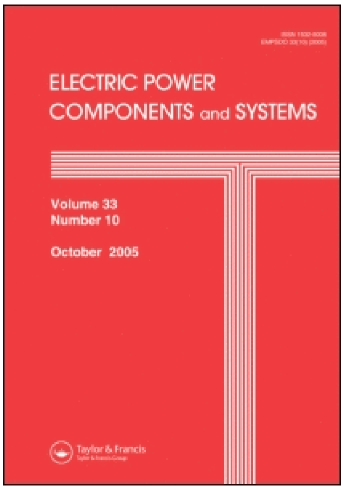

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A Review of Transformer Losses

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A Review of Transformer Losses

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Abstract *This article presents an extensive survey of current research on the transformer loss problem, particularly from the view of practical engineering applications. It reveals that the transformer loss problem remains an active research area. This article classified the transformer loss problem into three main groups: (a) tank losses due to high-current bushings, (b) losses in transformer core joints, and (c) stray losses in the transformer tank. It is based on over 50 published works, which are all systematically classified. The methods, the size of transformers, and other relevant aspects in the different works are discussed and presented.*

Keywords overheating, tank losses, transformer, core joints, stray losses, high-current

1. Introduction

There are several challenges when designing transformers: (a) to prevent transformers from too-high temperatures, (b) to provide sufficient insulation and to design the transformers so that they will withstand voltage conditions that are indicated on standards, (c) to manufacture transformers with low losses, (d) to produce transformer designs that can be manufactured, (e) to maximize transformer sales and to minimize transformer total owning cost, (f) to minimize transformer weight, (g) to minimize noise, etc. This article is devoted to design problem (c). This problem is critical because with the continuous increase in global electrical energy consumption, there is a necessity to improve the efficiency of transformers [1]. Low-efficiency transformers affect the environment, since they require more generation of power to supply greater losses. This causes more emissions of carbon dioxide, also contributing to the so-called greenhouse effect. Alternatively, energy-efficient transformers reduce generation requirements and air pollution.

The article contains a review of about 50 different studies, which have dealt with the transformer loss problem in different aspects from the point of view of calculation, measurement, and reduction. The main transformer losses can be classified as (a) tank losses due to high-current bushings, (b) losses in transformer core joints, and (c) stray losses in

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Table 1
Typical emissions reduction in metric tons over the 30-year life of the transformer

	Reduced generation only at coal-fired steam plants	Reduced generation only at distillate oil combustion turbine plants
CO_2	63,756,304.9	49,866,116
SO_x	1,275,126.1	54,918.63
NO_x	339,481.624	252,625.698

the transformer tank. This article investigates different aspects related with these studies such as (a) whether universities or industries do more research in transformer losses, (b) whether it is more common to see the application of loss reduction in distribution or power transformers, (c) the favorite method to study the transformer loss problem, (d) the continent that does the most research in transformer losses, (e) whether the experimental or numerical approach is more common in the study of transformer losses, and (f) whether 2D simulations are dominant over 3D simulations.

Small reductions in losses produce significant energy savings, since the number of transformers in power systems is high. For example, if a design change reduces no-load losses by 6.43 W, and if this loss reduction could be applied to the 50,000,000 transformers in the United States, then over the 30-year life of the transformer, we obtain: (50,000,000 transformers) $*$ (6.43 W) $*$ (8760 hr/year) $*$ (30 years) $=$ 84,490,200,000 kWh of energy savings. This energy savings represents the average electrical consumption of a typical Mexican transformer manufacturer, which manufactures 20,000 transformers per year from 5 kVA to 1500 kVA for 85,000 years. A reader interested in more details about this reduction of transformer losses can consult [2]. Previous research projects have used numerous ways to reduce transformer losses in the distribution transformer [2–11].

We apply the loss reduction of 6.43 W to the emissions reduction, where we can observe the significant amounts of pollution reductions; the results are shown in Table 1. This is a tangible benefit to the utility and its customers, and it should be considered when evaluating the merits of this improvement in transformer design.

The article is organized as follows. Section 2 describes works related to overheating in the high-current tank wall of transformers. Details on investigations of transformer core joints are described in Section 3. The stray losses in the transformer are presented in Section 4. Section 5 presents relevant aspects of the different works analyzed, followed by conclusions in Section 6.

2. Tank Losses Due to High-current Bushings

There are few studies related to a single current-carrying conductor in the presence of conducting permeable surfaces. The means of preventing local overheating in the windings and other elements of transformers have been studied, but the means to prevent overheating on the structure surrounding the distribution transformer bushings are very scarce.

In 1954, Poritsky and Jerrard [12] discussed the eddy-current losses in a semi-infinite solid slab subject to an alternating current by solving Maxwell's equations both in air space and in the conducting solid. In the case of transformer tanks, the steel plate thickness is greater than the depth of penetration at low frequencies such that it will act essentially like a semi-infinite solid slab. Saturation was neglected by assuming the permeability as constant. Maxwell's equations are solved by Fourier integral superposition.

Deuring [13] wrote a paper in 1957 about the problem of current-carrying conductors near conducting surfaces. At that time, the high-current connections could carry more than 6000 A RMS. The author presented empirical equations to calculate losses, finding that the induced tank losses in large power transformers vary with current to a power smaller than two when considering unshielded magnetic steel-plate materials. Deuring determined curves of watts per foot for unshielded, and also for shielded, plates. The results of this work are compared with Poritsky's calculations. No study about conductors at high-voltage levels was presented.

In 1981, Saito *et al.* [14] presented an experimental analysis of eddy currents in the structure that surrounds the large current bushings of transformers. They used a model with a conducting current of about 20 kA. The model consisted of three buses, a bushing pocket, a bushing base plate (made of stainless steel), a bus cover flange, bus covers, and isolated-phase bus enclosures. The magnetic density on the tank cover and bus cover flange was less than 0.001 T. Therefore, there was no possibility that leakage flux causes local overheating. The x components of eddy currents that appear along the edges of the bushing base plate are compared in Figure 1.

In 1988, Furman *et al.* [15] dealt with eddy-current losses and local heating in transformer tank parts by using high-current taps. The experiments of this work were

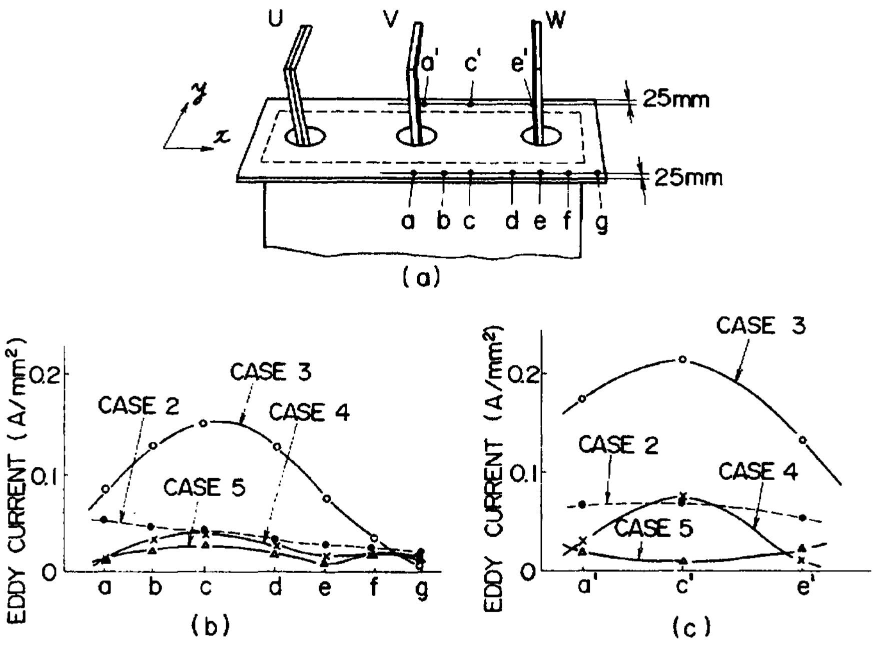

Figure 1. Variations in eddy-current distribution in the copper shields: (a) measuring positions, (b) measured x component at level 1, and (c) measured z component at level 2 (copyright © 1957 IEEE [13], reprinted with permission).

performed on a full-scale model, representing the tank cover of a 1000 MVA transformer. The authors presented several methods in order to reduce the transformer tank losses, some of them are (a) the increment of distance between the high-current conductor and the cover surface, (b) the connection of winding leads directly to the corresponding bushings to avoid sections parallel to the tank cover taps, (c) the close arrangement of different phase taps, (d) the use of non-magnetic conducting materials, (e) the splitting of a high-current conductor into parallel conductors, and (f) the choice of an optimal position of the tap and the hole in the tank cover.

In 1990, Renyuan *et al.* [16] presented an integral equation method to determine eddy-current losses produced by a heavy current in transformer leads. This method can be used to obtain the solution of the open region and boundary conditions that are taken into account inherently by this approach. The method is applied to calculate the sinusoidal eddy-current fields in three dimensions, assuming (a) constant conductivity, (b) isotropic magnetic materials, and (c) sinusoidal excitation current. Also presented was a parametric study of several factors, which include (a) tank materials, (b) distributions of low-voltage leads, (c) different current values, and (d) simulations with and without shields.

In another work, Renyuan *et al.* [17] applied the boundary element method in terms of the magnetic vector potential and the electric scalar potential finding the most serious overheating occurred among the low-voltage bushings. The maximum magnetic flux density considered was 22 mT. In this article, it is assumed that the exciting current varies sinusoidally with time.

In 1994, Junyou *et al.* [18] applied the boundary element method to the problem of overheating due to heavy current-carrying conductors in a 360-MVA, 500-kV transformer. The authors calculated the eddy-current loss density on the surface of the transformer cover. The total loss was 2.62 kW, and the maximum surface loss was 6.1 kW/m^2. It can be seen from these results that non-magnetic materials with an aluminum screen are favorable to prevent the overheating of the cover.

In 1997, Turowski and Pelikant [19] carried out a computer analysis based on Maxwell's equations and closed formulas of heavy current bushings passing through steel cover plates. The method of calculating eddy-current losses in steel walls was based on Poynting's theorem. The authors obtained a formula for the maximum permissible bushing current in the flat cover. Four cases were simulated: (a) a flat cover with a three-phase bushing without gaps between holes, (b) same as (a) but with non-magnetic metal inserts, (c) same as (a) but with metal turrets, and (d) same as (b) but with metal turrets. The formula for full cover losses obtained [19] is given by

$$A_p = m \cdot 5.5 \cdot 10^{-3} \cdot I \cdot A \cdot \left(1 + 0.0112 \frac{I}{D}\right), \tag{1}$$

where $m = 1$ or $\sqrt{3}$ for single- or three-phase transformers, respectively; D is the turret diameter, and A is turret distance. In Figure 2, the field distribution on surface of steel cover is shown.

In 1999, Kim *et al.* [20] presented an improved design of cover plates to reduce eddy-current losses due to heavy currents passing through the steel cover plates of a transformer. The authors applied the indirect boundary integral equation method to the problem of heavy currents in transformer leads and compared calculated and experimental results. The improved transformer cover plate consisted of two slits between the holes of the current leads. In this case, the eddy-current losses were reduced by 25% in comparison with the case when there are no slits on the cover (Figure 3).

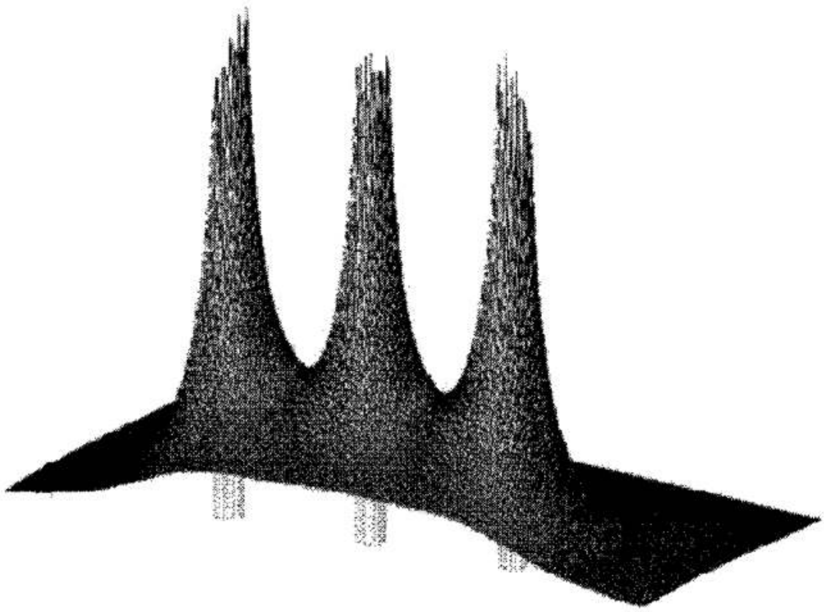

Figure 2. Magnetic field distribution on transformer steel cover (copyright © 1994 IEEE [18], reprinted with permission).

3. Transformer Core Joints

In 1973, Jones *et al.* [21] established that the efficiency of large power transformer cores depends on the type of corner joints used at the junction between the yokes and the limbs. The regions, where the flux deviates from the rolling direction, are the corners where the flux passes from the yoke to the limbs. Two cores of grain-oriented material were

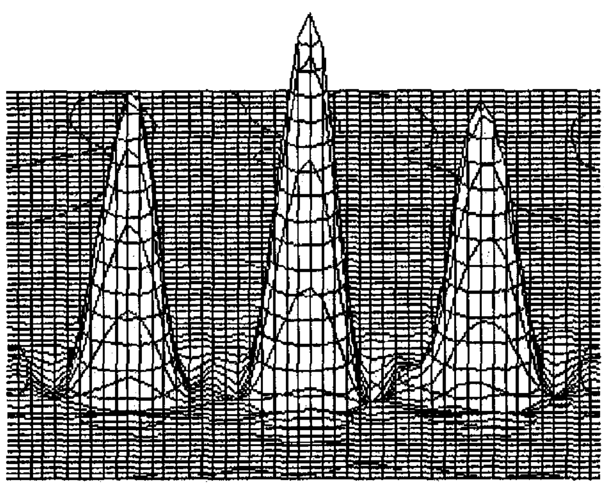

Figure 3. Power loss density distribution on the surface of cover plates for model where there are not slits (copyright © 1997 IEEE [19], reprinted with permission).

constructed with 45° mitered overlap joints. The overlap length in the core was varied and the effects on the power losses were determined. The authors showed the relationship between the losses and the air gap length. The conclusion was that losses increase linearly as the air gap length increases over the studied range. Minimum losses occur for overlaps between 0.4 and 0.6 cm. The core was built and dismantled several times to check the repeatability of the loss measurements at 1.5 T. Larger overlaps were used to add mechanical strength to the joints.

In 1982, Nakata *et al.* [22] analyzed the magnetic characteristics of cores with step-lap joints by using the finite element method. The authors obtained useful results and suggested that increasing the number of laminations per one group increases core losses. They also found that if the number of laminations per one group is small, the effect of gap length on magnetic characteristics is significant.

In 1992, Valkovic and Rezic [23] compared losses with conventional joints and with step-lap joints. It was found that a reduction of the total core losses by 2 to 4.4% was obtained with a step-lap joint. All core models were assembled with 120 laminations per stack and the core material was grain-oriented electrical steel.

In 1994, Löffler *et al.* [24] found that losses were increased due to air gaps; losses were not a simple function of the mean length but also of the local distribution of gaps. Much higher loss increases can be expected from regionally concentrated gaps.

In 1994, Pfützner *et al.* [25] found that the permeability μ_Z of the steel sheet is a key parameter for the inhomogeneity of magnetic density. Local inhomogeneities tend to affect the entire magnetic circuit. Air gaps in overlap regions may cause local magnetic densities in z of an order of 0.2 T.

In 1996, Pietruszka and Napieralska [26] presented a method that takes into account the overlapping areas in stacked transformer cores during magnetic field calculations. The method uses an equivalent homogenized reluctivity of the whole structure and the flux density in its layers. In the calculations of magnetic fields in the transformer core, the lamination is neglected, and the overlaps are neglected as well. In this work, the magnetic field distribution is obtained by solving a system of non-linear equations in finite element terms.

In 1998, Elleuch and Poloujadoff [27] presented a three-phase lumped circuit transformer model that takes into account the air gaps, saturation, core losses, and lamination anisotropy. The flux lines remain almost parallel to the rolling direction except in a small area around the joints. In order to take into account this anisotropy effect, transformer yokes and limbs are divided into longitudinal elements according to the rolling direction.

In 1998, Girgis *et al.* [28] presented experimental results about the effects of core quality, joint stacking, and clamping pressure on transformer core losses and excitation current. The effects were studied for different core material grades and for single- and three-phase cores. The authors showed that the number of steps per group and the number of laminations per step significantly affect the building factor. They showed that large core joint gaps dimensions increase the core losses and excitation current in non-step-lap three-phase cores.

In 2000, teNyenhuis *et al.* [29] presented core loss calculations and flux distributions for single- and five-limb three-phase core type units using a 2D finite difference method. The authors determined the flux density in various core types, the harmonic distortion for various core types, and the spatial flux distribution across core laminations. Finally, the authors compared measurements and computed results.

In 2000, Mechler and Girgis [30] presented a study to understand the role of joints in transformer losses. The authors used the finite element method for magnetic field calculations without considering the whole lamination package, which consisted of several hundred laminations due to periodical repetition of the sheet pattern. The joint gaps cause local disturbances of flux density. Without gaps, the flux density inside the sheets would be more uniform. The authors showed curves of flux distribution versus material grades and joint parameters.

4. Stray Losses in Transformer Tank

In 1954, Vogel and Adolphson [31] proposed a model to determine stray losses and heating of tanks for a core-type transformer. The authors obtained an analytical expression to determine losses in the magnetic material when the penetration depth is known. Eddy-current losses were found to vary directly with the square root of the resistivity for thick iron plates and to vary inversely with the resistivity for thin plates. An oval-shaped tank is considered in this article, and the losses in the tank wall versus the distance for the top of the high-voltage coils are determined.

In 1959, Agarwal [32] developed formulas for the calculation of eddy currents in solid and laminated iron. He very clearly explained what occurs when the depth of penetration is less than or greater than the half-thickness of the plate. The author used Maxwell's equations and assumed an ideal magnetization curve in order to obtain the losses per unit of area. Agarwal compared experimental and computed values of eddy-current losses for 1-, $\frac{1}{4}$-, $\frac{1}{8}$-, and $\frac{1}{16}$-inch laminations. Hysteresis losses were calculated for all test points and found to be less than 4–5% for the $\frac{1}{16}$-inch laminations at low values of frequency and magnetomotive force.

In 1966, Mullineux and Reed [33] presented a method to determine the eddy-current density and the tank flux for a transformer with any number of windings and distribution of turns. In the solution, it is assumed that the tank and core are of infinite permeability. The authors obtained a solution as a function of integrals and series.

In 1966, Berezovskii *et al.* [34] determined total stray losses from the tangential component of the magnetic field on the inside surface of the tank and from the surface resistance of the tank material. They found that any calculation of the electromagnetic field or the losses due to eddy currents in ferromagnetic bodies is complicated by the fact that the permeability of the material depends on the magnetic field itself. In this work, the authors calculated the surface losses in the ferromagnetic bodies using an equivalent permeability.

In 1972, Kozlowski and Turowski [35] presented principles for the selection of the type and thickness of tanks using analytical formulas. The authors presented an analytical formula to determine the power losses in unshielded tanks. They also assessed the maximum power above which tank losses grow so rapidly that shielding is indispensable. This limit ranges from 30 to 50 MVA depending on the desired reduction of tank losses. When shields are applied, unshielded tank losses should be multiplied by an analytical coefficient, which depends on the copper or aluminum conductivity, the steel parameters, and the shield thickness. The authors showed that minimum losses appear in a shielded arrangement with shield of thickness $d_{Cu} \geq 10$ mm and $d_{Al} \geq 12.4$ mm. When magnetic shunts are applied, unshielded tank losses should be multiplied by an empirical coefficient, which depends on the number of sheets that compose the thickness of the shunt.

In 1973, Allan *et al.* [36] presented formulas for the calculation of local losses due to eddy currents in aluminum tanks caused by nearby current-carrying leads or by the winding leakage flux. In this formulation, the sinusoidal current flows parallel to the core and the tank. The authors obtained formulas from Maxwell's equations for all the transformer regions (source region, tank region, and air region), applying an infinite cosine transform. From these equations, they calculated the losses (in watts/meter) caused by nearby current-carrying leads.

In 1973, Inui *et al.* [37] used a 1500-MVA transformer to examine the effects of the tank and tank shields on the magnetic fields in the windings by using a tank without shields, a tank with silicon steel sheet shields, and a tank with aluminum sheet steel shields. The authors calculated the magnetic flux density distribution in the windings using Biot-Savart's equation in two dimensions.

In 1976, Napoli and Paggi [38] sized the shield in a single-phase 100/3-MVA auto-transformer using the finite element method. The authors represented the maximum density of shielding as a function of the thickness, position, and distance from the windings and the radial and axial distribution of magnetic density for a biconcentric transformer.

In 1980, Valkovic [39] presented an analytical method for the calculation of stray losses in three-phase transformer tanks. The author assumed in this calculation that (a) the core had infinite permeability and it is of the three-legged type, (b) the thickness of the tank wall is several times greater than the penetration depth, (c) non-linearity and hysteresis were taken into account, and (d) all the electromagnetic quantities vary sinusoidally with time. Tank losses were calculated by means of Poynting's theorem. The tank losses were influenced by the winding geometry, *i.e.*, space arrangement of ampere turns if the high-voltage winding is shorter than low-voltage winding.

In 1984, Kazmierski *et al.* [40] evaluated methods for the reduction of heating. Local overheating of a tank wall caused by heavy current leads was presented, and various shielding methods were also discussed. The position of the magnetic shunts determines if the axial forces and additional losses on the edge of the windings are decreased or causes additional stray field concentration on the core and tank surface. The authors showed how temperature relates to (a) unshielded tank wall, (b) tank covered with a cooper sheet of 3 mm, (c) partial covering by a sheet, and (d) tank wall partially covered by two unsaturated magnetic shunts of transformer laminations, located under the leads.

In 1987, Szabados *et al.* [41] proposed an analytical method to predict eddy-current losses in large power transformer walls. The method required only the values of the incident flux density on the surface of the wall. This value may be obtained by flux solving programs or by experimental means. The article described how the incident flux may be analytically represented using a least mean error fit to a double Fourier series in order to produce the values of losses in the plate.

In 1988, Harrison and Richardson [42] described how transformer designers have reduced both load and no-load losses. The transformer designer, with the minimum effort, has substituted different types and grades of steel into the transformer cores, resulting in reduced no-load losses. The authors showed that load losses were reduced from 2300 kW to 1150 kW from 1964 to 1985 for a 600-MVA generator transformer. The authors described the main techniques to reduce stray losses; one of them involves rejection of the leakage flux, and the other involves the collection of the leakage flux. They simulated the leakage flux distribution with and without flux control.

In 1988, Komulainen and Nordman [43] reported results of stray losses in a three-phase transformer tank when it is unshielded. Application of shielding requires knowledge of stray loss distribution in a transformer tank. The tank is most important, as this houses a considerable proportion of the stray losses. The authors determined the unshielded tank losses from load losses between shielded and unshielded transformers. The authors concluded that core steel laminations offered a more economical tank shielding than aluminum in all the transformers.

In 1991, Namjoshi and Biringer [44] dealt with eddy-current shielding of steel structures, which surrounds power cables carrying large currents. Short-circuited copper rings, closely wound around the structure, were used as eddy-current shields. The authors made a parametric study by examining ring cross-section, number of rings, frequency, and permeability.

In 1992, Holland *et al.* [45] calculated the stray losses in a 90-MVA, three-phase, 132/33-kV transformer using a surface impedance method mixed with finite elements. This method allows the calculation of stray losses in large power transformers. The authors determined the stray losses in the tank with and without shunts. Aluminum components cannot be modeled using surface impedances since the skin depth is too thick. Hence, the procedure used to represent the whole transformer is to use a solid model, where solid components are considered with surface elements, deleting the solid elements inside.

In 1993, Pavlik *et al.* [46] calculated winding eddy-current losses, stray losses in the tank walls, in the core support frame, in the lockplates, and in the core laminations of core-type transformers using a finite element model. The authors presented a series of stray loss reduction studies, leading to changes of structural elements that affect the stray and eddy-current losses. They made three kinds of studies: topological changes, shielding, and sensitivity analyses. Three topological changes were studied out: (a) the addition of a wound pressure ring, (b) moving the frame axially away from the pressure ring, and (c) the changes in the positions of the end frame.

In 1993, Guérin *et al.* [47] dealt with the 3D electromagnetic modeling of eddy-current losses in transformer tanks. In this work, a single-phase, 390-kVA transformer was used. Mesh problems are found when the skin depth is small in relation to the dimensions of the solid conducting regions. This occurs when the permeability, the conductivity, or the frequency are high. The authors made several parametric analyses, changing the relative permeability of the tank, the tank thickness, and the relative permeability of the magnetic core. In every case, they determined the eddy-current losses (see Figure 4).

In 1993, O'Connor [48] determined the magnetic field of an 80-kVA transformer operating at no load, at full current load, and at different distances from the tank.

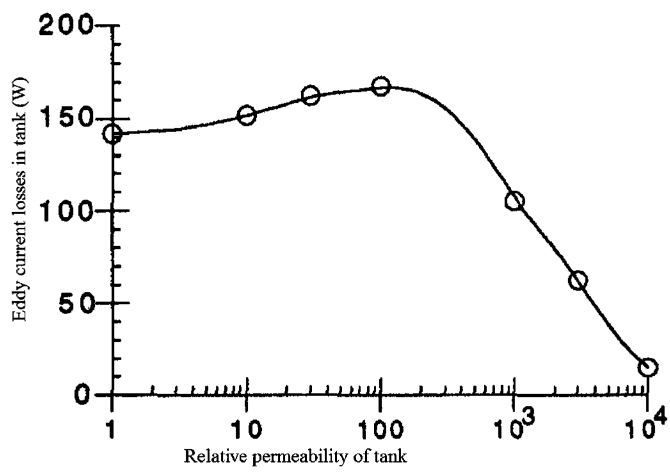

Figure 4. Eddy current losses versus tank permeability (copyright © 1993 IEEE [47], reprinted with permission).

The magnetic field varied from 3200–8.0 milligauss at a distance of 0 feet and 3 feet, respectively. It is assumed that pole-mounted transformers are far away from human life, but they are often used very near to buildings, similar to outside pad-mounted transformers. The author reduced the magnetic field from 120 milligauss to 60 milligauss on a group of 10-kVA transformers by placing a copper strap.

In 1994, Yongbin *et al.* [49] applied the T-Ω method to compute the eddy-current losses in a 360-MVA/500-kV transformer. The authors presented results using a tank wall with a magnetic shunt with an aluminum screen and without a shield (see Figure 5).

In 1999, Koppikar *et al.* [50] evaluated flitch plate losses in a 33-MVA, single-phase, 220/132/11-kV auto-transformer. The authors studied the effects of various factors on the losses in a mild steel flitch plate using a series of 2D finite element method simulations and a statistical technique. The authors determined the losses in mild and stainless-steel flitch plates. The authors modeled the laminated flitch plate (grade M4) using anisotropic material curves available in the MAGNET 2.3 software.

In 2000, Takahashi *et al.* [51] analyzed the tank model of a transformer. The "tank shield model" is a benchmark model for reducing the volume of the shielding plate and for constraining the eddy-current density in the tank within a specified value. The tank shield model is optimized using Rosenbrock's method and the finite element method. The shielding plate is made of grain-oriented silicon steel, where no eddy currents flow. The experimental design method (Taguchi's method) is used to determine the upper value of eddy-current density, which is suitable for the optimization method of the tank shield model and for determining the appropriate initial values.

In 2000, Kulkarni and Khaparde [52] presented a review paper about the estimation and control of stray losses in transformers. The authors presented the main eddy loss components: (a) winding eddy-current losses, (b) circulating current losses in windings, (c) flitch plate losses, (d) stray losses due to high currents, (e) frame losses, and (f) tank losses. The authors included a section related to magnetic and eddy-current shielding.

In 2007, Chen *et al.* [53] analyzed and compared the shielding effect of four materials: air, aluminum, steel, and an hypothetical material with zero conductivity and a high relative permeability of 10,000. The three-dimensional finite element method is

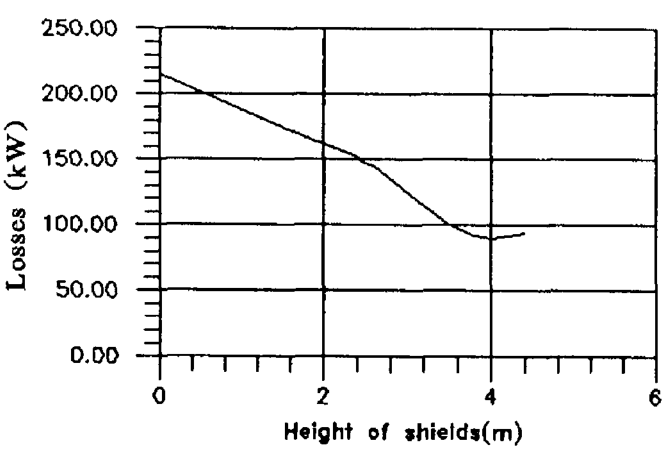

Figure 5. The height of magnetic shunts versus total stray losses in metallic parts (copyright © 1994 IEEE [49], reprinted with permission).

adopted to calculate the leakage field outside the transformer tank. The steel achieves the best performance among the three materials, which means that the shielding effect of the material with both high conductivity and high permeability is better than the one only with high conductivity and the one only with high permeability. This is an important conclusion for the power frequency magnetic shielding. The transformer enclosed by such material tanks can maintain the leakage magnetic field in a very small magnitude (see Figures 6 and 7).

5. Relevant Aspects of the Different Papers

The pie chart in Figure 8 shows the methods used to study transformer losses, and we see that more than half of the methods come from analytical research. The experimental methods make up the smallest amount of the total, and 7% of the research use both methods.

The pie chart in Figure 9 shows the type of transformer used to study transformer losses. We see that 17% of the total corresponds to distribution transformers and 52% to large power transformers.

Table 2 shows how the different types of transformers contribute to the annual transformer energy losses on a 5000-MW utility system [54]. The previous figures of losses are high in distribution transformers, and they are a consequence of the number of installed transformers. (It is estimated that there are 50 million distribution transformers in use within the United States [54].) For this reason, more research needs to be done in distribution transformers to reduce transformer losses due to the greater potential for loss savings in them.

The same percentage of studies has been carried out in 2D and 3D studies of transformer losses, as is shown in Figure 10. We see that 16% of the total corresponds to studies in which both dimensions are used. In Figure 11, it is shown that more papers that

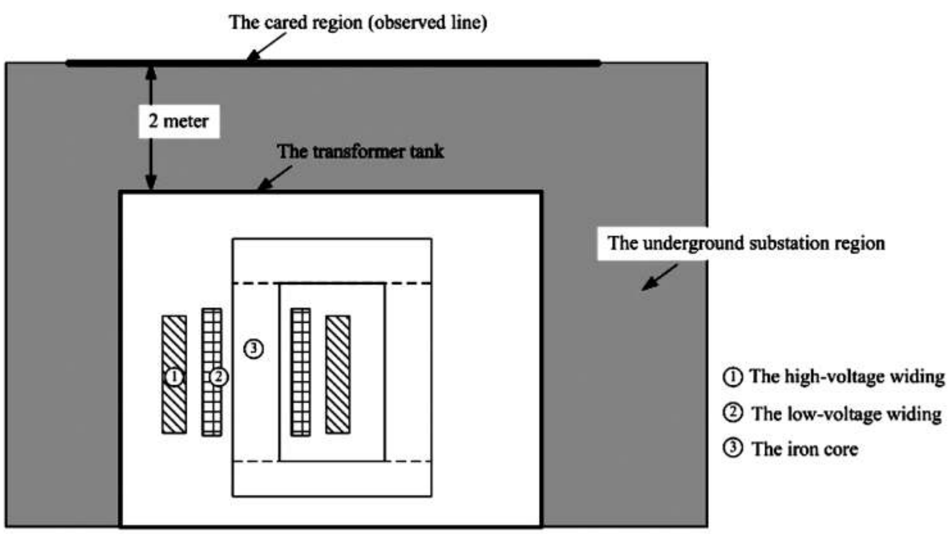

Figure 6. The schematic diagram of the 2000-kVA transformer under test (copyright © 2007 PIERS Online [53], reproduced courtesy of The Electromagnetics Academy/PIERS and reprinted with permission).

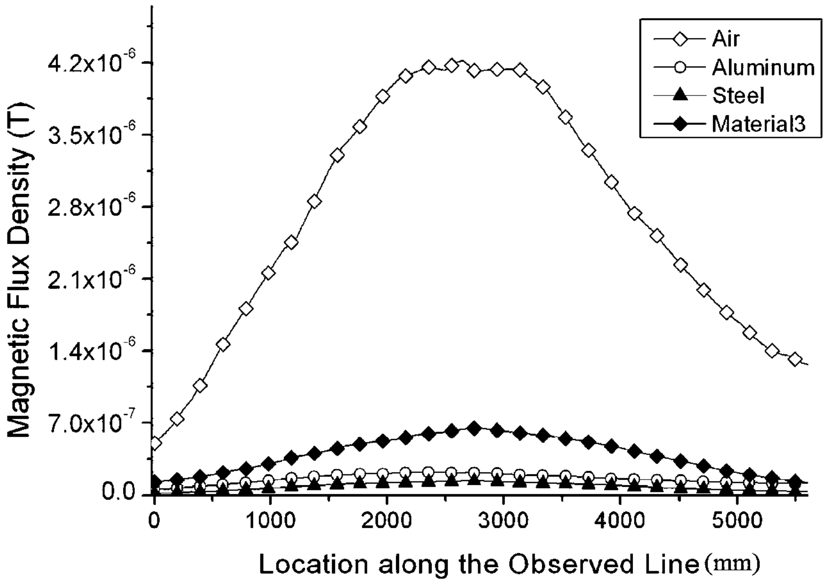

Figure 7. Leakage magnetic flux density along the observed line (copyright © 2007 PIERS Online [53], reproduced courtesy of The Electromagnetics Academy/PIERS and reprinted with permission).

study transformer losses come from Asia. The lower percentage corresponds to Europe with 28%, while America is between Asia and Europe. These results are congruent with Table 3. It is shown that industry has less interest in the publication of research in this area, as shown in Figure 12. The authors recommend the reading of [55] to encourage companies in the writing process of studies on this topic.

6. Conclusions

An extensive review of transformer losses has been presented based on a number of selected references (about 50 assorted works). In today's competitive environment, reduction of transformer losses will give a competitive advantage. This article has classified

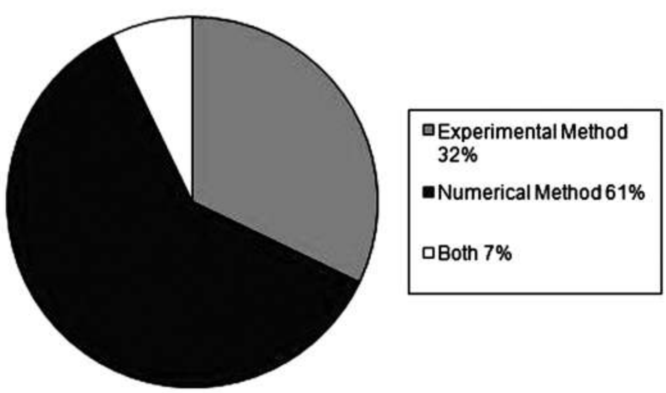

Figure 8. Methods used to study transformer losses.

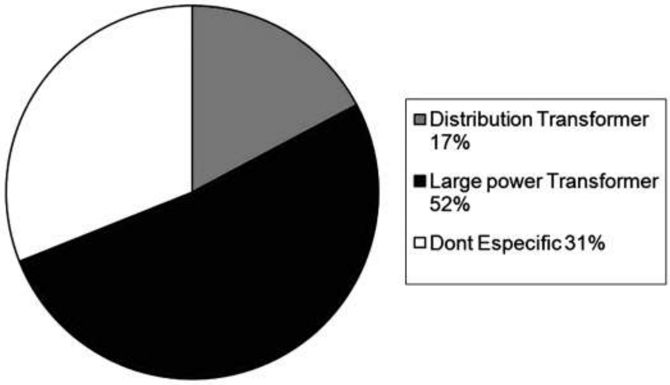

Figure 9. Types of transformers used to study transformer losses.

Table 2
Transformer losses on a typical utility system

Transformer type	Millions of kWh No-load losses	Millions of kWh Load losses
Generator step up	18	89
Bulk power sub-station	67	138
Distribution sub-station	97	114
Distribution	328	127
Total	510	468

Source: Electric Power Research Institute (EPRI).

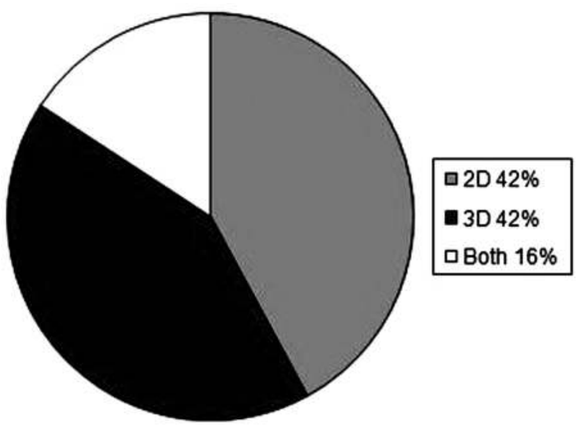

Figure 10. 2D and 3D studies used to study transformer losses.

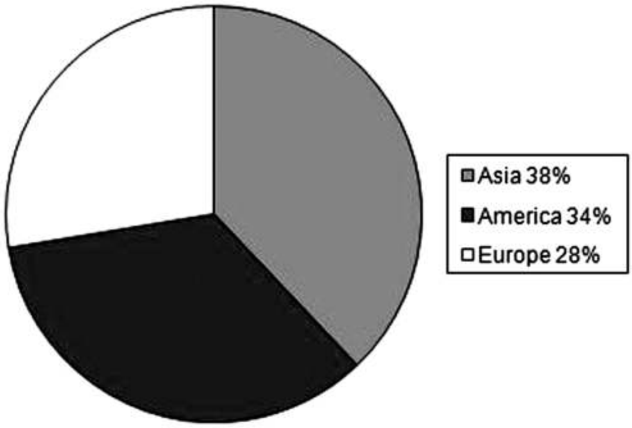

Figure 11. Continents that presented research to study transformer losses.

Table 3
Distribution of exenditure on R&D
as percent of GDP per continent

Continent	Expenditure on R&D as % of GDP
Africa	0.25
America	2.89
Europe	2.21
Asia	12.05

Source: UNESCO Statistical Book, 1994.

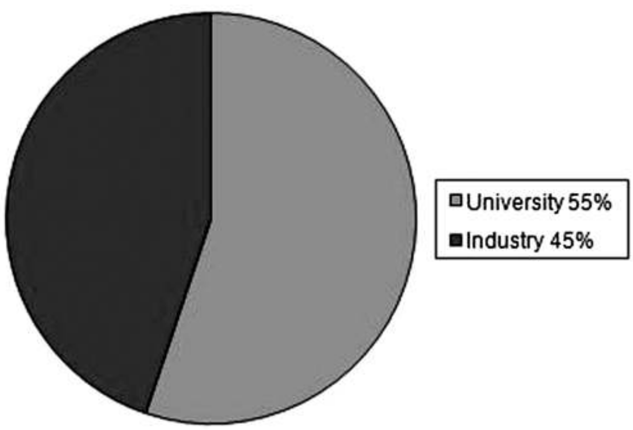

Figure 12. Presence of universities and industries in publishing literature to study transformer losses.

the problem of transformer losses into three groups: (a) tank losses due to high-current bushings, (b) losses in transformer core joints, and (c) stray losses in the transformer tank. A survey of literature reveals some interesting aspects about the research in transformer losses carried out since the 1950s, including methods preferred by researchers, type of transformers used for research, frequency of 2D or 3D approaches used for research, continents that do more research, and the presence of universities and industries in research on this topic. A survey of current literature reveals that transformer losses remain an active research area. Although some studies on loss transformer reduction have been carried out on different types of transformers by various researchers, there are more ways of reducing transformer losses, and considerable work for experiments and theoretical modeling needs to be developed and improved, such as the following: (1) improvement of no-load and load-loss measuring techniques, (2) use of new materials for transformers to reduce transformer losses, and (3) the development of new modeling of stray losses.

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