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Decision support system for evaluating transformer investments in the industrial sector

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Abstract

This paper presents a decision support system (DSS) for evaluating transformer investments in the industrial sector. The DSS evaluates transformer bids based on the total owning cost (TOC). Among all transformer offers, the most cost-effective and energy-efficient transformer is the one with the lowest TOC. The DSS compares the selected offer with the other competing offers. Moreover, the proposed DSS deals with the uncertainty of the values in the TOC formula by performing a sensitivity analysis.

Keywords: Transformer; Total owning cost; Transformer efficiency; No-load losses; Load losses; Decision support system

1. Introduction

Transformer losses are categorized as no-load losses (NLL) and load losses (LL). No-load losses include losses due to no-load current, hysteresis losses and eddy current losses in core laminations, stray eddy current losses in core clamps and bolts and losses in the dielectric circuit. Load losses comprise losses due to load currents, losses due to current supplying the losses and eddy current losses in conductors due to leakage fields.

Transformer efficiency is improved by reducing transformer losses. Costs for the transformer user comprise costs for the purchase of the transformer and cost of losses. An understanding of transformer economics is necessary to weigh the transformer cost against the benefits of transformer efficiency.

This paper presents a decision support system (DSS) for evaluating transformer investments in the industrial sector. The DSS evaluates transformer bids based on the total owning cost (TOC), where the TOC is defined as the first cost plus the calculated present value of future losses. Among all transformer offers, the most cost-effective and energy-efficient transformer is the one with the lowest TOC. The DSS compares the selected offer with the other competing offers. Moreover, the proposed DSS deals with the uncertainty of the values in the TOC formula by performing a sensitivity analysis.

The paper is organized as follows: Section 2 presents the methodology for the evaluation of transformer offers in the industrial sector. Section 3 overviews the decision support systems. Sections 4 and 5 use the decision support system to compare two and nine competing offers, respectively, and also to perform sensitivity analysis. Section 6 concludes the paper.

2. Transformer evaluation method

Transformer losses are categorized as no-load losses and load losses.

The transformer *no-load losses* arise from energy required to maintain the continuously varying magnetic flux in the core, thus the no-load losses are constant and independent of the transformer load [1]. Table 1 shows the no-load loss categories according to CENELEC [2].

If S is the transformer actual load (kVA) and S_r is the transformer rated power (kVA), then the per unit load L of the transformer is:

$$L = \frac{S}{S_r} \quad (1)$$

The transformer *load losses* arise mainly from resistance losses in the windings, so the load losses are proportional to the square of load current, and since the load current is proportional to the transformer actual load, it is concluded that the load losses are proportional to the square of the transformer actual load [3]. Table 2 presents the load loss categories according to CENELEC [2]. For example, a transformer belongs to the CENELEC loss category AC′ if its load losses belong to list A (Table 2) and its no-load losses belong to list C′ (Table 1).

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Nomenclature

A	no-load loss factor (US$/W)
B	load loss factor (US$/W)
BP	bid price (US$)
$\cos\varphi$	power factor
C_{TL}	annual cost (US$/year) of transformer total losses
C_{NLL}	annual cost (US$/year) of transformer no-load losses
C_{LL}	annual cost (US$/year) of transformer load losses
d	discount rate
EP	electricity price (US$/kWh)
EL	annual energy losses (kWh/year)
EL_i	annual energy losses (kWh/year) of transformer i
ES_{ij}	annual energy savings (US$/year) by using transformer j instead of transformer i
HPY	hours of transformer operation per year
L	per unit load
LL	transformer load losses (W) at rated power
LL_L	transformer load losses (W) at load L
n	transformer efficiency
N	transformer life (years)
NLL	transformer no-load losses (W)
PV_m	present value multiplier
PV_{TL}	present value of the cost (US$) of transformer total losses for the whole transformer life
PV_{NLL}	present value of the cost (US$) of transformer no-load losses for the whole transformer life
PV_{LL}	present value of the cost (US$) of transformer load losses for the whole transformer life
S	transformer actual load (kVA)
S_r	transformer rated power (kVA)
SP_{ij}	simple payback (years) by using transformer j instead of transformer i
TOC	total owning cost (US$)
TL_L	transformer total losses (W) at load L

If LL are the transformer load losses at rated power S_r, then the transformer load losses LL_L at load L are calculated from the formula:

$$LL_L = LL \cdot L^2 \quad (2)$$

If NLL are the transformer no-load losses, then the transformer total losses TL_L at load L are:

$$TL_L = NLL + LL_L \quad (3)$$

Combining Eqs. (2) and (3), we find that the transformer total losses (or wattage losses) TL_L at load L are given by the formula:

$$TL_L = NLL + LL \cdot L^2 \quad (4)$$

In the industrial sector, the transformer operates HPY hours per year. If EP is the electricity price (US$/kWh) that the industrial user pays for electricity, then the annual cost (US$/year) of transformer total losses C_{TL} is:

$$C_{TL} = TL_L \cdot EP \cdot HPY \cdot 10^{-3} \quad (5)$$

Substituting Eq. (4) to Eq. (5), we obtain:

$$C_{TL} = (NLL + LL \cdot L^2) \cdot EP \cdot HPY \cdot 10^{-3} \quad (6)$$

and finally:

$$C_{TL} = C_{NLL} + C_{LL} \quad (7)$$

where C_{NLL} is the annual cost (US$/year) of transformer no-load losses and C_{LL} is the annual cost (US$/year) of transformer load losses, which are calculated from the following equations:

$$C_{NLL} = NLL \cdot EP \cdot HPY \cdot 10^{-3} \quad (8)$$

$$C_{LL} = LL \cdot L^2 \cdot EP \cdot HPY \cdot 10^{-3} \quad (9)$$

The industrial user pays the cost of transformer total losses C_{TL} (US$/year) for each one of the N years of the transformer life. If d is the discount rate, then the present value PV_{TL} of these N payments is:

$$PV_{TL} = \frac{C_{TL}}{(1+d)} + \frac{C_{TL}}{(1+d)^2} + \cdots + \frac{C_{TL}}{(1+d)^N}$$
$$\Rightarrow PV_{TL} = C_{TL} \cdot PV_m \quad (10)$$

where PV_m is the present value multiplier and is calculated as follows:

$$PV_m = \sum_{i=1}^{N} \frac{1}{(1+d)^N} = \frac{1 - 1/(1+d)^N}{1 - 1/(1+d)}$$
$$\Rightarrow PV_m = \frac{(1+d)^N - 1}{d \cdot (1+d)^{N-1}} \quad (11)$$

The present value PV_{NLL} of the cost (US$) of transformer no-load losses for the whole transformer life is calculated as follows:

$$PV_{NLL} = C_{NLL} \cdot PV_m \quad (12)$$

The present value PV_{LL} of the cost (US$) of transformer load losses for the whole transformer life is calculated as follows:

$$PV_{LL} = C_{LL} \cdot PV_m \quad (13)$$

The following equation holds:

$$PV_{TL} = PV_{NLL} + PV_{LL} \quad (14)$$

If the transformer is offered to the industrial user at a bid price BP, then the total owning cost TOC of the transformer is equal to the sum of its bid price BP and the present value PV_{TL} of the cost of transformer total losses for the whole transformer life:

$$TOC = BP + PV_{TL} \quad (15)$$

Substituting Eq. (14) to Eq. (15), we obtain:

$$TOC = BP + PV_{NLL} + PV_{LL} \quad (16)$$

Table 1
No-load loss categories according to CENELEC [2]

Rated power (kVA)	List A′		List B′		List C′		Short-circuit voltage (%)
	No-load losses (W)	Noise (dB)	No-load losses (W)	Noise (dB)	No-load losses (W)	Noise (dB)	
50	190	55	145	50	125	47	4
100	320	59	260	54	210	49	4
160	460	62	375	57	300	52	4
250	650	65	530	60	425	55	4
400	930	68	750	63	610	58	4
630	1300	70	1030	65	860	60	4
630	1200	70	940	65	800	60	6
1000	1700	73	1400	68	1100	63	6
1600	2600	76	2200	71	1700	66	6
2500	3800	81	3200	76	2500	71	6

Substituting Eqs. (12) and (13) to Eq. (16), we have:

$$\mathrm{TOC} = \mathrm{BP} + C_{\mathrm{NLL}} \cdot \mathrm{PV_m} + C_{\mathrm{LL}} \cdot \mathrm{PV_m} \quad (17)$$

Substituting Eqs. (8) and (9) to Eq. (17), we obtain:

$$\mathrm{TOC} = \mathrm{BP} + (\mathrm{NLL} + \mathrm{LL} \cdot L^2) \cdot \mathrm{PV_m} \cdot \mathrm{EP} \cdot \mathrm{HPY} \cdot 10^{-3} \quad (18)$$

An equivalent and simpler expression for the TOC is the following:

$$\mathrm{TOC} = \mathrm{BP} + A \cdot \mathrm{NLL} + B \cdot \mathrm{LL} \quad (19)$$

where BP is the transformer bid (purchasing) price (US$), NLL the transformer no-load losses (W), LL the transformer load losses (W), A the no-load loss factor (US$/W) and B is the load loss factor (US$/W).

The factors A and B of Eq. (19) are calculated as follows:

$$A = \mathrm{PV_m} \cdot \mathrm{EP} \cdot \mathrm{HPY} \cdot 10^{-3} \quad (20)$$

$$B = A \cdot L^2 \quad (21)$$

The purchasing decision is based on the minimization of the TOC. This means that if we have to evaluate m alternative transformer offers $O_i = \{\mathrm{BP}_i, \mathrm{NLL}_i, \mathrm{LL}_i\}$, $i = 1, \ldots, m$, then for each one of the offers we calculate its total owning cost TOC_i, $i = 1, \ldots, m$, using the Eq. (19) and the optimum transformer (to be purchased) is the one with the minimum total owning cost and not the transformer with the minimum purchasing price.

Table 2
Load loss categories according to CENELEC [2]

Rated power (kVA)	Load losses (W)			Short-circuit impedance (%)
	List A	List B	List C	
50	1100	1350	875	4
100	1750	2150	1475	4
160	2350	3100	2000	4
250	3250	4200	2750	4
400	4600	6000	3850	4
630	6500	8400	5400	4
630	6750	8700	5600	6
1000	10500	13000	9500	6
1600	17000	20000	14000	6
2500	26500	32000	22000	6

The transformer efficiency n is defined as follows:

$$n = \frac{S\cos\varphi}{S\cos\varphi + \mathrm{TL}_L} \quad (22)$$

where $\cos\varphi$ is the power factor, S the transformer actual load and TL_L are the transformer wattage losses at load L.

The transformer wattage losses (W) are calculated from Eq. (4). The transformer annual energy losses (kWh/year) are calculated as follows:

$$\mathrm{EL} = \mathrm{TL}_L \cdot \mathrm{HPY} \cdot 10^{-3} \quad (23)$$

The annual energy savings (US$/year) by using transformer j instead of transformer i are given by the formula:

$$\mathrm{ES}_{ij} = (\mathrm{EL}_i - \mathrm{EL}_j) \cdot \mathrm{EP} \quad (24)$$

where EL_i are the annual energy losses of transformer i and EP is the electricity price.

The simple payback (years) by using transformer j instead of transformer i is calculated as follows:

$$\mathrm{SP}_{ij} = \frac{\mathrm{BP}_i - \mathrm{BP}_j}{\mathrm{ES}_{ij}} \quad (25)$$

where BP_i is the bid price for transformer i.

3. Decision support systems

One of the most important tasks faced by decision makers in business and government is that of selection. Selection problems are challenging, because they require the balancing of multiple, often conflicting objectives, criteria or attributes.

Decision support systems constitute an application of the capabilities provided by computer science to support decision making [4].

The basic structural components of a decision support system are the following [5]:

1. *The database*: this part of the DSS comprises all the necessary information and data required to perform the analysis of the problem at hand. Data management, i.e. data entry, access, update, storage, retrieval, etc., is performed through the database management system.

Table 3
Data for two competing transformer offers

Parameter	Offer 1	Offer 2
Rated Power (kVA)	250	250
No-load losses (W)	650	425
Load losses (W)	4200	2750
Loss category [2]	BA′	CC′
Bid price (US$)	5820	7020

2. *The model base*: similarly to the database, the model base of a DSS is a collection of decision analysis tools that are used to support decision-making. The model base and the database are directly related so that the models are fed with the necessary information and data. The model base management system is responsible for handling the model base including the storage and retrieval of models that are developed, their update and adjustment.
3. *The user interface*: this is one of the key components of a DSS, with respect to the successful implementation of the system in practice. The form of the user interface defines the level of flexibility of the system and its user-friendliness. The user interface is responsible for the communication of the user with the system. A special part of the user interface, the dialog generation and management system is specifically designed to manage this communication.

In this paper, a DSS tool has been developed in Microsoft Excel. The DSS tool assists in the comparison of competing transformer offers. Moreover, the DSS tool deals with the uncertainty of the values in the TOC formula by performing a sensitivity analysis.

4. Comparison of two competing offers

Table 3 shows two competing transformer offers for three-phase, oil-immersed, power transformers, with loss categories as defined in Tables 1 and 2 [2].

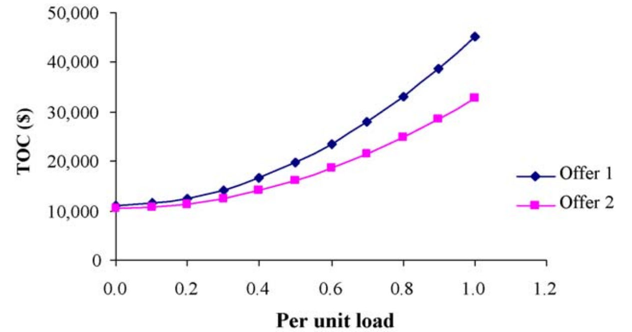

Fig. 1. Sensitivity analysis of per unit load on the total owning cost of offers 1 and 2 of Table 3.

In Table 3, offer 2 is more expensive and more energy-efficient than offer 1.

Let us suppose that EP = 0.07 US$/kWh, $d = 7\%$, HPY = 8760 and $N = 30$ years. Using Eq. (11), we find that $PV_m = 13.28$. Table 4 presents an analysis of offer 1 of Table 3, i.e. it shows the annual cost of losses, the present value of the cost of transformer total losses for the whole transformer life and the transformer total owning cost, when the per unit load varies from 0.0 to 1.0. If we repeat the calculations of Table 4 for the offer 2 of Table 3 and we plot the total owning cost of offers 1 and 2, we obtain the graph shown in Fig. 1. The sensitivity analysis of per unit load of Fig. 1 shows that for all the different values of per unit load, the total owning cost of offer 2 is lower than the total owning cost of offer 1.

5. Comparison of nine competing offers

5.1. Selection of the most energy efficient offer

Table 5 shows nine transformer offers for three-phase, oil-immersed, power transformers, with loss categories as defined in [2].

Let us suppose that EP = 0.06 US$/kWh, $d = 7\%$, HPY = 8760 and $N = 30$ years, $L = 0.5$ and $\cos\phi = 0.9$.

Using Eq. (11), we find that $PV_m = 13.28$. Using Eqs. (20) and (21), we find $A = 6.98$ US$/W and $B = 1.74$ US$/W. Table 6

Table 4
Analysis of offer 1 of Table 3

Per unit load, L	Wattage losses, TL_L (W)	Annual energy losses, EL (kWh/year)	Annual cost of losses, C_{TL} (US$/year)	Present value of total losses, PV_{TL} (US$)	Total owning cost, TOC (US$)
1.0	4850	42486	2974	39488	45308
0.9	4052	35496	2485	32991	38811
0.8	3338	29241	2047	27178	32998
0.7	2708	23722	1661	22048	27868
0.6	2162	18939	1326	17603	23423
0.5	1700	14892	1042	13841	19661
0.4	1322	11581	811	10764	16584
0.3	1028	9005	630	8370	14190
0.2	818	7166	502	6660	12480
0.1	692	6062	424	5634	11454
0.0	650	5694	399	5292	11112

Table 5
Transformer offers

Supplier	Rated power (kVA)	Bid price (US$)	No-load losses (W)	Load losses (W)	Loss category
S1	1000	10732	1700	10500	AA′
S2	1000	11432	1400	10500	AB′
S3	1000	12135	1100	10500	AC′
S4	1000	10198	1700	13000	BA′
S5	1000	10368	1400	13000	BB′
S6	1000	10497	1100	13000	BC′
S7	1000	11425	1700	9500	CA′
S8	1000	11584	1400	9500	CB′
S9	1000	12508	1100	9500	CC′

Table 6
Evaluation based on the total owning cost

Supplier	Efficiency (*n*, %)	Wattage losses (W)	Energy losses (kWh/year)	NLL cost (US$)	LL cost (US$)	Cost of losses (US$/year)	Total cost of losses (US$)	TOC (US$)	BP ranking	TOC ranking
S1	99.05	4325	37887	11864	18319	2273	30183	40915	4	7
S2	99.11	4025	35259	9770	18319	2116	28089	39521	6	4
S3	99.18	3725	32631	7677	18319	1958	25996	38131	8	3
S4	98.91	4950	43362	11864	22681	2602	34545	44743	1	9
S5	98.98	4650	40734	9770	22681	2444	32451	42819	2	8
S6	99.04	4350	38106	7677	22681	2286	30358	40855	3	6
S7	99.10	4075	35697	11864	16575	2142	28438	39863	5	5
S8	99.17	3775	33069	9770	16575	1984	26345	37929	7	2
S9	99.23	3475	30441	7677	16575	1826	24251	36759	9	1

Table 7
Savings due to the selection of S9 instead of S4 supplier ($EP = 0.06$ US$/kWh)

BP (US$)	*n* (%)	Wattage losses (W)	Energy losses (kWh/year)	Cost of losses (US$/year)	Simple payback (year)	Total cost of losses (US$)	TOC (US$)
−2310	0.33	1475	12921	775	2.98	10294	7984

presents an analysis of the offers of Table 5. It is concluded from Table 6 that the TOC ranking is different than the BP ranking. More specifically, the transformer from supplier S4 is the cheapest (BP ranking is 1), however it has the highest total owning cost (TOC ranking is 9). On the other hand, the transformer from supplier S9 is the most expensive (BP ranking is 9), however it has the lowest total owning cost (TOC ranking is 1).

Table 7 shows the savings due to the selection of S9 supplier (most expensive BP but lowest TOC) instead of S4 supplier (cheapest BP but highest TOC).

Table 8 performs a sensitivity analysis of the electricity price when analyzing the savings due to the selection of S9 instead of S4 supplier. Table 8 shows that the simple payback is 1.79 years, if the electricity price is 0.1 US$/kWh. Fig. 2 shows that the TOC

Table 8
Savings due to the selection of S9 instead of S4 supplier (sensitivity analysis of electricity price)

EP (US$/kWh)	BP (US$)	*n* (%)	Wattage losses (W)	Energy losses (kWh/year)	Cost of losses (US$/year)	Simple payback (year)	Total cost of losses (US$)	*TOC* (US$)
0.04	−2310	0.33	1475	12921	517	4.47	6862	4552
0.05	−2310	0.33	1475	12921	646	3.58	8578	6268
0.06	−2310	0.33	1475	12921	775	2.98	10294	7984
0.07	−2310	0.33	1475	12921	904	2.55	12009	9699
0.08	−2310	0.33	1475	12921	1034	2.23	13725	11415
0.09	−2310	0.33	1475	12921	1163	1.99	15440	13130
0.10	−2310	0.33	1475	12921	1292	1.79	17156	14846

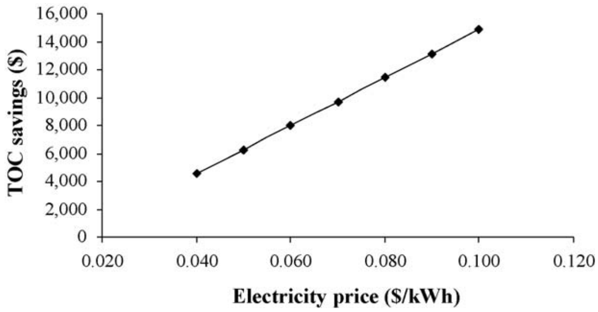

Fig. 2. Sensitivity analysis of electricity price on the TOC savings due to the selection of S9 instead of S4 supplier.

savings (due to the selection of S9 instead of S4 supplier) are increased when the electricity price increases.

6. Conclusion

The cost of transformer losses plays a major part in the evaluation of competitive transformer designs. This paper presents a decision support system (DSS) tool for evaluating transformer investments in the industrial sector. The DSS tool evaluates transformer bids based on the total owning cost (TOC). Among all transformer offers, the most cost-effective and energy-efficient transformer is the one with the lowest TOC. The DSS tool compares the selected offer with the other competing offers. Moreover, the proposed DSS tool deals with the uncertainty of the values in the TOC formula by performing a sensitivity analysis.

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