^2 \tag{13}$$

The coefficient that converts the reactive power losses to active power losses [6] is as follows:

$$k_e = \frac{\partial}{\partial Q}\left(\frac{P^2 + Q^2}{V^2}\right) \cdot \ R_{Tr.} = \ \frac{2 \cdot Q}{V^2} \cdot R_{Tr.} \tag{14}$$

where the resistance of the transformer windings can be calculated by (15):

$$R_{Tr.} = \Delta P_{Cu} \cdot \frac{V_n^2}{S_n^2} \tag{15}$$

where β- transformer loading degree [unit less, or in %]; ΔP- active power losses [kW]; ΔP_{Cu}- active power load losses [kW]; ΔP_{Fe}- active power no-load losses [kW]; ΔP_p- active power losses caused by the flow of active power [kW]; ΔP_q- active losses caused by the flow of reactive power [kW]; ΔQ_L- reactive power load losses [kVAR]; ΔQ_o- reactive power no-load losses [kVAR]; $I_o\%$- no-load current [%]; k_e- equivalent coefficient converting the reactive power losses to active power losses [kW/kVAR]; P- transformer's active power load [kW]; Q- transformer's reactive power load [kVAR]; $\Delta V_x\%$- percentage of voltage drop in transformer reactance [%]; $R_{Tr.}$- equivalent transformer windings resistance [Ω];S_L- maximum apparent power loading of the transformer [kVA]; S_n- rated capacity of the transformer [kVA]; and V_n- rated voltage of the transformer [V].

Usually, the value of (k_e) is given by the electricity provider for certain points of the network which are subject to the voltage level [7] as presented in Table 1.

TABLE 1
EQUIVALENT COEFFICIENT VALUES FOR DIFFERENT LOADING

Network	Max. loading	Min. loading
110 [kV]	0.1	0.06
6-60 [kV]	0.12 -0.15	0.08 - 0.15
1 [kV]	0.18-0.23	0.12 - 0.15

For the mathematical analysis, the arithmetic average of upper and lower values of a certain voltage level can be considered. However, for simplicity and in the case of lacking the value of (k_e) information, then (7) is used instead of (13). This will be occupied by the accuracy of the achieved result. Hence, the total losses amount becomes less for low voltage transformers. ΔP is less by (15%-25%).

2) The Energy Losses: The energy losses are calculated from the power losses integration over a certain period of time. As a result, if the time-varying of power losses values are arranged in a descending order from maximum to minimum values as depicted in Fig. 1, the areas under the curve of the dotted and straight line will be equal. This can be mathematically expressed as in (16):

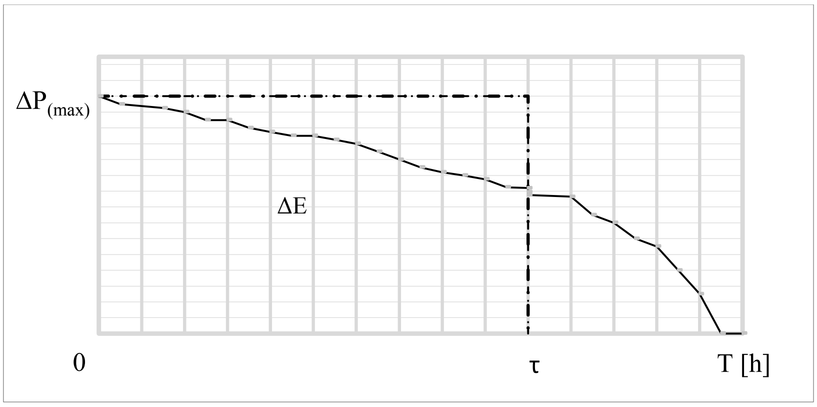

Fig. 1. Electrical energy losses

$$\Delta E = \int_0^T \Delta P_{(t)} \cdot dt = \Delta P_{(t)} \cdot T = \Delta P_{(max.)} \cdot \tau \tag{16}$$

Considering the relation between τ and LSF [6], we obtain:

$$\tau = LSF \cdot T \tag{17}$$

where ΔE- active energy losses [kWh]; $\Delta P_{(max.)}$- maximum value of active power losses [kW]; $\Delta P_{(Min.)}$- minimum value active power losses [kW]; $\Delta P_{(t)}$- time-varying of the power losses [kW]; LSF- load loss factor [unitless or %]; τ- equivalent load losses [h]; and T- time of transformer loading [h].

LSF is a factor that gives the overall average energy loss ΔE [6], [8], when multiplied by the energy lost at the time of peak $\Delta P_{(max)}$ and the number of load periods T.

Substituting (17) with (16) yields:

$$\Delta E = \Delta P_{max.} \cdot T \cdot LSF \tag{18}$$

Moreover, there is a relationship between LF and LSF given in [8], [9], where the classical mathematical formula is presented as in (19):

$$LSF = (1 - k) \cdot LF^2 + k \cdot LF \tag{19}$$

The value of (k) in (19) has values varying between zero and one. For instance, k=0.2 in GB; 0.3 in US; and 0.333 in PL. In this paper and for further calculations, the value of k is assumed to be equal to 0.333.

Accordingly, LF in (19) is defined as the ratio of the average load supplied during the designated period of time to the maximum load occurring in that period of time as expressed in (20), [10], [11].

$$LF = \frac{P_{(avg.)}}{P_{(max)}} = \frac{E}{P_{(max)} \cdot T} = \frac{P_{(max)} \cdot T_{(eq.)}}{P_{(max)} \cdot T} = \frac{T_{(eq.)}}{T} \tag{20}$$

When taking (13) into consideration, the energy loss consists of two parts. The first is related to the no-load current occurring during the time T and called the no-load energy loss. The second part is related to the load current during the time τ and called the energy load loss as expressed in (21) and simplified in (22):

$$\Delta E = (\Delta P_{Fe} + k_e \cdot \Delta Q_o) \cdot T + (\Delta P_{Cu} + k_e \cdot \Delta Q_L) \cdot \beta^2 \cdot \tau \tag{21}$$

$$\Delta E = \Delta E_{NLL} + \Delta E_{LL} \tag{22}$$

where ΔE_{NLL}- active energy no-load losses [kW.h]; ΔE_{LL} - active energy load losses [kW.h]; $P_{(avg.)}$- average value of active power load [kW]; $P_{(max.)}$- maximum value of active power load [kW]; and $T_{(eq)}$- equivalent working hours per year [h].

B) Power and Energy Losses Cost

Consumers in different utilities are paying for their electricity bill mainly for the following items: an amount for maximum demand (MD), an amount for the consumed energy with day and night tariffs, and an extra amount for penalty when the power factor becomes less than a specified value as determined by the electricity provider.

According to the existing tariff [12], the power factor shall be not less than ($\cos\varphi \geq 0.88$ "i.e.: $tag\varphi \cong 0.54$"). The additional active power loss due to the flow of additional reactive power is causes an additional cost. Thus, the cost of losses of the transformer can be expressed as in (23):

$$C_{losses} = C_p \cdot \Delta P + C_e \cdot \Delta E + C_Q \tag{23}$$

where

$$C_Q = k_q \cdot \Delta Q_{(add.)} \tag{24}$$

and

$$\Delta Q_{(add.)} = \Delta Q_{(max)} - 0.54 \cdot \Delta P_{(max)} \tag{25}$$

The (k_q) is an additional payment [\$/kVAR] imposed on the electricity bill as a penalty due to low power factor value. For simplicity, we assume that the power factor is within its allowed value; and no penalty is applied. This means that (C_Q) is equal to zero.

The capacity system cost C_p in (23), which is the cost of producing one additional [kW], can be expressed as in (26):

$$C_p = C_{MD} \cdot RF \tag{26}$$

where MD- maximum demand period [h]; C_e- active energy cost [\$/kWh]; C_{MD}- maximum demand charge [\$/kW.month]; C_Q- additional cost of reactive power consumption due to low power factor [\$]; C_p- capacity system cost [\$/kW]; $\Delta Q_{(add.)}$- additional reactive power consumption due to low power factor [kVAR]; k_q- additional payment (penalty) due to low power [\$/kVAR]; and RF- responsibility factor which is the contribution of component in the system peak [%].

C_p is reduced by peak losses responsibility factor (RF). Since the peak of the transformer losses does not necessarily occur at the maximum demand time load, the value of RF is varying between zero and one. RF is just over zero if the transformer is not loaded during the maximum demand MD period. However, RF is just equal to one if the maximum loading of the transformer occurs during the MD period. Hence, MD is a part of existing electricity tariff. The total cost of the transformer losses C_{losses} as given in [13] is obtained when substituting (21) or (22) with (23) and considering (26). After some modification, (27) is obtained:

$$\begin{aligned} C_{losses} = {} & [(C_{MD} \cdot RF + C_e \cdot T) \cdot (\Delta P_{Fe} + k_e \cdot \Delta Q_o)] \\ & +[(C_{MD} \cdot RF + C_e \cdot \tau) \cdot [\Delta P_{Cu} + k_e \cdot \Delta Q_L] \cdot \beta^2] \end{aligned} \tag{27}$$

III. ECONOMIC EVALUATION

In this section, the impact of using different methods on TOC will be investigated in details. The main difference between these methods was in the presumptions used for the mathematical analysis. These differences are discussed and presented in section IV. The formula presents the amortization of the annuity value [5]. The annual installments cost of the transformer and interest is as expressed in (28).

$$C_{c.Tr.(annual)} = C_{c.Tr.} \cdot \left[\frac{p \cdot (1+p)^n}{(1+p)^n - 1}\right] \tag{28}$$

To find the capital cost of the transformer per month, the present value (discounted value) is calculated using the following formula:

$$C_{c.Tr.(PV/month)} = C_{c.Tr.(annual)} \cdot \frac{m}{12} \cdot \left[\frac{1}{(1+p)^{\frac{m}{12}}}\right] \tag{29}$$

where (m) is the month number. Thus, m=1 for 1st month; 2 for the 2nd month; till 12 for the last month in the year. Therefore, the monthly owing cost of the transformer is obtained by substituting (28) with (29), to yield (30):

$$C_{Tr.i(per\ month)} = C_{c.Tr.(PV/month)} + C_p \cdot \Delta P_m + C_e \cdot \Delta E_m \tag{30}$$

where $C_{c.Tr.}$- the total cost of the transformers [\$]; $C_{c.Tr.(Annual)}$- annual installment of the transformer using the present value of an annuity [\$/year]; $C_{c.Tr.(PV/month)}$ - monthly installment of the transformer using the present value of an annuity [\$/month]; ΔP_m– active power losses in a month (m) [kW]; ΔE_m- active energy losses in a month (m) [kWh]; r- discount rate (interest rate) per periods [%]; m- number of month [m=1to 12]; and n- number of periods [years].

Equation (30) allows the calculation of the transformers monthly owing cost with varying capital cost and varying values of the no-load and loaded losses. It makes it easier to take the investment decision. The impact of the above will be thoroughly demonstrated in a numerical example in the following section of IV.

IV. NUMERICAL EXAMPLE

In this section, a numerical example is presented to explain the proposed method. The input data and the conducted calculations are as follow.

A) Load Input Data

An object consumes 515 [MWh/year] with MD of 150 [kW] and power factor of 0.882. The unit price of the consumed energy for the existing tariff issued by ECR [12] and for "H-Medium Industries [\$/kWh] is as presented in Table 2.

TABLE 2
POWER AND ENERGY UNIT COST

Peak Load, MD [\$/kW]	5.338
Day Energy, C_e[\$/kWh]	0.125
Night Energy, C_e[\$/kWh]	0.105

B) Transformers Technical Data

The object is fed by a dry-type transformer. The suppliers [14] offered two transformers from different manufacturers. Both transformers have the same capacity [kVA], but different load and no- load power losses. The first transformer has windings made of Al, whereas the second transformer has windings made of Cu. The power losses of the transformers as indicated in the manufacturers' data sheet are as shown in Table 3.

TABLE 3
TRANSFORMERS TECHNICAL DATA

Item	Transformer 1 (Al)	Transformer 2 (Cu)
$S_{(Tr.\ Rated)}$ [kVA]	200	200
ΔP_{Cu} [kW]	3.2	2.36
ΔP_{Fe} [kW]	0.91	0.62
I_o[%]	2	1
ΔVsc [%]	4	4

However, the followings costs shall be added to the CIF price of the transformers as indicated in Table 4.

TABLE 4
TRANSFORMERS TOTAL PURCHASE COST (TRANSFORMER PRICE)

Item	Transformer 1 (Al)	Transformer 2 (Cu)
$C_{Tr.\ (EX\text{-}work\ Price)}$ [$]	6100	8000
Customs (20%)	1220	1600
VAT (16%)	976	1280
TAX (5%)	305	400
Erection (8%)	488	640
$C_{Tr.\ (total\ cost)}$ [$]	9089	11920

For the purpose of calculations, the energy price is assumed to be the arithmetic average for the day and night tariff. The average cost of 1kwh ($C_{e(Avg)}$ can be obtained in [$/kWh] which is equal to 0.115).

C) Transformer Loading

Based on the given data, the maximum loading of the transformer can be found as follows:

$$S_{L(Tr.)} = \frac{P_{(max)}}{\cos\varphi} = \frac{150}{0.882} = 170\ \mathrm{kVA}$$

Using (20) to calculate LF:

$$LF = \frac{E}{P_{(max.)} \cdot T} = \frac{515\ [MWh]}{150\ [kW] \cdot 8760\ [h]} = 0.392 = 39.2\ \%$$

and

$$T_{(eq.)} = LF \cdot T = 0.392 \cdot 8760 = 3433\ h/yr$$

from (19), τ is calculated (for k=1/3) as:

$$\tau = LSF \cdot 8760 = [(1 - 0.333) \cdot 0.392^2 + 0.333 \cdot 0.392] \cdot 8760 = 2039\ h$$

Based on (12) and (13), $\beta_{(Tr)}$ is calculated as:

$$\beta_{(Tr)} = \left(\frac{S_L}{S_n}\right)^2 = \left(\frac{170}{200}\right)^2 = 0.850 = 85\%$$

The equivalent coefficient (k_e) for low voltage networks is taken as an average value of the minimum and maximum loading presented in Table 1. It is obtained as:

$$ke = (0.12 + 0.15)/2 = 0.135\ kW/kVAR$$

D) Energy Loss Evaluation

As an example for the TOC of the transformer, the calculation is conducted for the transformer with the Al windings. However, for the transformer of Cu windings, the procedure of the calculation remains the same; and the difference is only in the input data. The active power loss is calculated using (13), which gives:

$$\Delta P = 0.91 + 0.135 \cdot \frac{2}{100} \cdot 200 + (3.2 + 0.135 \cdot \frac{4}{100} \cdot 200) \cdot 0.850^2 = 5.43\ kW$$

The energy losses are obtained by using (21):

$$\Delta E = (0.91 + (0.135 \cdot 0.02 \cdot 200) \cdot 8760 + (3.2 + 0.135 \cdot 0.04 \cdot 200) \cdot 0.850^2 \cdot 2039 = 6325.54 \text{ kW.h/ year}$$

Assuming that RF=1, for simplicity, the cost of the total losses is obtained using (27):

$$\begin{aligned} C_{\text{losses}} = & \left[(5.338 \cdot 1 + 0.115 \cdot 8760) \cdot \left(0.91 + 0.135 \cdot \frac{2}{100} \cdot 200 \right) \right] \\ & + \left[(5.338 \cdot 1 + 0.115 \cdot 2039) \cdot \left(3.2 + 0.135 \cdot \frac{4}{100} \cdot 200 \right] \cdot 0.85^2 \right] \\ & = 2{,}219.6 \text{ \$/year} \end{aligned}$$

The calculations summary of the active and reactive power losses and the active energy losses along with their costs are presented in Table 5.

TABLE 5
TRANSFORMERS POWER LOSSES, ENERGY LOSSES AND LOSSES COST

Item	Transformer- 1 (Al)	Transformer- 2 (Cu)
ΔQ_o [kVAR]	4.00	2.00
ΔQ_L [kVAR]	8.00	8.00
ΔP_{NLL} [kW]	1.45	0.89
ΔP_{LL} [kW]	3.98	3.14
ΔP [kW]	5.43	4.03
ΔE[kWh]	6325.93	9390.18
$C_{(\text{losses})}$ [\$/y]	2,219.62	1,503.88
$C_{(\text{losses})}$ [\$/Month]	184.97	125.32

where

$$\Delta P_{NLL} = \Delta P_{Fe} + ke \cdot \Delta Q_o \Rightarrow> 0.91 + (4 \cdot 0.135) = 1.45 \text{ kW}$$

and

$$\Delta P_{LL} = \Delta P_{Cu} + ke \cdot \Delta Q_L \Rightarrow> 3.2 + (0.135 \cdot 8) \cdot 0.852 = 3.98 \text{ kW}$$

E) Economic Evaluation of TOC

Different cases with different assumptions have been investigated and analyzed in order to determine the TOC of the transformers. The differences between these cases are as follow:

1) Case 1: all values are not discounted (i.e. the transformer price and the losses cost).
2) Case 2: only the transformer price is discounted using the present value method.
3) Case 3: all values are discounted using the present value method (the transformer price and the losses cost).
4) Case 4: all values are discounted using the annuity factor.
5) Case 5: the transformer price (not discounted) considering the discounted values of the factors (A and B). This method is used by the European Copper Institute [1]. A and B represent the no-load losses and load losses [\$/kW] respectively.

The results of the calculations for the first to the fourth cases are as summarized in Table 6.

TABLE 6
COMPARISON BETWEEN DIFFERENT TRANSFORMERS TOC METHODS

Case	Values Not discounted[1]		Only Transformer Values Discounted[2]		Values Discounted (PV)[3]		Values Discounted (Annuity)[4]	
Item	Tr.1 (Al)	Tr.2 (Cu)	Tr.1 (Al)	Tr.2 (Cu)	Tr.1 (Al)	Tr.2 (Cu)	Tr.1 (Al)	Tr.2 (Cu)
$C_{Tr.}$	9,089	11,920	9251	1214	926	1,214	926	1214
$C_{(\Delta PNLL)}$	1,475	905	920	627	9,039	6,158	1475	905
$C_{(\Delta PLL)}$	959	756	2,072	1,528	2,657	1,810	959	756
$C_{(Losses)}$	2,434	1,662	2992	2155	11696	7968	2434	1662
TOC [$]	11523	13582	3,918	3369	12622	19889	3359	2876
1, 2, 3, 4- is the number of the case								

While for the fifth case, the results are given in Table 7

TABLE 7
TRANSFORMERS POWER , ENERGY LOSSES AND TOC COST

Item	Transformer-1 (AL)	Transformer- 2 (Cu)
A [$/W]	9,986	9,986
B [$/W]	11,097	8,633
TOC [$]	53,686	38,485

The values of the factors A and B in Table 7 are obtained based on the following price level: the capital cost of the transformer $C_{Tr.}$=9089 $, the cost of active energy (average day and night tariff) C_e=0.1155 $/kWh, the system capacity cost C_p=5.338 $/kW, the life time of the transformer n=20 years, and the interest rate r=8%. As above, the calculation is made for Tr.1 (Al).

$$A = \frac{(1+r)^n-1}{r\cdot(1+r)^n}\cdot(C_e\cdot 8760 + C_p) = \frac{(1+0.08)^{20}-1}{0.08\cdot(1+0.08)^{20}}\cdot(0.115493\ \cdot\ 8760 + 5.338) = 9986$$

$$B = A\cdot(\frac{I_L}{I_r})^2\cdot F = 9986\ \ \cdot 0.85^2\cdot\frac{1475}{959} = 11097$$

The total owing cot of the transformer is equal to:

$$TOC = C_{Tr.} + A\cdot\Delta P_{Fe} + B\cdot\Delta P_{Cu} = 9089 + 9986\cdot 0.91 + 11097\cdot 3.2 = 53686\ \$$$

where I_L- loading current [A]; I_r- rated current [A]; $(\frac{I_L}{I_r})^2 = (\frac{S_L}{S_n})^2 = \beta^2$ - loading degree [unitless or in %]; F- the ratio of the unit load losses cost to no-load losses (F= $C_{(\Delta PNLL)}$ [$/yr]/ $C_{(\Delta PLL)}$ [$/yr]) [unit less, or in %].

V. RESULTS AND CONCLUSIONS

This paper presents a comparative study for different methods to assess the TOC of transformers. Different assumptions were used for the economic evaluation of the transformers. The analysis shows that there is no definite answer to the question, "which transformer has the lowest total owing cost TOC'. Thus, the calculations should be performed for each transformer separately to determine its TOC. This is because TOC is a subject matter of the existing energy tariff, the capital cost of the transformer, the discount rate and the lifespan of the transformer, etc.

The numerical example shows that the capital cost of the transformer of Al windings is lower than Cu windings by around 25%. However, due to the existing energy tariff and price level of the two presented transformers, the Al windings become more expensive than Cu windings. This was due to the accumulated values of the power and energy losses.

For a better understanding of the achieved results in Tables 6 and 7, for example, TOC of transformer-1 (Al) and transformer-2 (Cu) are 11523$ and 13582$, respectively (case 1: all values are not discounted i.e. the transformer price and the losses cost).

In case 1, all values of TOC of the transformer (i.e. the transformer initial cost, the cost of no-load and the load losses) are not discounted. This means that when the present value of a future single sum of money at a certain rate of interest is not considered, a serious mistake is made because the value at the time of buying the transformer will not stay the same after few years due to inflation.

Therefore, the initial cost of the transformer has a crucial point in transformer selection for case No. 1. If this transformer is proposed to be used only during the project construction stage which is normally around two years, then it will be better to select transformer-1 (Al) as it has less TOC. Consequently, the overall project cost will be less. However, if this transformer is proposed to be used as a distribution transformer for a long period of time, i.e. 20 years or more, then ignoring the effect of the rate change as a result of inflation could lead to a serious error.

For big transformers with high initial cost, it will be better to use the formula presenting the amortization of the annuity value and the annual installments cost of the transformer and interest.

The factors A and B are normally used for the transformers evaluation of the received offer. They are widely used in tenders to evaluate the power and distribution transformer for their concentration on the cost of the losses over the lifespan of the transformer but not on the initial cost of the transformers. No economical background is needed to conduct the evaluation of the transformers.

Five different cases have been investigated and economically evaluated. The results of the calculations presented in Tables 6 and 7 reveal the following observations:

1) Case 1 could lead to a serious mistake and wrong decision through the transformer investment.
2) Case 2 provides a reasonable and quick answer for the decision maker if the life time of the project is less than 5 years (for instance, the transformer is used for temporary but not investment purposes).
3) Case 3 provides a reasonable result if the period of the project (lifespan) is not less than 3 years; otherwise, the use of this method could lead to wrong decisions.
4) Case 4 is the more accurate than the evaluated methods used in this paper. Hence, this method considers the amortization of the capital cost and interest required to pay off the present value of an annuity.
5) Case 5 is opposite to case 2 and close to case 3. However, the results achieved by using this method of calculation are reasonable and close to results of case 3, where the cost of losses was discounted over the lifespan of the project.

Finally, as there is no definite and quick answer to find the transformer's minimum TOC, separate calculations for each transformer unit are performed to achieve the right result.

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