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ORIGINAL PAPER

Core lamination selection for distribution transformers based on sensitivity analysis

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Abstract In this paper, the sensitivity analysis is used to select the core lamination thickness of single-phase distribution transformers rated from 5 to 50 kVA. Three different magnetic materials (M2, M3 and M4) with thicknesses of 0.18, 0.23 and 0.27 mm are considered. Transformer designs are compared based on the total owning cost as well as on the transformer bid price. The impact of the different laminations on total owning cost and bid price is calculated for a total of 144 transformers (72 for each criterion). All transformers fulfill all the operating and construction constraints. The paper considers the impact on core losses of the space factor (core-assembling pressure) and of the building factor and also describes how core losses are affected by core design parameters such as the number of laminations per step, air gap and overlap. It is concluded that for the analyzed power range, M3 lamination is the best choice since all of the studied cases have smaller bid price and 79% of the studied cases have lower total owning cost. This paper gives guidelines to select the appropriate thickness and can help transformer manufacturers to select the optimal thickness for distribution transformers.

Keywords Costing · Design engineering · Magnetic cores · Magnetic materials · Losses · Transformer · Transformer cores

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1 Introduction

Due to the importance of improved electrical core performance, researchers are very active in the development of better transformer cores and core modeling techniques [1–7]. Better manufacturing techniques have been developed as a consequence of a better understanding of the factors that influence magnetic properties. Nowadays, the quality of electrical steel has been substantially improved. Factors that impact core loss of electrical steel are reported in [8,9]: (a) quality of sheet insulation, (b) percentage of silicon in the alloy, (c) chemical impurities, (d) grain size, (e) crystal orientation control and (f) core lamination thickness.

A useful model in literature is presented in [1]; the model covers steady-state unbalanced conditions of three-phase transformers including three-legged, five-legged and triplex core designs. In this model, Córcoles et al. [1] used phase and sequence nodal equations for all winding connections. Guerra et al. [2] used a nonlinear electric circuit to describe the behavior of magnetic cores in low-frequency conditions. In this electric circuit, the hysteresis modeling takes into account minor loops and remanent magnetic flux. Classic eddy current losses and anomalous losses are represented by a linear resistor and a nonlinear resistor, respectively.

Zirka et al. [3] compared the two-component method where total loss is subdivided into hysteresis (static) and eddy current (dynamic) components with the three-component method where the total loss is subdivided into hysteresis, classical and excess components. Authors of [3] found that total losses obtained with the three-component method are more accurate than that calculated using the two-component method. In [4], the authors modeled the dynamic loops and losses in grain-oriented electrical steels under arbitrary magnetization regimes using the concept of magnetic viscosity; they found that the steel could be modeled, for frequencies up to 200 Hz, using the thin sheet model (the instantaneous value of the applied field is subdivided into hysteresis field, classical eddy current field and excess field) and at higher frequencies using a finite-difference solver.

Schultz et al. [5] built and tested oil-cooled, amorphous-core (Metglas TCA) distribution transformers prototypes; they installed four 100 kVA and one 50 kVA transformers on the Hydro-Québec power system and tested them over a period of 1 year. They recommend using amorphous-core transformers in areas where the cost of the no-load losses exceeds USA $5.20/W. In [6] Thompson describes the main advancements in grain-oriented silicon iron for transformers (reduction of magnetostriction, improvements of magnetic properties, reduction of core loss) and suggests possible lines of research (basic properties improvements, variation of thickness within a lamination, domain behavior). In [7] Kefalas et al. propose an iron loss minimization of wound core transformers using a combination of different grade steels; they used permeability tensor finite element model and simulated annealing.

Overall, improvements in core materials and manufacturing processes have a significant impact on the total cost of the transformer. When the performance of the magnetic material improves, the size of the core can be reduced. Use of better material with improved core joints allows higher operating flux density. Nevertheless, the production cost per unit weight of electrical steels increases rapidly as lamination thickness is reduced. While the thinnest materials may be necessary for certain applications, the use of laminations thinner than necessary is wasteful.

Transformer prices are normally compared in terms of the total owning cost (TOC) and the purchasing price usually called bid price. TOC of a transformer is the sum of the purchasing price plus the cost of transformer losses throughout the transformer life [10]. Electric utilities usually purchase transformers based on the TOC, i.e., they select the offer that minimizes TOC. On the other hand, industrial users usually purchase transformers based on transformer bid price, i.e., they select the offer with minimum purchasing price. Consequently, transformer manufacturers have to minimize either the TOC or the bid price depending on customer and transformer specifications.

This paper gives clear guidelines to select the appropriate thickness for core lamination in distribution transformers based on the minimization of either TOC or bid price. Three different grades of magnetic materials are considered: M2, M3 and M4. The importance of this research is based on the fact that the cost of magnetic steel in single-phase shell-type distribution transformers (Fig. 1) represents 27–38% of the total cost of materials as shown in Table 1 [11]. This table was obtained taking into account shell-type transformers designed with M3 lamination. Figure 2 shows the core manufacturing parameters and the values used in the wound-core distribution-transformer ratings of this research. Section 2 includes the model used in the analysis and gives an insight on how core loss components are affected by lamination thickness. Section 3 describes in detail the manufacturing factors that can produce a core loss increment and how they are included in the analysis. Section 4 describes the software program and objective functions used to obtain

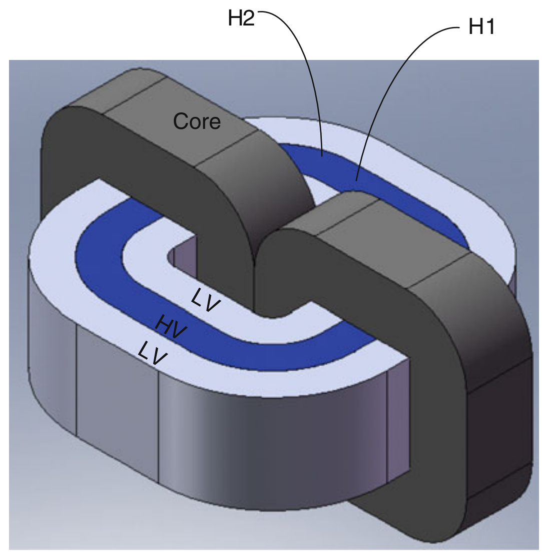

Fig. 1 Single-phase shell type transformer (*LV* low voltage, *HV* high voltage, *H1* and *H2* high voltage terminals)

Table 1 Percent of material cost in the manufacturing of distribution transformers

Transformer material	Cost (%)
Magnetic steel	32.5 ± 5.5
Windings (copper or aluminium)	22 ± 6
Insulation	14.1 ± 5.5
Carbon steel	16.4 ± 8.5
Fabricated parts	15 ± 9
Total	100

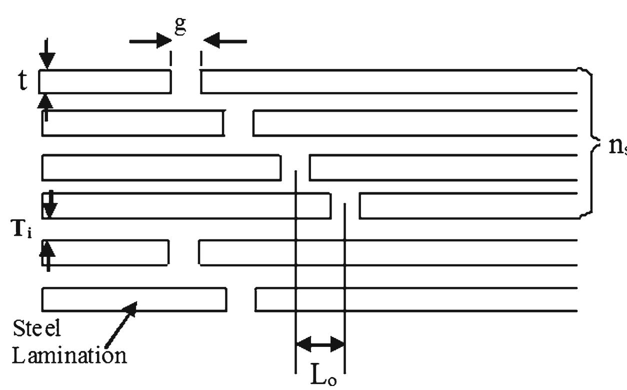

Fig. 2 Core with step-lap joint (g = air gap, d = lamination thickness. T_i = insulation thickness, L_o = overlap, n_s = number of laminations per step), where 1 mm $< g <$ 2 mm, L_o = 1cm, $T_i/2 = 0.0001$ cm per surface

the transformer designs with the three different magnetic materials and includes the obtained results. Appendix A describes how core losses are affected by core design parameters such as the number of laminations per step, air gap and overlap.

The lamination thickness for 60 Hz transformers is usually in the range of 0.17–0.27 mm, depending on the relative importance of core losses in the total losses of the transformer and on price criteria. There is no general agreement among transformer manufacturers about the optimal thickness of laminations.

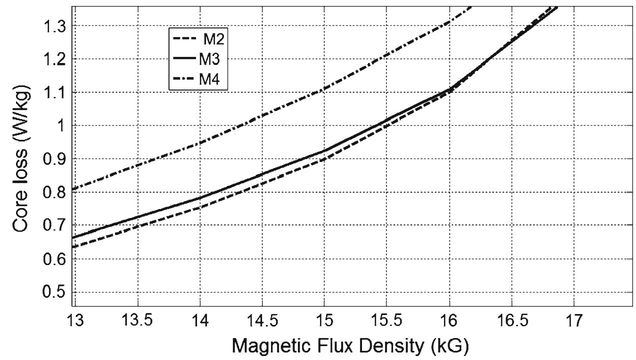

Fig. 3 Core loss as a function of magnetic flux density [13]

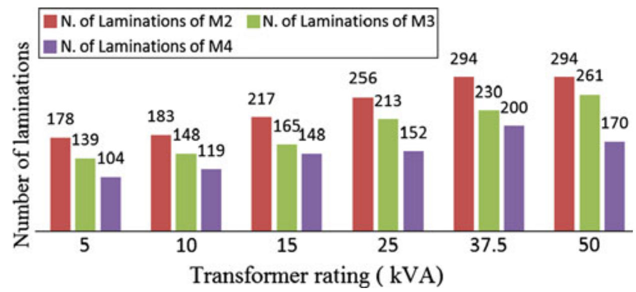

Fig. 4 Number of core laminations versus transformer rating

2 Core lamination modelling

The term "electrical steels" has been universally accepted as the designation for flat rolled magnetic materials in which silicon is an important alloying element [12]. The American Iron and Steel Institute (AISI) designation for electrical steel grades consists of the letter M (magnetic material) followed by a number (e.g., M2) to specify the type of lamination. At the time the AISI system was adopted, the type number assigned to each grade was approximately ten times the core loss expressed in watts per pound for a given thickness. Today, type numbers do not have this specific association with core loss. The thicknesses of electrical steels studied in this paper are presented in Table 2.

In the analysis performed in this paper, the model used to calculate core losses for the three magnetic materials (M2, M3 and M4) is that of [13], where the core loss is in watts per kilogram for the considered laminations at 60 Hz as a function of the peak magnetic flux density B_p (T):

$$w_{\mathrm{kg}}^{\mathrm{M2}} = -21.11312203 + 8.583546123 \cdot B_\mathrm{p} + 1.390035903 \cdot B_\mathrm{p}^2 + 0.113207533 \cdot B_\mathrm{p}^3 - 0.004609366 \cdot B_\mathrm{p}^4 + 7.54374 \cdot 10^{-5} \cdot B_\mathrm{p}^5 \quad (1)$$

$$w_{\mathrm{kg}}^{\mathrm{M3}} = -45.94322511 + 17.94316167 \cdot B_\mathrm{p} - 2.787213965 \cdot B_\mathrm{p}^2 + 0.21646225 \cdot B_\mathrm{p}^3 - 0.008382569 \cdot B_\mathrm{p}^4 + 0.000129908 \cdot B_\mathrm{p}^5 \quad (2)$$

$$w_{\mathrm{kg}}^{\mathrm{M4}} = -0.08058632 + 0.07744565 \cdot B_\mathrm{p} - 0.01948912 \cdot B_\mathrm{p}^2 + 0.00350717 \cdot B_\mathrm{p}^3 - 0.0002352 \cdot B_\mathrm{p}^4 + 5.9045 \cdot 10^{-6} \cdot B_\mathrm{p}^5 \quad (3)$$

Graphs for equations (1)–(3) are shown in Fig. 3, where it can be observed that M2 and M3 materials have a very similar behavior and cores manufactured with thicker materials have less loss per unit weight, although transformers built with thinner laminations need less core material. The distribution transformers analyzed here use a different number of laminations depending on the selection of the magnetic material. The number of laminations needed to form the transformer cores (Fig. 1) for the ratings of the analysis (5–50 kVA) are given in Fig. 4. The average increase in the number of laminations is 19.1% when using M2 instead of M3 and is 22.0% when using M3 instead of M4. Thus, the impact of lamination thickness in losses and costs can only be evaluated in terms of the core weight and hence on the design of the transformer. Incidentally, it is more difficult and time consuming to handle and process thinner laminations. Equations (1)–(3) are included in the computer program used to design the transformers.

Table 2 Electrical steel thicknesses

Grade AISI designation (ASTM designation)	Thickness in inches (mm)
M2 (Type 18G041)	0.007 (0.18)
M3 (Types 23G045 and 23H070)	0.009 (0.23)
M4 (Types 27G051 and 27H074)	0.011 (0.27)

Note: M2 is approximately equivalent to ASTM Type 18G041

Although the model used for the sensitivity analysis is the one described in (1)–(3), it is interesting to use other models that represent core loss components to briefly illustrate the difficulty in finding the lamination thickness to have the minimum core losses. The core loss is summarized using the conventional technique [14]:

$$P = P_{\mathrm{cl}} + P_\mathrm{h} + P_{\mathrm{ex}} \quad (4)$$

where P_{cl} are the classical eddy current losses, P_h are the hysteresis losses and P_{ex} are the excess losses.

Classical eddy current losses per unit volume at power frequency excitation can be expressed as [15]:

$$P_{\text{cl}} = \frac{\left(t \cdot \pi \cdot B_{\text{p}} \cdot f\right)^2}{6 \cdot \rho} \tag{5}$$

where ρ is the electrical resistivity of the material, t is the lamination thickness, B_{p} is the peak sinusoidal magnetic flux density and f (Hz) is the frequency. It is evident from (5) that lamination thickness reduction means a squared reduction of eddy current losses.

Hysteresis loss per unit volume at power frequencies is [16]:

$$P_{\text{h}} = \frac{2\ f\ S\ B_{\text{p}}^2}{\mu} \tag{6}$$

where μ (H/m) is the permeability of the material, and S is the shape factor.

An expression that describes excess loss in terms of classical core loss has been derived by Pry and Bean [17]:

$$P_{\text{ex}} = \left(1.628\frac{2L}{t} - 1\right) P_{\text{cl}}, \quad \text{when } 2L/t >> 1 \tag{7a}$$

$$P_{\text{ex}} << P_{\text{cl}}, \quad \text{when } 2L/t << 1 \tag{7b}$$

Equation (7) shows that a fundamental parameter to characterize excess losses is the ratio $2L/t$ between the domain width $(2L)$ and the lamination thickness (t).

The excess eddy current loss is a direct consequence of the domain structure of the material and arise from the currents localized at the moving domain walls [18]. The excess loss P_{ex} can be minimized further by refining domain structure or by metallurgically pinning domain walls.

At power frequencies, the difference between measured and calculated losses, the so-called anomalous or excess loss, may be not significant for non-oriented steel used in motors and generators. The percentages of hysteresis, classical eddy current and excess losses for 0.27 mm thick grain oriented steel are 42, 21 and 37%, respectively [19]. Losses were measured for other materials in [20] and they are listed in Table 3.

The decrease in the lamination thickness leads to a quadratic decrease of the classical eddy current loss as can be seen in (5). There is experimental evidence that hysteresis loss increases as lamination thickness decreases below 0.20 mm [21]. Excess loss is impacted by the lamination thickness as can be seen in (7). It is important to mention that the domain width $(2L)$ increases as lamination thickness decreases [21]. Lamination thickness has a different impact on core losses components, thus the total core loss as a function of thickness has a minimum [21,22]. The choice of lamination thickness is a compromise between loss reduction and transformer cost.

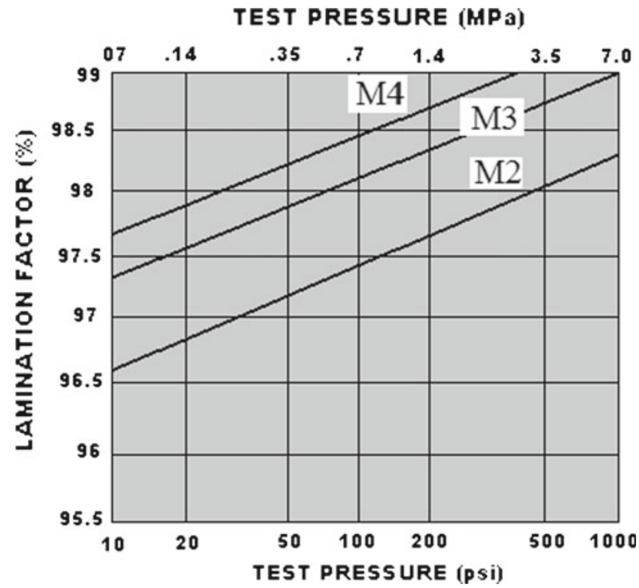

Fig. 5 Lamination factor versus test pressure for the most widely used forms of grain-oriented silicon steel produced by AK Steel Corporation

3 Space factor and building factor

Space factor or lamination factor is the measure of compactness of an electrical steel core. This is also referred to as stacking factor. Space factor is the ratio of the equivalent "solid" volume, calculated from the weight and density of the steel, to the actual volume of the compressed pack. Figure 5 illustrates how the space factor varies as a function of pressure for the laminations compared in this paper. Pressure compressing the sheets should not exceed a maximum limit of 1.0 MPa to avoid excessive reduction of resistivity of the lamination sheet insulation [15].

Bandages as the ones shown in Fig. 6 are used in distribution transformer cores for a uniform pressure distribution. If a typical core assembling pressure of 20 psi (0.14 MPa), as the one obtained with manual strapping machines, is considered, the space factors for M2, M3 and M4 result in 96.8,

Table 3 Losses (W/kg) measured with the three-component method for various materials

Material	Thickness (10^{-4} m)	P_{h}	P_{cl}	P_{ex}
Grain-oriented 3% SiFe longitudinally cut	2.9	0.34	0.29	0.53
Grain-oriented 3% SiFe transversally cut	3.4	1.7	0.31	1.8
Nonoriented 3% SiFe	3.5	1.8	0.29	0.33
Amorphous METGLAS 2605 CO	0.3	0.29	8.5×10^{-4}	0.094

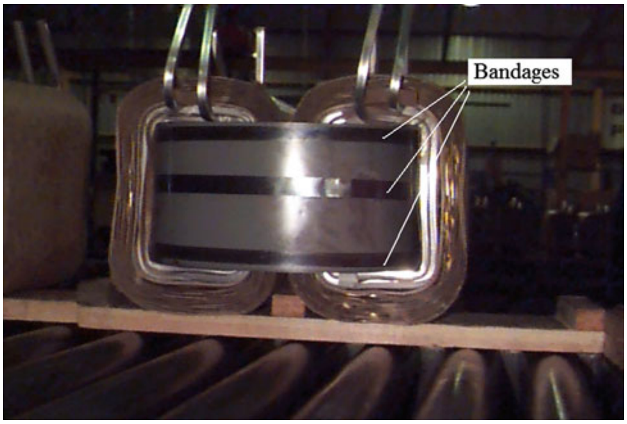

Fig. 6 Use of bandages in transformer cores for a uniform distribution of pressure

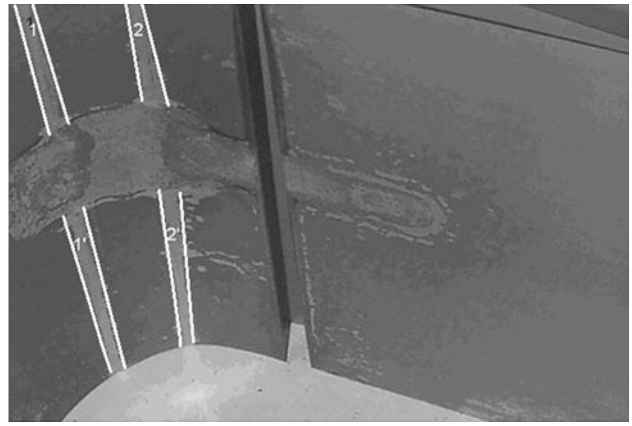

Fig. 7 The insulating coating of the laminations can be damaged when there is improper handling of the core steel during steel manufacturing or core assembling. The canals 1–1′ and 2–2′ (highlighted in white on the edges) were done intentionally to show the appearance of the lamination when insulation is damaged

97.6 and 97.8%, respectively (Fig. 5) [12]. When core-assembling pressure is high, the effective superficial resistance is reduced [23]. Normally, cores are assembled with manual strapping machines that represent a pressure of 0.14 MPa. To increase the core-assembling pressure, pneumatic strapping machines are used, as a result a 0.63 MPa pressure is obtained [24]. Two cores of 15 kVA single-phase transformers were used for experimentation, one core assembled with manual straps and the other one with pneumatic straps. Measurements were performed and an increment of 4% in core loss was observed when coil core was assembled with pneumatic machines. The difference in core losses can be seen in Table 4.

There are other factors that are considered as possible causes of increase in core losses: (a) improper handling of the core steel during transformer manufacturing; (b) poor insulation coating within lamination layers (Fig. 7); (c) improper arrangements of core joints; (d) burrs forming at slit edges or at the cut joints (if burrs are present in the lamination, interlamination short circuits can occur); (e) incomplete stress relief annealing. The additional losses due to all these factors were taken into account by including a building factor. The building factor is the ratio of the test measured core loss per weight (W/kg) for a fully assembled core, to the specified manufacturer loss (W/kg) for the considered magnetic material.

Table 4 Core loss measurements of 15 kVA transformers with different core assembling pressure

Sample	Core loss (W) for 0.63 MPa assembling pressure	Core loss (W) for 0.14 MPa assembling pressure
1	44.5	43
2	45.5	44

In all designs of all the ratings of the single-phase transformers considered in this research, the space factors for the three lamination thicknesses are 96.8% for M2, 97.6% for M3 and 97.8% for M4, and a building factor of 1.06.

4 Results and discussion

The software program for the optimal design of single-phase shell-type distribution transformers uses equations (1)–(3) in Sect. 2 and includes the space factor and building factor given in Sect. 3 in order to obtain the dimensions of the core, core weight and the no-load losses, based on the algorithm described in Table 5. More details on the optimization methodology and the software can be found in [25]. This computer program was validated with the design, construction and laboratory tests of a 25 kVA transformer. The intention is to obtain the design of distribution transformers from 5 to 50 kVA considering the three different magnetic materials and to optimize the design using two different objective functions [26]:

(1) Minimizing the transformer bid price (usually the objective when transformers are for industrial and commercial users).
(2) Minimizing TOC (usually the objective for transformers that are purchased by electric utilities).

The transformer bid price, BP ($), is computed as follows [26]:

$$BP = \frac{MC + LC}{1 - SM} \quad \text{or} \quad BP = \frac{TMC}{1 - SM} \tag{8}$$

Table 5 Simplified flowchart for transformer design optimization

Call routine of given variables
For $i = 1$ to N_{MFD} (number of options for the peak magnetic flux density)[a]
For $j = 1$ to N_{CG} (number of options for high voltage conductors)[b]
For $k = 1$ to N_{LVT} (number of options for low voltage turns)[c]
For $l = 1$ to N_{LW} (number of options for laminations width)[d]
For $m = 1$ to N_{LVA} (number of options for low voltage conductors)[e]
Calculate volts per turn
Calculate dimensions of the core
Calculate current densities for low voltage and high voltage
Calculate coil dimensions and its insulation
Calculate winding weight
Calculate transformer impedance
Calculate core weight and no-load losses
Calculate load losses
Calculate total losses
Calculate efficiency
Calculate tank dimensions and oil volume
Calculate oil–copper gradient
Calculate the value of the objective function
End
End
End
End
End
Optimum transformer is the one with the optimum value of the objective function that satisfies all the constraints

[a] Range of Magnetic flux density (T): 1.5–1.7
[b] Range of high-voltage conductor cross-sectional area (mm^2): 6–15 AWG
[c] Range of low-voltage turns: q−5 to q+5, where $q = 81.198 \times (\text{transformer rating})^{-0.4725}$
[d] Range of lamination width (mm): 152.4–203.2
[e] Range of low-voltage conductor cross-sectional area (mm^2): 34.29–452.12

where MC ($) is the cost of transformer materials, LC ($) is the labor cost, TMC ($) is the transformer manufacturing cost (TMC = MC + LC), and SM is the sales margin ($0 < \mathrm{SM} < 1$). All the quantities in $ are expressed in USA dollars. The labor cost used in all simulations is equal to 10% of the corresponding transformer material cost. The TOC ($), is computed as follows:

$$\mathrm{TOC} = \mathrm{BP} + \mathrm{CL}, \tag{9}$$

where BP ($) is the transformer bid price computed from (8) and CL ($) is the cost of losses throughout the transformer life (25 years), given by:

$$\mathrm{CL} = A \cdot \mathrm{NLL} + \mathrm{B} \cdot \mathrm{LL}, \tag{10}$$

where A ($/W) is the no-load loss cost rate, NLL (W) is the transformer no-load loss, B ($/W) is the load loss cost rate, and LL (W) is the transformer load loss. An in-depth description on how the loss cost rates A and B are determined is given in [27]. $A = \$8.18/\mathrm{W}$ and $B = \$4.03/\mathrm{W}$ are current values used by Mexican utilities [28].

The optimization problem for a specific 25 kVA transformer design example is formulated by (11a) and (11c) or by (11b) and (11c), depending on whether the objective function is the minimization of BP or TOC:

$$\min\{\mathrm{BP}\} = \min\left\{\frac{\mathrm{MC} + \mathrm{LC}}{1 - \mathrm{SM}}\right\} \tag{11a}$$

$$\min\{\mathrm{TOC}\} = \min\{\mathrm{BP} + A \cdot \mathrm{NLL} + B \cdot \mathrm{LL}\} \tag{11b}$$

$$\text{subject to, } I < 1.5\%, \mathrm{NLL} < 86\ \mathrm{W}, \mathrm{NLL} + \mathrm{LL} < 368\ \mathrm{W}, \quad 1.5\ \% < Z < 3.0\%, n \geq 98.55\% \tag{11c}$$

where I, Z, and n denote the percentage of excitation current, impedence, and efficiency of transformer, respectively.

All the designs with the three different laminations considered (M2, M3 and M4) have to fulfil all the construction constraints and the operating constraints: maximum no-load losses, maximum total losses, minimum efficiency, maximum and minimum impedance value and maximum limit of magnetizing current. Table 5 shows the computer program flowchart for minimizing an objective function, such as bid price or TOC.

4.1 Selection of core lamination when minimizing bid price

The objective function of this section is to minimize the bid price with the purpose of selecting the best lamination thickness. A large enough sample of transformer ratings has been

Table 6 Variation of sales margin and lamination cost ratios

Case identifier	MMC_{M2}/MMC_{M3}	$MMC_{M3}/MMCx_{M4}$ (%)	Sales margin
BP_{15-35} (base case)	1.15	1.15	35
BP_{15-20}	1.15	1.15	20
BP_{15-50}	1.15	1.15	50
BP_{05-35}	1.05	1.05	35

chosen to observe the cost trend. Six of the most common transformer ratings in Mexican utilities [29] were chosen, namely, 5, 10, 15, 25, 37.5 and 50 kVA (in Mexico, the range of power for single-phase distribution transformer is from 5 to 167 kVA for three different levels of voltage class: 15, 25 and 34.5 kV). Let MMC_{M2}, MMC_{M3}, and MMC_{M4} be the magnetic material cost per unit of weight ($/kg) for M2, M3 and M4 laminations respectively. Table 6 describes a set of cases that are representative of real-life scenarios for different sales margin and lamination cost ratios, applicable to the analyzed transformers.

Table 7 presents the transformer bid price (in % of the minimum bid price) of the six transformer ratings from 5 to 50 kVA for the four cases described in Table 6, manufactured with different lamination thicknesses: M2 (0.18 mm), M3 (0.23 mm) and M4 (0.27 mm). The first column of Table 7 shows the results for the base case and there are three more columns where the sales margin and the lamination cost ratios are changed according to the values in Table 6. Based on the 72 designs shown in Table 7, it is concluded that for all transformer ratings and for all analyzed cases, the minimum bid price corresponds to magnetic material M3.

4.2 Selection of core lamination when minimizing TOC

In this section, the objective function is to minimize the transformer TOC. The same six transformer ratings of Sect. 4.1 are studied here. Table 8 describes four combinations of no-load cost rate A and load loss cost rate B that have been chosen to cover all practical scenarios.

Table 8 Variation for no-load loss cost and load loss cost rates covering all practical design scenarios. $A = \$8.18/\text{W}$ and $B = \$4.03/\text{W}$ are current values used by Mexican utilities

Case identifier	No-load loss cost rate A($/W)	Load loss cost rate B($/W)
$A_{8.18}B_{4.03}$	8.18	4.03
$A_{8.18}B_{2.01}$	8.18	2.01
$A_{8.18}B_{8.18}$	8.18	8.18
$A_{4.03}B_{4.03}$	4.03	4.03

Note: in all these cases the laminations cost ratios are: $MMC_{M2}/MMC_{M3} = MMC_{M3}/MMC_{M4} = 1.15$ and the sales margin is 35%

Fig. 8 TOC (in % of the minimum TOC) for case $A_{8.18}B_{8.18}$ of Table 9. Smaller TOC when 10–50 kVA ratings use M2 lamination. Case $A_{8.18}B_{8.18}$ implies: $A = \$8.18/\text{W}$, $B = \$8.18/\text{W}$, sales margin is 35% and $MMC_{M2}/MMC_{M3} = MMC_{M3}/MMC_{M4} = 1.15$

The results of the 72 transformer designs obtained when TOC is minimized are reported in Table 9. It can be seen that for cases $A_{8.18}B_{4.03}$, $A_{8.18}B_{2.01}$, and $A_{4.03}B_{4.03}$ (for all transformer ratings), the minimum TOC corresponds to M3. Case $A_{8.18}B_{8.18}$ for 5 kVA transformers has a minimum TOC also corresponding to M3. However, five transformer ratings (10, 15, 25, 37.5 and 50 kVA) of case $A_{8.18}B_{8.18}$ have the minimum TOC with M2 material (corresponding to the

Table 7 Transformer bid price (in % of the minimum bid price) for 5–50 kVA single-phase transformers for three lamination thicknesses and four cases defined in Table 6

kVA	Bid price (%)											
	Case BP_{15-35}			Case BP_{15-20}			Case BP_{15-50}			Case BP_{05-35}		
	M2	M3	M4	M2	M3	M4	M2	M3	M4	M2	M3	M4
5	131	123	154	106	100	125	170	160	200	126	123	155
10	131	123	137	107	100	111	170	160	178	126	123	138
15	133	123	134	108	100	109	172	160	174	127	123	135
25	132	123	143	107	100	116	172	160	186	126	123	144
37.5	133	123	131	108	100	107	172	160	171	127	123	133
50	132	123	135	108	100	109	172	160	175	127	123	136

Note: sub index of cases: lamination cost ratio-sales margin

Table 9 TOC (in % of the minimum TOC) of 5–50 kVA transformers for three lamination thicknesses versus four cases of different combinations of loss cost rates A and B defined in Table 8

kVA	Total owning cost–TOC (%)											
	Case $A_{8.18}B_{4.03}$ (A = \$8.18/W, B = \$4.03/W)			Case $A_{8.18}B_{2.01}$ (A = \$8.18/W, B = \$2.01/W)			Case $A_{8.18}B_{8.18}$ (A = \$8.18/W, B = \$8.18/W)			Case $A_{4.03}B_{4.03}$ (A = \$4.03/W, B = \$4.03/W)		
	M2	M3	M4	M2	M3	M4	M2	M3	M4	M2	M3	M4
5	119	114	120	104	100	103	189	142	153	134	101	106
10	122.4	119.5	123.2	103.4	100	104	153.4	153.8	163.2	108	103.7	107.3
15	124	121	123	103	100	100.4	160.7	160.8	169	110	106	107
25	126	123	131	103	100	105	161	164	175	110	106	114
37.5	131.9	128.8	133	102.3	100	103.5	166.5	171.2	188	115	111	115
50	125.8	123.7	129.1	102.1	100	103.5	164.2	166.4	178.5	110.2	106.3	111.6

following TOC percentages: 153.4, 160.7, 161, 166.5, 164.2) as can be seen in Fig. 8, where it can also be noted that the TOC of M3 transformers is very close to the TOC of M2 transformers. Consequently, 19 (79%) of the 24 scenarios (4 cases for 6 ratings in Table 9) have the minimum TOC when the transformers are manufactured with M3 laminations.

5 Conclusion

The parametric sensitivity analysis is used to select the core lamination thickness of shell-type distribution transformers. All the transformer designs have been obtained with a computer program described in detail in [25]. The methodology has been applied to single-phase distribution transformers with rated power ranging from 5 to 50 kVA and rated frequency of 60 Hz. Three different core laminations have been analyzed, namely, M2, M3 and M4. To carry out the analysis presented in this study, 144 transformer designs were optimized: 72 designs where the objective function is to minimize bid price (usually the objective for transformers that are purchased by industrial and commercial users) and 72 designs where the objective function is to minimize TOC (usually the objective for transformers that are purchased by electric utilities). All 144 transformer designs were obtained considering a core assembling pressure of 20 psi (0.14 MPa), resulting in space factors of 96.8, 97.6 and 97.8% for M2, M3 and M4 laminations, respectively.

The sensitivity analysis includes the variation of parameters (real-life scenarios) such as: the no-load loss cost rate A(\$/W), the load loss cost rate B(\$/W), the magnetic material cost per unit of weight (\$/kg) for all the electrical steels, and the sales margin.

Results show that based on the bid price criterion all transformers included in the comparison (72 in Table 7) have lower bid price when designed with M3 lamination. If TOC is minimized, 79% of the analyzed transformers have a lower TOC when designed with M3 lamination and 21% when designed with M2 lamination (Table 9). The TOC results were obtained by parametrically varying the no-load loss cost rate and the load-loss cost rate in a wide range to cover the entire range of interest for Mexican utilities.

The importance of this research lies in the fact that the cost of cores in single-phase shell-type distribution transformers ranges from 27 to 38% of the total cost of materials. The choice of lamination thickness is a compromise between loss reduction and transformer cost. This paper gives general guidelines for any manufacturer to select the appropriate thickness for the core lamination in distribution transformers based on the minimization of either TOC or bid price.

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A Appendix

This section presents core loss dependency on three core design parameters, namely, number of laminations per step, air gap and overlap that are exclusive for the kind of wound-core distribution-transformers analyzed in this paper.

A.1 Number of laminations per step

The number of laminations per step (n_s) can vary between 5 and 20. A minimum of five laminations per step is recommended to minimize local saturation effects in the gap region. It is advisable to assemble as many laminations per step as possible—up to a maximum of 20—to reduce the local saturation in the air gap region. The maximum number of laminations per step for wound cores can be determined

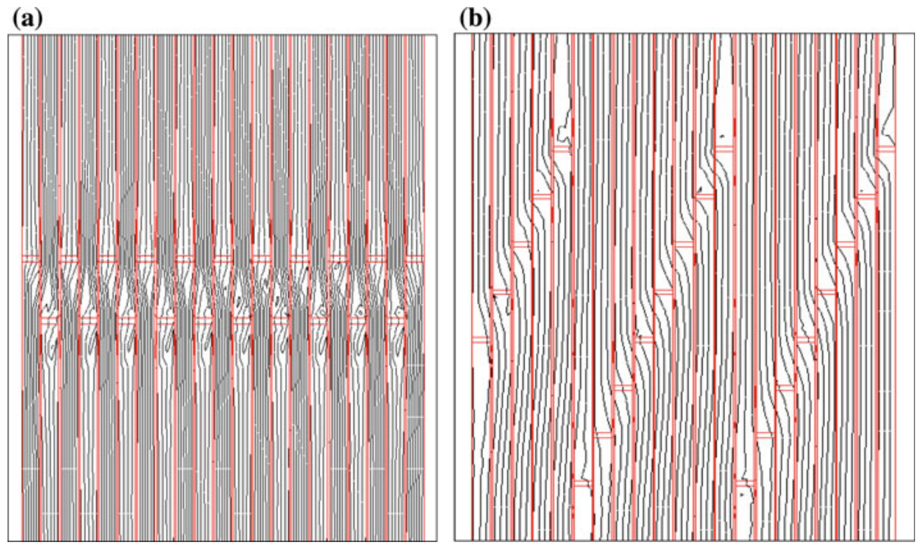

Fig. A.1 Magnetic flux trajectories for an air gap of 3 mm and overlap length of 1.0 cm, **a** two laminations per step; **b** eight laminations per step

by:

$$n_s^{\max} = \frac{G - 40}{L_0} \tag{A.1}$$

where G is the window length, and L_o is the overlap length.

Figure A.1 shows the influence of the number of laminations per step in the magnetic flux trajectories. When the number of laminations per step is small, the region close to the air gaps is saturated, and some of the magnetic flux passes through the air gaps and the core losses are increased. When the number of laminations per step is large, the percentage of the magnetic flux passing the gap is reduced and the core losses are reduced. The number of steps per core will vary depending on the following factors, (a) core radial thickness; (b) air gap length; (c) laminations per step; and (d) lamination thickness.

A.2 Air gap

The air gap g is the separation between laminations in the rolling direction. In practice this value is less than 3.0 mm. In [30] authors show that as the air gap of the core is increased, the excitation current is also increased. The same increase is observed in core losses by increasing the air–gap length.

A.3 Overlap

The overlap (L_o) is the length between the midpoints of the air gaps of two laminations contiguous to the rolling direction. This parameter typically ranges from 0.5 to 2.0 cm. An experiment examined a sample of 12 transformer cores of 37.5 kVA, in which 85% of the cores were manufactured with an overlap length of 1.0 cm and 15% of the cores were manufactured with an overlap length of 2.0 cm [11]. In this experiment, only one core was tested in each measurement. It was found that the samples with an overlap length of 2.0 cm had higher core losses [11]. This is most likely due to the increased area, where the flux is forced to pass perpendicularly to the laminations, as the core steel is anisotropic in nature.

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