INTERNATIONAL TRANSACTIONS ON ELECTRICAL ENERGY SYSTEMS
Int. Trans. Electr. Energ. Syst. 2013; **23**:364–379
Published online 30 December 2011 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/etep.665

Evaluation of distribution transformer banks in electric power systems

Juan Carlos Olivares-Galvan[1]*, Rafael Escarela-Perez[1],
Pavlos S. Georgilakis[2] and Issouf Fofana[3]

[1] *Departamento de Energia, Universidad Autonoma Metropolitana de Azcapotzalco, Ciudad de Mexico, D.F., 02200, Mexico*
[2] *School of Electrical and Computer Engineering, National Technical University of Athens, GR-15780, Athens, Greece*
[3] *Canada Research Chair on Insulating Liquids and Mixed Dielectrics for Electrotechnology (ISOLIME), Université du Québec à Chicoutimi, Québec, Canada*

SUMMARY

This article compares the total mass and the total owning cost (TOC) of three-phase distribution transformer banks with standard three-phase distribution transformers. The comparison is based on the minimum TOC. This is achieved through a field-validated distribution transformer design program that automatically minimises the objective function (TOC). In particular, 12 oil-immersed distribution transformers are designed: 6 three-phase transformer banks and 6 three-phase transformers; these designs meet all the requirements of a given transformer standard. As a result, curves of minimum TOC versus transformer rating are obtained for three-phase transformer banks and three-phase transformers. Moreover, similar curves from seven transformer manufacturers are collected; the advantage of this collection is that these different manufacturers have different types of transformers: oil immersed or dry type, core or shell type, various voltage classes and power ratings, and so on, and consequently more general conclusions can be drawn regarding the comparison of three-phase transformer banks and three-phase transformers. From these investigations, it was found that from the viewpoint of minimum total mass and minimum TOC, three-phase transformer banks should be recommended in case of small-size transformers (rating lower than 45 kVA). This is an important finding that is not emphasised in recommended practices reported in transformer textbooks. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: cost of transformer materials; total owning cost; transformer total mass; distribution transformers; single-phase distribution transformers; three-phase distribution transformers

1. INTRODUCTION

Transformers are essential components in the electrical power system. A typical transformer consists of coils of copper or aluminium conductors (that may be insulated with paper insulation for large units), which are wound around a magnetic core. Transformers are filled with dielectric fluid, which has two important functions [1]:

a) to strengthen the dielectric properties of solid insulation by impregnation and to electrically insulate active parts from grounded ones, and
b) to remove heat generated by the windings during service.

There are three main reasons why three phases are used in electrical power systems:

a) a three-phase machine can generate up to 95.5% of an ideal machine with infinite number of phases [2],
b) the use of three conductors in a three-phase system can provide 173% more power than two conductors in a single-phase system [2], and

*Correspondence to: Juan Carlos. Olivares-Galvan, Departamento de Energia, Universidad Autonoma Metropolitana de Azcapotzalco, Ciudad de Mexico, D.F., 02200, Mexico.
E-mail: jolivare_1999@yahoo.com

c) three-phase power can be transmitted with transmission lines over long distances with small wire gauges.

Three single-phase transformers can be connected to form a three-phase transformer bank. There are three advantages of using a three-phase transformer instead of a three-phase transformer bank [3–8]:

a) cost reduction,
b) total mass reduction, and
c) space saving.

When a transformer is used for distribution service (the secondary is connected directly to the customer load), it is called a distribution transformer. Distribution transformers are distinguished from large power transformers, which are used in high-voltage transmission systems for the transmission of large amount of power. Both large power and distribution transformers are used for transmission and distribution applications. The difference between large power and distribution transformers refers to size and input voltage. Distribution transformers vary typically between 5 kVA and 10 MVA, with input voltage between 1 and 36 kV. Power transformers are typically units from 5 to 500 MVA, with input voltage higher than 36 kV. Distribution transformers may be oil filled or dry filled. Because small distribution transformers do not generate much heat, a higher proportion of them tend to be dry type.

2. THREE-PHASE TRANSFORMER BANK VERSUS STANDARD THREE-PHASE TRANSFORMER

Power is transmitted and distributed using three-phase transmission lines. This requires the use of three-phase transformers to transform the voltages from one level to another. There are two options: a three-phase transformer bank or a standard three-phase transformer. A three-phase transformer bank is composed of two or three single-phase transformers connected as a three-phase transformer. A three-phase transformer has three primary windings and three secondary windings mounted on the same magnetic core and internally connected. These two possible options of transformers are shown in Figure 1. There are four standard ways of connecting three-phase transformers: Y–Y, Δ–Δ, Δ–Y and Y–Δ. Some factors that are taken into account in the selection of the type of connection are as follows [8]: grounded or ungrounded neutral, neutral stabilisation, voltage stresses and current flow during line to ground faults, single-phase power requirements at phase to neutral voltage, reduction

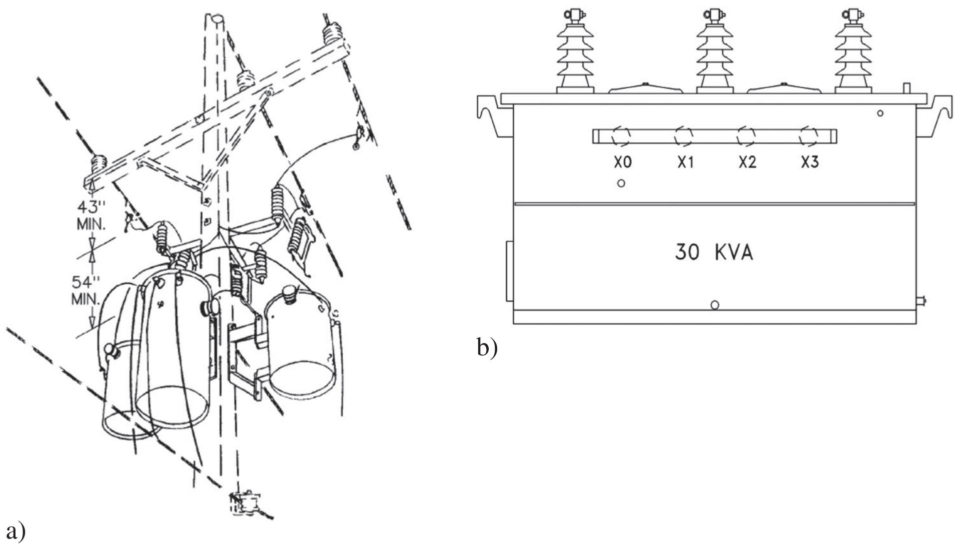


Figure 1. Transformer for three-phase circuits can be constructed in two ways: (a) three-phase transformer bank on a pole and (b) three-phase transformer.

DOI: 10.1002/ete

of harmonic voltages and currents and angular phase displacement between the different voltage levels in the distribution system.

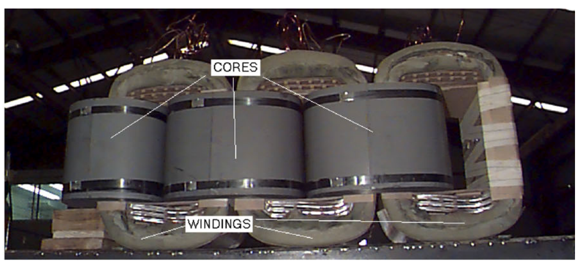
An important advantage of a three-phase transformer bank over a standard three-phase transformer is that each unit in the bank may be replaced/repaired individually in case of failure. For example, the open delta (V–V) and the open–Y–open-delta connections are generally used in case of emergency to guarantee continued service. These are two ways to perform three-phase transformation with only two transformers. Each of these types of connections has certain advantages and disadvantages that influence their selection. Furthermore, one spare single-phase transformer is usually all that is required to assure sufficient reliability for the entire bank. With a three-phase transformer, an additional spare three-phase transformer would be required, so the total cost of the installation plus a spare transformer is twice the cost of the installation itself. On the other hand, the total cost of a three-phase transformer bank plus a spare single-phase transformer is only 133% the cost of the bank alone. Therefore, the total cost of a bank of single-phase transformers plus a spare is probably less than the cost of a three-phase transformer plus a spare. For instance, it may be impossible or impractical to fabricate and/or deliver a three-phase power transformer with an extremely large kilovolt-ampere capacity, although a bank of three single-phase transformers may then be the solution.

Loads on a distribution system consist of a combination of three-phase and single-phase loads. To feed these combined loads, an unsymmetrical transformer bank is required. The bank will consist of a lighting transformer and one or two distribution transformers. The lighting transformer serves all the single-phase loads and part of the three-phase loads, whereas the distribution transformers serve only the three-phase loads. Kersting *et al*. [9] presented an analysis of normal and abnormal operating conditions on unsymmetrical transformer banks.

The shell-type three-phase transformer includes the five-legged core form design. In the five-legged core form design, three sets of windings are placed over three central vertical core legs. The shell-type single-phase transformer includes the three-legged core form design. In the three-legged core form design, one set of windings is placed over the central vertical core legs. A shell-type single-phase transformer and a shell-type three-phase transformer are shown in Figure 2.

This article arises because of the interest to further investigate three-phase distribution transformers versus three-phase distribution transformer banks, taking into account the current cost of transformer materials and the labour cost to manufacture the transformer. This is particularly important taking into account the fact that some of transformer materials are stock exchange commodities with fluctuating prices on a daily or weekly basis. The comparison of three-phase distribution transformer banks with three-phase distribution transformers is performed by using a field-validated transformer design program, for single-phase and three-phase transformers, by minimising the transformer TOC while meeting all the restrictions that are imposed by a given transformer standard [10].

a)



b)

Figure 2. (a) Shell-type single-phase transformer. (b) Shell-type three-phase transformer.

DOI: 10.1002/ete

3. OVERVIEW OF TRANSFORMER DESIGN METHODOLOGY

This section provides an overview of the methodology and the computer program developed for the optimal design of single-phase and three-phase distribution transformers [11]. This computer program is used in this article for the study and comparison of three-phase transformer banks with three-phase transformers.

3.1. Input data

The input data required by the transformer design program are the following:

a) Transformer capacity (kVA)
b) Number of phases
c) Connection type
d) High voltage (V)
e) Low voltage (V)
f) Frequency (Hz)

3.2. Variables

The optimisation routine (see Section 3.5), considers five design variables. These variables and their variation ranges are as follows:

a) High-voltage conductors' size varying from 6 to 27 AWG.
b) Magnetic flux density varying from 1.4 to 1.7 T.
c) Number of turns of the low-voltage winding, N_{LV}. This parameter varies from 5 to 50, in the case of single-phase transformers. From the transformer kilovolt-ampere rating, the number of turns of the low-voltage winding can be computed from the expression $N_{LV} = 89.6828 \cdot \text{kVA}^{-0.5}$ [12].
d) Width of core steel sheet. There are six widths between 152.4 and 304.8 mm.
e) Cross-sectional area of aluminium foil for low voltage. There are seven values available. The width of aluminium foil varies from 114.3 to 254.0 mm, and its thickness varies from 0.30 to 1.78 mm.

3.3. Output parameters

The transformer design program computes the following four fundamental parameters:

a) Transformer impedance (%)
b) Transformer mass
c) Transformer material cost
d) Transformer total owning cost (TOC)

3.3.1. Transformer impedance. In rectangular windings of distribution transformers, the low-voltage winding is placed close to the core producing the L–H–L configuration. The transformer impedance (%*Z*) for shell-type and wound core transformers is calculated by the following formulas [13]:

$$\%Z = \sqrt{(\%R)^2 + (\%X)^2} \tag{1a}$$

$$\%R = \frac{W_c}{10\ \text{kVA}} \tag{1b}$$

$$\%X = \frac{8 \times \pi^2 \times f \times \text{IN} \times K \times \text{MLT}_{\text{wind}} \times g \times 10^{-8}}{\gamma V_t} \tag{1c}$$

where $\%R$ = winding resistance (%) at 85°C, W_c = conductor losses at 85°C (W), kVA = transformer rating, $\%X$ = winding reactance (%), f = frequency (Hz), IN = ampere turn of transformer, $K = 1.00$ for three-phase transformers, $K = 0.85$ for single-phase transformers, MLT_{wind} = mean turn length of

DOI: 10.1002/ete

windings (mm), g = length of magnetic linkage (mm), γ = average winding height plus average winding thickness (mm) and V_t = Volt per turn.

3.3.2. Transformer total mass. The transformer mass includes the mass of the core, the high- and low-voltage conductors, the tank and the mineral oil. The core mass for shell-type three-phase transformers is given by [14]:

$$M_{c-3\phi} = 2(P_{l1} + P_{l2}) \tag{2}$$

where P_{l1} is the lateral core mass (kg) and P_{l2} is the central core mass (kg). To be less repetitive, the equations for the three-phase case are presented here. The single-phase case can be easily deduced. Details concerning the calculation of P_{l1} and P_{l2} can be found in the studies of Olivares-Galvan *et al.* [11], Harlow [15], Georgilakis [16] and Cogent Power Inc. [14].

The mean turn length is required to calculate the winding resistance and the mass for any given winding (for the calculation of the winding mean turn length, see Rubaai [17] and McLyman [17,18]). The high-voltage conductor mass for three-phase transformers, M_{Cu}, is given by [19]:

$$M_{Cu} = 3\mathrm{MLT_{HV}} \cdot N_{HV} \cdot \mathrm{cs_{HV}} \cdot \rho_{HV} \tag{3}$$

where $\mathrm{MLT_{HV}}$ is the mean turn length of high voltage (m), N_{HV} is the number of turns of high-voltage conductor, $\mathrm{cs_{HV}}$ is the cross-sectional area of high-voltage conductor (m^2) and ρ_{HV} is the density of high-voltage conductor (kg/m^3).

The low-voltage conductor mass for three-phase transformers M_{Al} is given by [19]

$$M_{Al} = 3\mathrm{MLT_{LV}} \cdot N_{LV} \cdot \mathrm{cs_{LV}} \cdot \rho_{LV} \tag{4}$$

where $\mathrm{MLT_{LV}}$ is the mean turn length of low voltage (m), N_{LV} is the number of turns of low-voltage conductor, $\mathrm{cs_{LV}}$ is the cross-sectional area of low-voltage conductor (m^2) and ρ_{LV} is the density of low-voltage conductor (kg/m^3).

The tank mass, M_{ta}, is derived from [20]

$$M_{ta} = (V_{ct} + V_{ft} + V_{tt})\rho_{ac} \tag{5}$$

where V_{ct} is the volume of carbon steel plate content of the tank body (m^3), V_{ft} is the volume of carbon steel plate content of the bottom of the tank, V_{tt} is the volume of carbon steel plate content of tank cover and ρ_{ac} is the density of steel (kg/m^3).

The three-phase transformer total mass $M_{t-3\phi}$ is given by [20]

$$M_{t-3\phi} = M_{HV-3\phi} + M_{LV-3\phi} + M_{c-3\phi} + M_{ta-3\phi} + M_{oil-3\phi} \tag{6}$$

where $M_{ta-3\phi}$ and $M_{oil-3\phi}$ are the tank mass and the mineral oil mass, respectively, of the three-phase transformer.

3.3.3. Transformer material cost. The material cost of the three-phase transformer is given by [21]

$$C_{mat-3\phi} = \mathrm{uc_{HV}} M_{HV-3\phi} + \mathrm{uc_{LV}} M_{LV-3\phi} + \mathrm{uc_c} M_{c-3\phi} + \mathrm{uc_{ta}} M_{ta-3\phi} + \mathrm{uc_{oil}} M_{oil-3\phi} \tag{7}$$

where $\mathrm{uc_{HV}}$ is the per unit cost of high-voltage conductor ($/kg), $\mathrm{uc_{LV}}$ is the per unit cost of low-voltage conductor ($/kg), $\mathrm{uc_c}$ is the per unit cost of core magnetic material ($/kg), $\mathrm{uc_{ta}}$ is the per unit cost of tank steel ($/kg) and $\mathrm{uc_{oil}}$ is the per unit cost of mineral oil ($/kg).

3.3.4. Transformer TOC. The TOC takes into account not only the initial transformer cost but also the cost to operate the transformer over its life. The TOC is given by [22]

$$\mathrm{TOC} = \mathrm{BP} + \mathrm{A} \times \mathrm{NLL} + \mathrm{B} \times \mathrm{LL} \tag{8}$$

where

$$\mathrm{BP} = \frac{C_{mat} + C_{lab}}{1 - \mathrm{SM}} \tag{9}$$

where BP is the transformer bid price ($), A is the transformer no-load loss cost rate ($/W), NLL is the transformer no-load loss (W), B is the transformer load loss cost rate ($/W), LL is the transformer load loss

(W), C_{mat} is the transformer material cost ($) computed from Equation (7), C_{lab} is the transformer labor cost ($) and SM is the transformer sales margin. Details concerning the computation of A and B loss cost rates can be found in the work of Kennedy [23].

Strictly speaking, the TOC should also consider the maintenance and the failure repair costs, according to [24]

$$\mathrm{TOC} = \mathrm{BP} + A \times \mathrm{NLL} + B \times \mathrm{LL} + C_m + C_r \tag{10}$$

where C_m and C_r denote the maintenance and the failure repair costs, respectively.

C_m is negligible because maintenance is typically not performed on distribution transformers in service by electric utilities, and C_r is also negligible, given the very low rate of transformers annual failures. Major refurbishments such as rewinding the transformer represent a small percentage (0.02%) of the transformers removed from service (3.0%). Maintenance is usually not performed on distribution transformers in service by electric utilities. Typically, maintenance is only performed when distribution transformers are removed from service. The maintenance program used by most utilities consists of the following basic elements: inspection and testing, minor in-house refurbishments, major refurbishments in the form of rewinding transformers and retirements. Distribution transformers are not normally removed from service because of age alone [25].

3.4. Standard specifications (constraints)

The optimisation process considers a group of constraints related to the excitation current, no-load losses, total losses, impedance and efficiency [16]. Table 1 shows the values of the no-load and total loss constraints for distribution transformers according to a given transformer standard [10]. The values of the minimum efficiencies versus the transformer rating and the basic impulse insulation level for single-phase transformers and three-phase transformers can be found in Table 2 [10]. Alternatively, other efficiency standards [26] could be also used. According to Norma Mexicana ANCE [10], the excitation current should not exceed 1.5% of nominal current in all single-phase transformers as well as for three-phase transformers with capacity higher than 45 kVA. In case of three-phase transformers up to 45 kVA, the excitation current should not be higher than 2.0% of nominal current. Table 3 shows the impedance specifications for single-phase and three-phase distribution transformers. The impedance depends on both the insulation class and the transformer rating.

Table I. Maximum no-load losses (W) and maximum total losses (W) required by the standard [10] for single-phase and three-phase transformers.

		BIL (kV)					
		BIL ≤ 95		95 < BIL ≤ 150		150 < BIL ≤ 200	
Size (kVA)		No load	Total	No load	Total	No load	Total
Single-phase transformers	5	30	107	38	112	63	118
	10	47	178	57	188	83	199
	15	62	244	75	259	115	275
	25	86	368	100	394	145	419
	37.5	114	513	130	552	185	590
	50	138	633	160	684	210	736
	75	186	834	215	911	270	988
	100	235	1061	265	1163	320	1266
	167	365	1687	415	1857	425	2028
Three-phase transformers	15	88	314	110	330	135	345
	30	137	534	165	565	210	597
	45	180	755	215	802	265	848
	75	255	1142	305	1220	365	1297
	112.5	350	1597	405	1713	450	1829
	150	450	1976	500	2130	525	2284
	225	750	2844	820	3080	900	3310
	300	910	3644	1000	3951	1100	4260
	500	1330	5561	1475	6073	1540	6588

BIL, basic impulse insulation level.

DOI: 10.1002/ete

Table II. Minimum efficiencies (%) required by the standard [10] for single-phase and three-phase transformers.

	Size (kVA)	BIL (kV)		
		BIL ≤ 95	95 < BIL ≤ 150	150 < BIL ≤ 200
Single-phase transformers	5	97.9	97.8	97.7
	10	98.25	98.15	98.05
	15	98.4	98.3	98.2
	25	98.55	98.45	98.35
	37.5	98.65	98.55	98.45
	50	98.75	98.65	98.55
	75	98.9	98.8	98.7
	100	98.95	98.85	98.75
	167 to 500	99	98.9	98.8
Three-phase transformers	15	97.95	97.85	97.75
	30	98.25	98.15	98.05
	45	98.35	98.25	98.15
	75	98.5	98.4	98.3
	112.5	98.6	98.5	98.4
	150	98.7	98.6	98.5
	225	98.75	98.65	98.55
	300	98.8	98.7	98.6
	500	98.9	98.8	98.7

BIL, basic impulse insulation level.

Table III. Impedance constraints required by the standard [10] for single-phase and three-phase transformers.

Insulation class (kV)	Impedance (%)		
	Single-phase transformers		Three-phase transformers
	5–167 kVA	Pole type 15–150 kVA	Substation type 225–500 kVA
1.2–25	1.5–3.00	2.00–3.00	2.50–5.00
25	1.50–3.25	2.00–3.25	2.75–5.50
34.5	1.50–3.50	2.00–3.50	3.00–5.75

3.5. Multiple design optimisation algorithm

The transformer design optimisation problem is achieved using a multiple design method that assigns many alternative values to the design variables so as to generate a large number of alternative designs and finally to select the design that satisfies all the problem constraints with the optimum value of the objective function [16,27]. Consequently, this method guarantees the finding of the optimum among the alternative designs considered [11,16,27].

The five design variables and their ranges of variation have been presented in Section 3.2. From these ranges (see Section 3.2), the computer program investigates various potential solutions. For each solution, the specifications (constraints) are evaluated. If all these constraints are satisfied, the value of the objective function is calculated and the solution is characterised as ‘acceptable’. On the other hand, the potential solutions that do not meet the specifications are characterised as ‘nonacceptable’ solutions. Finally, among the acceptable solutions, the transformer with the optimum value of the objective function is selected, which is the optimum transformer.

Figure 3 shows the flowchart for optimising TOC, where kVbt is the low voltage, kVat is the high voltage, AV_{mfd} is the number of alternative values for the magnetic flux density, AV_{cccsa} is the number of alternative values of copper conductor cross-sectional areas, AV_{accsa} is the number of alternative values of aluminium conductor cross-sectional area, AV_{lw} is the number of alternative values of lamination width and AV_{lvt} is the

DOI: 10.1002/ete

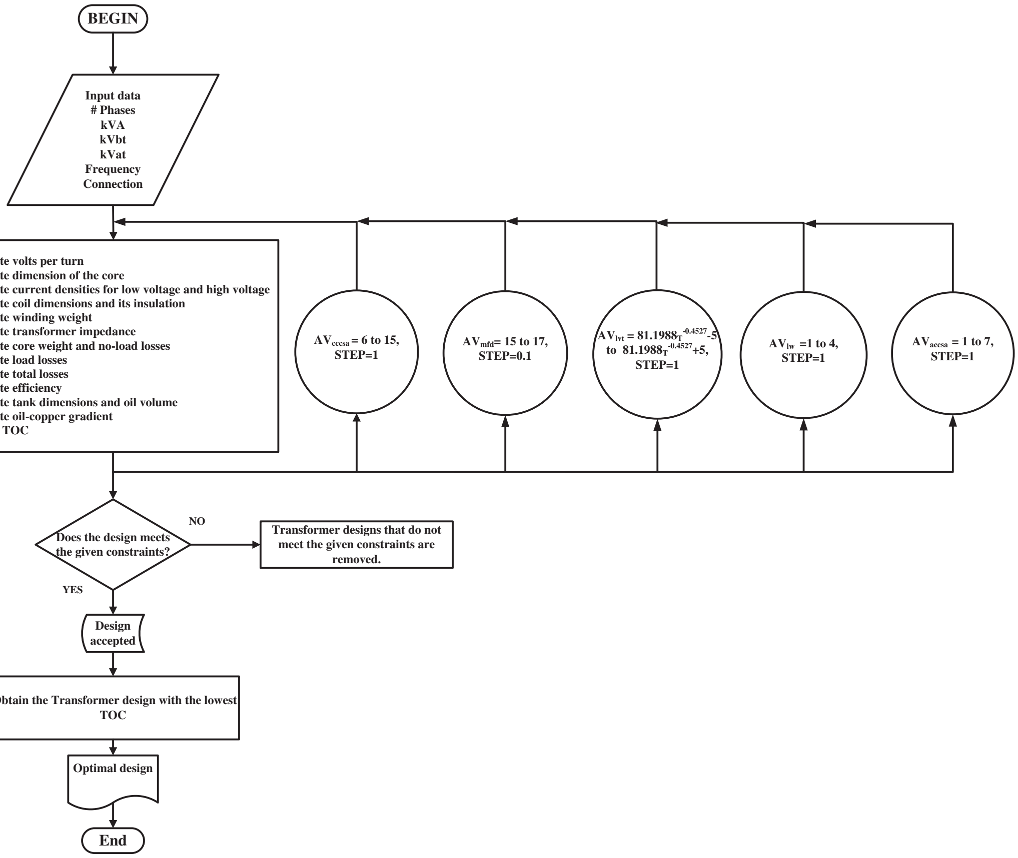


Figure 3. Simplified flow diagram for transformer optimisation using TOC as an objective function

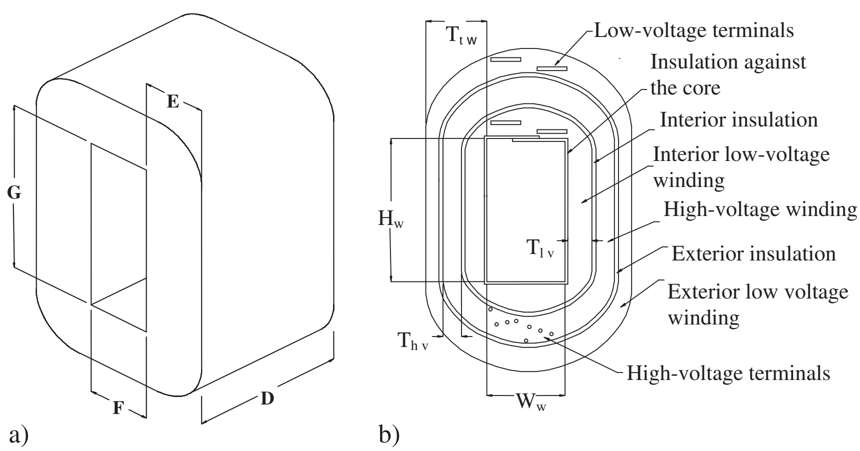


Figure 4. Active element. (a) Core dimensions and (b) low–high–low winding dimensions.

number of alternative values of turns of low voltage. Other objective functions (e.g. total material cost or total mass) can substitute TOC objective function in Figure 3.

In addition to Equations (1a), (1b) and 1c–9(1c)–, the most important formulas can be found in the study of Olivares-Galvan *et al.* [11], which are involved in the transformer design program (shown in the flowchart of Figure 3) to compute quantities such as core mass, no load loss, excitation current, winding mass, load losses and efficiency.

DOI: 10.1002/ete

4. RESULTS AND DISCUSSIONS

4.1. Simulation results

In the context of this research, 12 oil-immersed distribution transformers are designed: 6 three-phase transformer banks and 6 three-phase transformers. These designs meet all the requirements of a given transformer standard [10]. The transformer designs are optimised using the multiple design method of Section 3.5. M3 lamination was used for the magnetic material of all transformers (Figure 4).

Figures 5 to 8 were generated using a field-validated transformer design program [11]. Figure 5 shows the tendency of three-phase transformers to have less weight than three-phase transformer banks, but for lower power ratings, the opposite is observed, which is depicted with details in Figure 6.

The total mass for a three-phase transformer is always lower than total mass of three-phase transformer bank, although at lower ratings, these mass differences are smaller. More specifically:

- For the 30-kVA rating, the total mass of the three-phase transformer is 7.21% higher than that of the three-phase transformer bank, as Figure 6 shows.
- For the 112.5-kVA rating, the total mass of the three-phase transformer is 21.7% lower than that of the three-phase transformer bank, as can be seen in Figure 5.

Figure 7 shows the comparison of TOC between three-phase transformer banks and three-phase transformers. There is a trend of higher cost for three-phase transformer banks. However, the difference in cost of low-rating transformers is significantly reduced. More specifically:

- For the 30-kVA rating, the TOC of the three-phase transformer is 8.69% lower than that of the three-phase transformer bank.

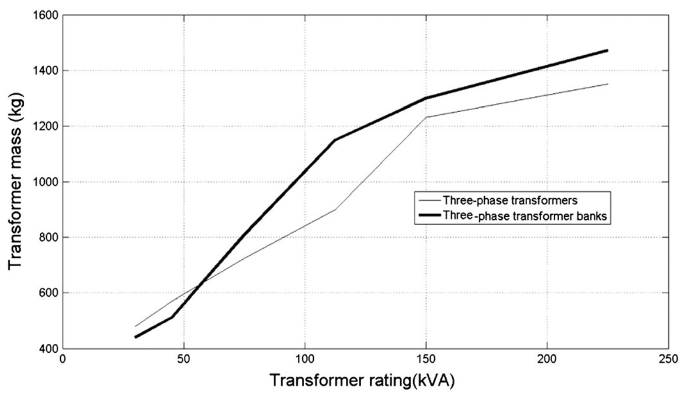


Figure 5. Total weight comparison for three-phase transformers and three-phase transformer banks.

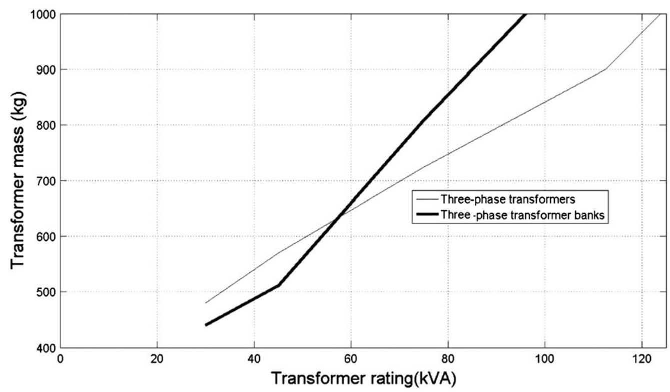


Figure 6. Zoom of Figure 5 for low-size transformers.

DOI: 10.1002/ete

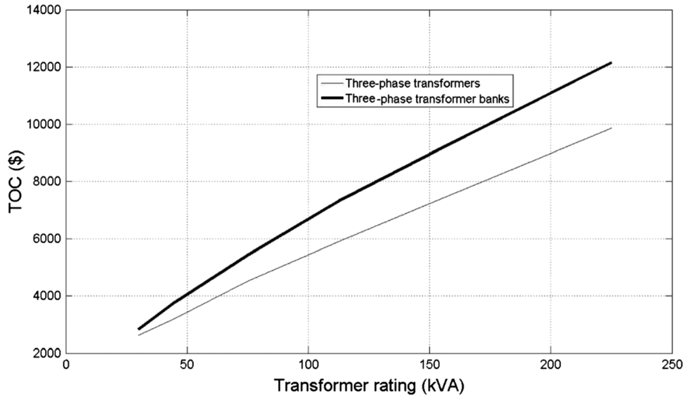


Figure 7. TOC comparison between three-phase transformers and three-phase transformer banks.

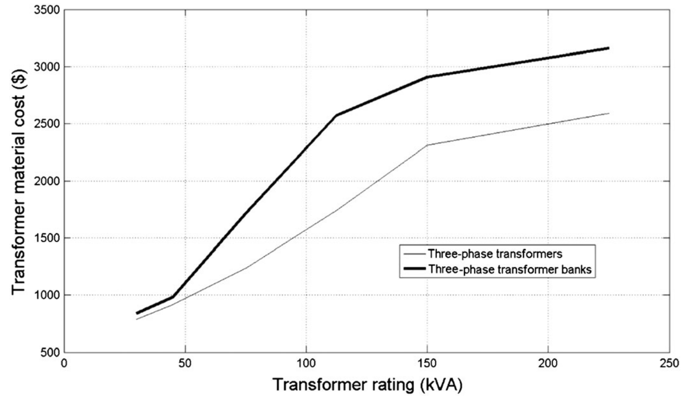


Figure 8. Material cost comparison between three-phase transformers and three-phase transformer banks.

- For the 112.5-kVA rating, the TOC of the three-phase transformer is 18.17% lower than that of the three-phase transformer bank.

The cost of materials for a three-phase transformer is always lower than the material cost of a three-phase transformer bank, although at lower ratings, these costs differences are smaller, as can be seen in Figure 8. More specifically:

- For the 30-kVA rating, the cost of materials of the three-phase transformer is 8.33% lower than that of the three-phase transformer bank.
- For the 112.5-kVA rating, the cost of materials of the three-phase transformer is 33.33% lower than that of the three-phase transformer bank.

4.2. Manufacturers curves

Figures 9–16 show the tendency of weight and cost of seven different transformer manufacturers. These graphs concern dry-type and oil-immersed transformers for different voltage class: 15 and 25 kV.

In particular, Figures 9 and 10 show comparative graphs of transformer manufacturer 0, indicating that at low power ratings, three-phase transformer banks are less expensive and have less weight than the three-phase transformers [28]. These results were our main motivation to conduct the research reported in this article.

Figures 11–18 also show that low-rating three-phase transformers have higher weight, and their cost tends to be equal or higher than the cost of three-phase transformer banks (for conclusions, see captions of Figures 11 to 18).

DOI: 10.1002/ete

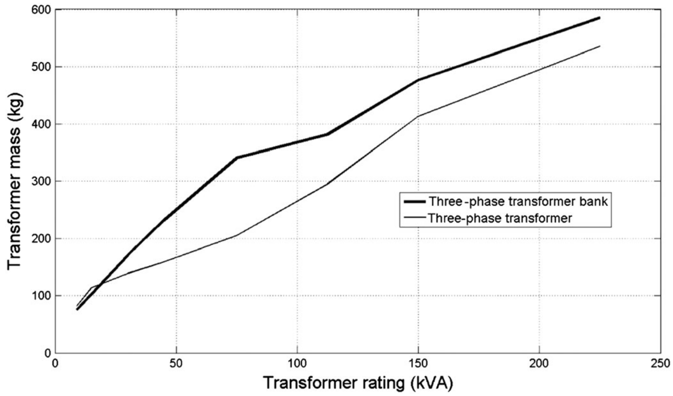


Figure 9. Weight comparison between three-phase transformers and three-phase transformer banks (transformer manufacturer 0).

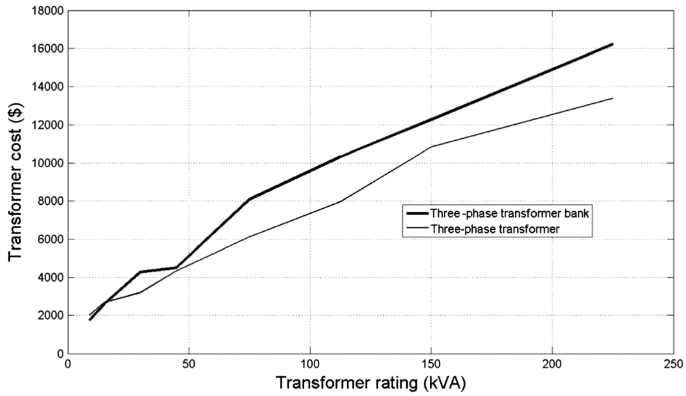


Figure 10. Cost comparison between three-phase transformers and three-phase transformer banks (transformer manufacturer 0).

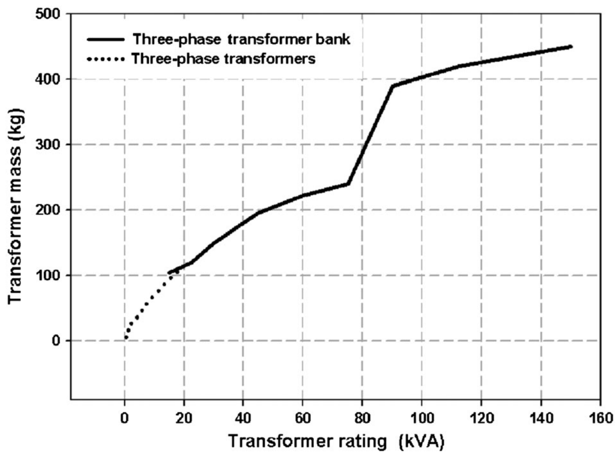


Figure 11. Total mass comparison for the 15-kV dry-type three-phase transformers and transformer banks (manufacturer 1). We can see that in case of the 20-kVA rating, the mass of transformer bank is almost the same with the mass of the three-phase transformer.

DOI: 10.1002/ete

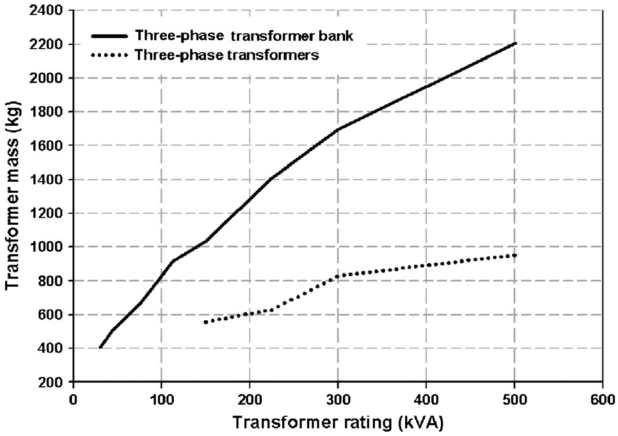


Figure 12. Total mass comparison for the 15-kV three-phase transformers and transformer banks (manufacturer 2). The mass of the 500-kVA three-phase transformer represents 43.18% of the mass of the 500-kVA transformer bank. We observe that as transformer rating is reduced, the curves tend to meet. This manufacturer did not have an available design of three-phase transformers lower than 150 kVA.

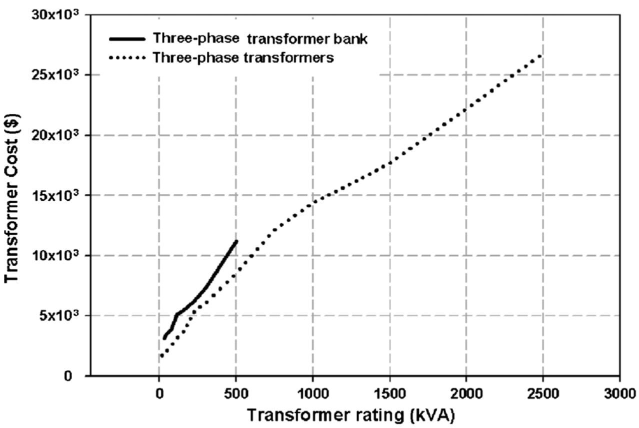


Figure 13. Cost comparison for the 15-kV three-phase transformers and transformer banks (manufacturer 3). This manufacturer did not have available designs for single-phase transformers higher than 167 kVA, that is, transformer bank higher than 500 kVA. It is observed that lower than 500 kVA, three-phase transformers are slightly less expensive than the corresponding transformer banks.

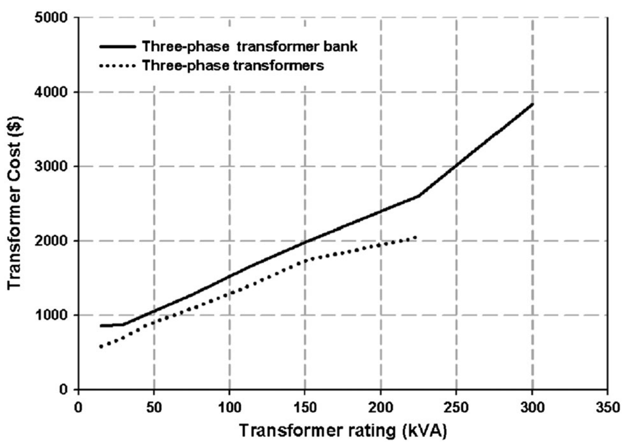


Figure 14. Total cost comparison for the 15-kV three-phase transformers and transformer banks (manufacturer 4). The cost of three-phase transformers is always less than the cost of the corresponding transformer bank.

DOI: 10.1002/ete

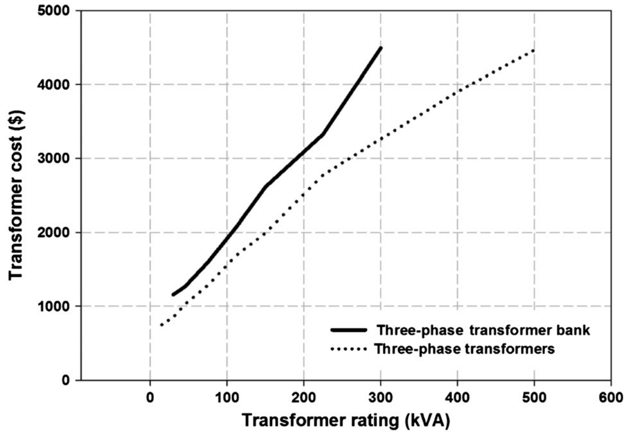


Figure 15. Transformer cost comparison for three-phase transformers and transformer banks (manufacturer 4). The transformer cost curves tend to converge at around 30 kVA.

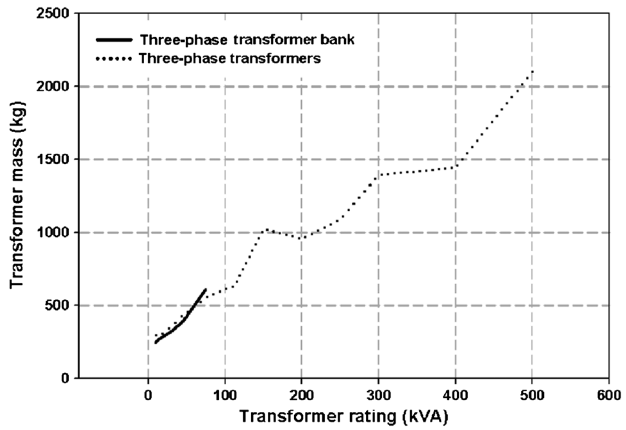


Figure 16. Total mass comparison for the 15-kV three-phase transformers and transformer banks (manufacturer 5). The mass of the transformer bank is less than the mass of the three-phase transformer for transformer rating lower than 50 kVA.

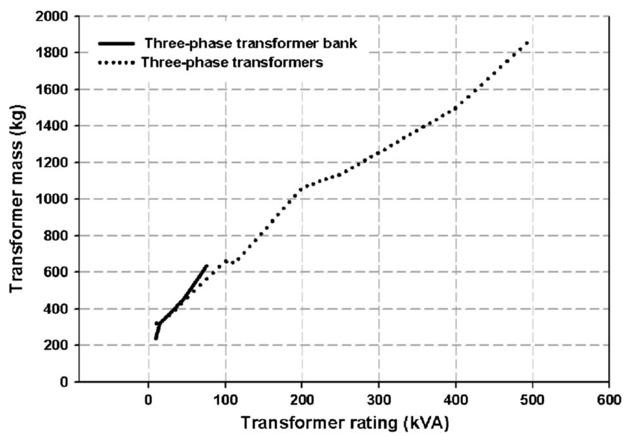


Figure 17. Total mass comparison for the 25-kV three-phase transformers and transformer banks (manufacturer 5). The mass of the transformer bank is practically equal to the mass of the three-phase transformer for transformer rating lower than 50 kVA.

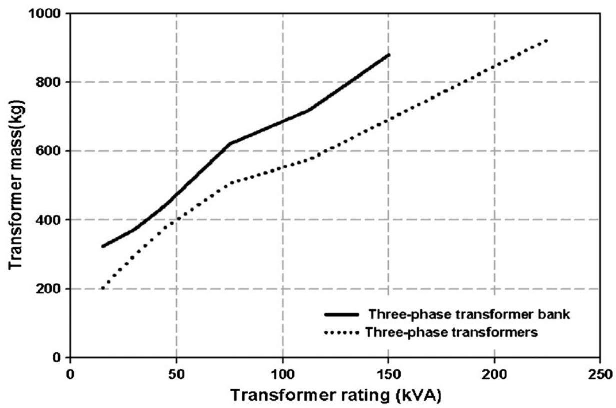


Figure 18. Total mass comparison for the 15-kV three-phase transformers and transformer banks (manufacturer 6). For transformer rating higher than 75 kVA, we observe that mass curves tend to diverge.

4.3. Future research

In the near future, an extension of this study will be made; we are planning to compare three-phase transformers against transformer banks in many aspects, such as temperature distribution in transformer windings [29–31], tank rupture [32] and inrush current [33,34].

5. CONCLUSIONS

In this article, three-phase transformer banks and three-phase transformers are studied and compared. The comparison is based on a transformer design optimisation methodology that minimises the transformer TOC while meeting all the requirements imposed by transformer design standards and specifications. Optimum single-phase and three-phase transformers are designed using a field-validated transformer design optimisation computer program that has been used for many years in a mid-size transformer factory. Specifically, 12 optimum transformer designs are computed for the comparison of three-phase transformer banks versus the three-phase transformers. As a result, curves of minimum TOC versus transformer rating are obtained for three-phase transformer banks and three-phase transformers. Moreover, similar curves from seven transformer manufacturers are collected. The advantage of this collection is that these different manufacturers have different types of transformers: oil immersed or dry type, core or shell type, various voltage classes and power ratings, and so on, and consequently more general conclusions can be drawn regarding the comparison of three-phase transformer banks and three-phase transformers. Specifically, a wide range of transformers with different power ratings, from 30 to 2500 kVA, is compared. On the basis of this study, it is concluded that the advantage of using three-phase transformers with power rating higher than 45 kVA is strong in terms of cost and weight. However, low-size three-phase transformers have more weight, and their cost tends to be equal or higher than the cost of three-phase transformer banks. We are presenting many evidence of this behaviour in the form of figures of seven different transformer manufacturers. The main reason behind this finding is related to the higher weight of transformer tank, oil and high-voltage conductor of three-phase transformer over three-phase transformer banks.

6. LIST OF ABBREVIATIONS AND SYMBOLS

N_{LV}	number of turns of the low voltage winding
TOC	transformer total owning cost
$\%Z$	transformer impedance
$\%R$	winding resistance (in %) at 85^{o} C
W_c	conductor losses at 85^{o} C (Watts)

DOI: 10.1002/ete

kVA	transformer rating
$\%X$	winding reactance (in %)
f	frequency (Hz)
IN	ampere turn of transformer
K	1.00 for three-phase transformers
K	0.85 for single-phase transformers
MLT_{wind}	mean turn length of windings (mm)
g	length of magnetic linkage (mm)
γ	average winding height plus average winding thickness (mm)
V_t	volt per turn
$M_{c-3\theta}$	core mass (kg)
P_{11}	lateral core mass (kg)
P_{12}	central core mass (kg)
M_{Cu}	high-voltage conductor mass for three-phase transformers
MLT_{HV}	mean turn length of high-voltage (m)
N_{HV}	number of turns of high-voltage winding
cs_{HV}	cross-section area of high-voltage conductor (m^2)
ρ_{HV}	density of high-voltage conductor (kg/m^3)
M_{Al}	low-voltage conductor mass for three-phase transformers
MLT_{LV}	mean turn length of low-voltage winding (m)
N_{LV}	number of turns of low-voltage winding
cs_{LV}	cross-section area of low-voltage conductor (m^2)
ρ_{LV}	density of low-voltage conductor (kg/m^3)
M_{ta}	tank mass
V_{ct}	volume of carbon steel plate content of the tank body (m^3)
V_{ft}	volume of carbon steel plate content of the bottom of the tank
V_{tt}	volume of carbon steel plate content of tank cover
ρ_{ac}	density of steel (kg/m^3)
$M_{t-3\theta}$	three-phase transformer total mass
$M_{ta-3\theta}$	tank mass of the three-phase transformer
$M_{oil-3\theta}$	mineral oil mass of the three-phase transformer
$C_{mat-3\theta}$	material cost of the three-phase transformer
uc_{HV}	per unit cost of high-voltage conductor ($/kg)
uc_{LV}	per unit cost of low-voltage conductor ($/kg)
uc_c	per unit cost of core magnetic material ($/kg)
uc_{ta}	per unit cost of tank steel ($/kg)
uc_{oil}	per unit cost of mineral oil ($/kg)
BP	transformer bid price ($)
A	transformer no-load loss cost rate ($/W)
NLL	the transformer no-load loss (W)
B	transformer load loss cost rate ($/W)
LL	transformer load loss (W)
C_{mat}	transformer material cost ($) computed from Equation (7)
C_{lab}	transformer labor cost ($)
SM	transformer sales margin
C_m	maintenance costs
C_r	failure repair costs
kVbt	low voltage
kVat	high voltage
AV_{mfd}	number of alternative values for the magnetic flux density
AV_{cccsa}	number of alternative values of copper conductor cross-sectional areas
AV_{accsa}	number of alternative values of aluminum conductor cross-sectional area
AV_{lw}	number of alternative values of lamination width and
AV_{lvt}	number of alternative values of turns of low voltage

DOI: 10.1002/ete

REFERENCES

1. Fofana I, Sabau J. Application of petroleum-based oil in power transformer. In *Natural Gas Research Progress*, David N, Michel T (eds). Nova Science Publishers: USA, 2008.
2. Chiasson J. *Modeling and High-Performance Control of Electric Machines*. IEEE Press Series on Power Engineering: USA, 2005.
3. Siskind CS. *Electrical machines*, 2nd edn. International Student Edition: USA, 1959.
4. Fitzgerald AE, Kingsley C, Jr., Umans SD. *Electrical Machines*. McGraw-Hill: USA, 1992; 87–89.
5. Laithwaite ER, Freris LL. *Electric Energy: its generation, transmission and use*. McGraw-Hill: Great Britain, 1980; 35–41.
6. Chapman SJ. *Electrical Machines*. McGraw-Hill: USA, 2005.
7. Gibbs JB. *Transformer principles and practice*. McGraw-Hill: USA, 1950; 6–11.
8. Blume LF, Boyajian A. *Transformer Connections, Including Auto-Transformer Connections*. General Electric Company, Publication GET-2B: Hickory, N.C., 1940.
9. Kersting WH, Phillips WH. Modeling and Analysis of Unsymmetrical Transformer Banks Serving Unbalanced Loads. *IEEE Transactions on Industry Applications* May/Jun 1996; **32**(3):720–725.
10. Norma NMX-J116-ANCE-2006, Norma Mexicana ANCE, Pole mounted and substation transformers, (In Spanish), pp. 7, 29–31.
11. Olivares-Galvan JC, Georgilakis PS, Escarela-Perez R, Campero Littlewood E. Optimal Design of Single-Phase Shell-Type Distribution Transformers based on a Multiple Design Method Validated by Measurements. *Electrical Engineering*, 6 June 2011, 1–10, DOI:10.1007/s00202-011-0211-9.
12. Say MG. *The performance and design of alternating current machines*, 3rd edn. Pitman Paperbacks: Great Britain, 1958.
13. Olivares JC, Antonio Trujillo J, Jara F. Methodology for optimization of distribution transformer cost, (in Spanish), Reunión de Verano de Potencia. Tomo 1, IEEE Sección México Julio 1998. Acapulco, Guerrero, México.
14. Cogent Power Inc. *Catalog of design and manufacture of transformer cores*. Cogent Power Inc.: Canada, 2001.
15. Harlow JH (ed). *Electric Power Transformer Engineering*. CRC Press LLC: USA, 2004.
16. Georgilakis PS. *Spotlight on Modern Transformer Design*. Springer: London, 2009.
17. Rubaai A. Computer aided instruction of power transformer design in the undergraduate power engineering class. *IEEE Transactions on Power Systems* 1994; **9**:1174–1181.
18. McLyman CWT. *Transformer and Inductor Design Handbook*, 3rd edn (revised and expanded). Marcel Dekker: NY, 2006; 183–184.
19. Kuhmann JJ. *Design of electrical apparatus*. J. Wiley and Sons: New York, 1940.
20. Elleuch M, Poloujadoff M. Technical and Economical Analysis of 3-LIMB and 4-LIMB Three Phase Transformers in Y_N/y_n Network. *European Transactions on Electrical Power* November/December 2002; **12**(6):397–402.
21. Corrales Martín J. *Optimal calculation of transformers (in Spanish)*. Marcombo: Barcelona, 1977.
22. Olivares-Galvan JC, de León F, Georgilakis PS, Escarela-Perez R. Selection of Copper versus Aluminum Windings for Distribution Transformers. *IET Electric Power Applications* 2010; **4**(6):474–485.
23. Kennedy BW. *Energy Efficient Transformers*. McGraw-Hill: New York, 1998.
24. Frau J, Arcos Á, Ruíz E, Ramis A. Energy Efficiency and Profitability Analysis of Reduced Loss Transformers: Experiences in Spain. 17th International Conference on Electricity Distribution, Barcelona, 12–15 May 2003.
25. Barnes PR, Van Dyke JW, McConnell BW, Cohn SM, Purucker SL. The feasibility of replacing or upgrading utility distribution transformers during routine maintenance, Power Systems Technology Program, Oak Ridge National Laboratory, RNL-6804/Rl, April 1995.
26. Georgilakis PS, Amoiralis EI. Distribution transformer cost evaluation methodology incorporating environmental cost. *IET Generation, Transmission and Distribution* July 2010; **4**(7):861–872.
27. Georgilakis PS, Tsili MA, Souflaris AT. A heuristic solution to the transformer manufacturing cost optimization problem. *Journal of Materials Processing Technology* 2007; **181**:260–266.
28. http://www.phaseconverter.com/sptransformer.html
29. Faiz J, Sharifian MBB, Fakhri A. Two-dimensional finite element thermal modeling of an oil-immersed transformer. *European Transactions on Electrical Power* 2008; **18**(6):577–594.
30. Weigen C, Chong P, Yuxin Y. Power transformer top-oil temperature model based on thermal–electric analogy theory. *European Transactions on Electrical Power* 2009; **19**(3):341–354.
31. Taghikhani MA, Gholami A. Temperature distribution in ONAN power transformer windings with finite element method. *European Transactions on Electrical Power* 2009; **19**(5):718–730.
32. Culver B, Fröhlich K, Widenhorn L. Prevention of tank rupture of faulted power transformers by generator circuit breakers. *European Transactions on Electrical Power* 1996; **6**(1):39–45.
33. Theocharis AD, Milias-Argitis J, Zacharias T. Three-Phase Transformer Model Including Magnetic Hysteresis and Eddy Currents Effects. *IEEE Transactions on Power Delivery* July 2009; **24**(3):1284–1294.
34. Theocharis AD, Milias-Argitis J, Zacharias T. A systematic method for the development of a three-phase transformer non-linear model. *International Journal of Circuit Theory and Applications*, Published online in Wiley InterScience, DOI: 10.1002/cta.599, 2009.