Transformer Design and Optimization: A Literature Survey

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***Abstract*—With the fast-paced changing technologies in the power industry, new references addressing new technologies are coming to the market. Based on this fact, there is an urgent need to keep track of international experiences and activities taking place in the field of modern transformer design. The complexity of transformer design demands reliable and rigorous solution methods. A survey of current research reveals the continued interest in application of advanced techniques for transformer design optimization. This paper conducts a literature survey and reveals general backgrounds of research and developments in the field of transformer design and optimization for the past 35 years, based on more than 420 published articles, 50 transformer books, and 65 standards.**

***Index Terms*—Analytical methods, artificial intelligence, equivalent circuits, experimental methods, hybrid methods, numerical techniques, standards, survey, transformer books, transformer design, transformer design optimization, transformer modeling, transformers.**

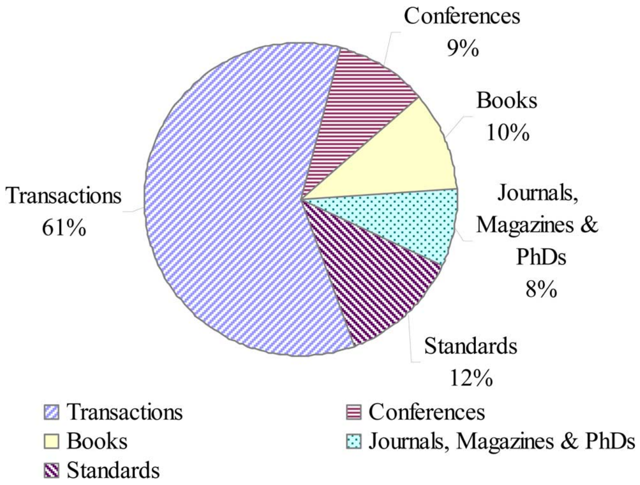

Fig. 1. Sources of the literature survey.

I. INTRODUCTION

IN the last years, research in the area of transformer design experienced an expansion. Many papers, standards, books, and reports about new models have been published in the technical literature due mostly to the improvement of the computer power availability, new innovative optimization algorithms, and the greater uncertainty level introduced by the power sector deregulation.

Transformer design is a complex task in which engineers have to ensure that compatibility with the imposed specifications is met, while keeping manufacturing costs low. Moreover, the design methodology may vary significantly according to the transformer type (distribution, power or instrument transformer) and its operating frequency (ranging between 50/60 Hz and a few megahertz), while many alterations according to the core constructional characteristics, the cooling method, or the type of the magnetic material may be encountered [1], [2]. This paper provides an overview of research, development, and the application of various computational methods for transformer design, based on an extensive number of published papers [3]. The referred publications are mainly extracted from IEEE TRANSACTIONS, IEEE Magazines, IEEE Proceedings, IEE/IET (Institution of Electrical Engineers, currently Institution of Engineering and Technology) Proceedings as well as a few, yet very important conferences in an effort to cover the majority of published papers in the transformer design field (Figs. 1 and 2). However, due to the amplitude of this field, such a survey, no matter how comprehensive, cannot be exhaustive. The review is divided into six major sections: 1) Research efforts focusing on the prediction and/or optimization of specific transformer characteristics; 2) techniques adopted for global transformer design optimization, taking into account all of the relevant performance parameters; (3) transformer post-design performance and modeling; 4) standards governing the transformer qualification; 5) recent trends on transformer technology; and 6) transformer books giving to the reader a convenient starting point concerning important aspects of transformer engineering. The references are grouped and presented according to their methodological approach, however, no comparative analysis or specific details of the methodologies are provided in order to keep the survey as compact and comprehensive as possible. The research focuses mainly on power and distribution transformers and other types of transformers operating at low frequencies, and is not expanded to transformers for high frequency applications, apart from several cases of design models and methodologies applicable to this range of frequencies.

The present bibliographical survey will be particularly useful for: 1) transformer designers and researchers engaged in transformer design, optimization, and quality-enhancement activities

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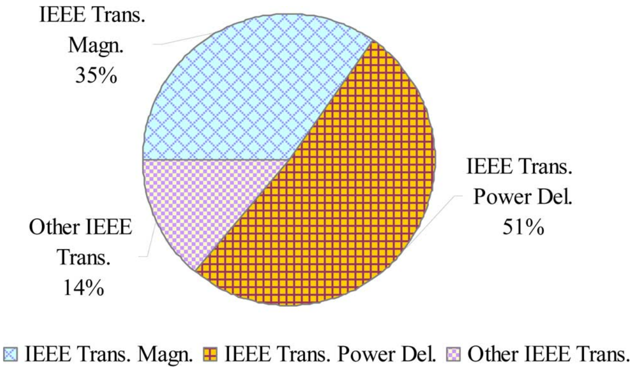

Fig. 2. Percentage participation of different IEEE Transaction Journals in the overall amount of IEEE Transaction Journals of the survey.

in today's competitive environment; 2) utility engineers who would like to enrich their educational background about the system interaction aspects of transformers in a power system; and 3) undergraduate and postgraduate students who wish to integrate traditional transformer theory with modern computing practices.

The paper is organized as follows: Section II describes the various transformer types that are present in the relevant bibliography as well as the main considerations during the transformer design process. Section III includes the survey overview of research dedicated to transformer characteristics, while Section IV provides an overview of the research conducted on transformer design optimization. Section V lists publications dedicated to modeling transformers for power system studies. Section VI provides a comprehensive overview of transformer standards that are issued by international organizations. Section VII addresses new considerations in transformer design, under the light of recent developments in the electric power industry as well as the technologies involved in transformer construction, providing an up-to-date review of modern trends in transformer design. Section VIII presents a brief description of transformer books. Finally, Section IX concludes this paper.

II. TRANSFORMER DESIGN

A transformer has been defined by ANSI/IEEE [4] as a static electric device consisting of a winding, or two or more coupled windings, with or without a magnetic core, for introducing mutual coupling between electric circuits. Transformers are extensively used in electric power systems to transfer power by electromagnetic induction between circuits at the same frequency, usually with changed values of voltage and current. Transformers are one of the primary components for the transmission and distribution of electrical energy. Their design results mainly from the range of application, the construction, the rated power and the voltage level.

A. Transformer Types

Different kinds of transformer types may be encountered, according to their use, their cooling method or the construction of their magnetic circuit. A major classification is realized according to the power and voltage ratings: transformers with a rated power up to 2.5 MVA and a voltage up to 36 kV are referred to as distribution transformers, while all transformers of higher ratings are classified as power transformers.

In particular, a power transformer has been defined by ANSI/IEEE [4] as a transformer that transfers electric energy in any part of the circuit between the generator and the distribution primary circuits. Power transformers may be further classified according to their scope of application, as described in the following. Transformers that are directly connected to the generator of a power station are called generator transformers. Their power range goes up to far above 1000 MVA and their voltage range extends to approximately 1500 kV. The connection between the different high-voltage system levels is made via network transformers (network interconnecting transformers), which are mainly autotransformers (i.e., transformers where the primary and secondary winding of each phase have a common section). Their power range exceeds 1000 MVA and their voltage range exceeds 1500 kV.

On the other hand-side, distribution transformers are used in the distribution networks in order to transmit energy from the medium voltage network to the low voltage network of the consumers. In particular, a distribution transformer has been defined by ANSI/IEEE [4] as a transformer for transferring electrical energy from a primary distribution circuit to a secondary distribution circuit or consumer's service circuit. In addition, there are various special purpose transformers such as converter transformers, test transformers, instrument transformers or telecommunications transformers, which can be both in the range of power transformers and in the range of distribution transformers as far as rated power and rated voltage are concerned.

As far as the cooling method is concerned, transformers may be designed either as liquid-immersed or dry type transformers. In liquid-immersed transformers, the insulating medium is mineral oil or synthetic insulating liquid while in dry type transformers, the cooling is implemented with natural air circulation. The identification of liquid-immersed transformers according to the cooling method is expressed by a four-letter code (Fig. 3) (IEEE C57.12.00 and IEC 60076-2 standards). The first letter expresses the internal cooling medium in contact with the windings (Letter **O** designates the mineral oil or synthetic insulating liquid with fire point below 300 °C, letter **K** designates the insulating liquid with fire point above 300 °C, and letter **L** designates the insulating liquid with no measurable fire point). The second letter identifies the circulation mechanism for internal cooling medium (Letter **N** designates the natural convection flow through cooling equipment and in windings, letter **F** designates the forced circulation through cooling equipment (i.e., coolant pumps) and natural convection flow in windings (also called nondirected flow), and letter **D** designates the forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings). The third letter expresses the external cooling medium (Letter **A** designates the air and letter **W** designates the water). The fourth letter identifies the circulation mechanism for external cooling medium (Letter **N** designates the natural convection and letter **F** designates the forced circulation [fans (air cooling) or pumps (water cooling)]). For example, if the internal cooling medium is mineral oil, which is circulated with natural flow, and the external

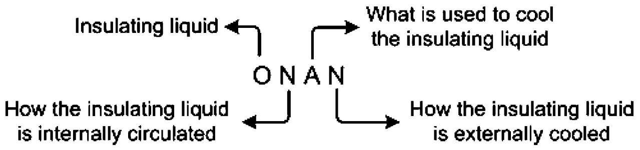

Fig. 3. Transformer cooling designations.

cooling medium is air, which is circulated with natural convection, then this cooling method is coded as ONAN (Oil Natural Air Natural). In power transformers, various cooling methods are used including oil circulation by pumps, or forced air circulation by fans, or both of the above. As a result, a number of different cooling methods exist: oil natural air forced (ONAF), oil forced air natural (OFAN), oil forced air forced (OFAF), oil forced water forced (OFWF). Combinations such as ONAN/ONAF, ONAN/OFAN, or ONAN/OFAF are also applicable [5].

Transformer magnetic circuit is constructed in either a shell or a core structure. They are distinguished from each other by the manner in which the primary and secondary coils are placed around the laminated steel core. The shell-type transformer is one where the windings are completely surrounded by transformer steel in the plane of the coil. In core type, the windings surround the laminated iron core. There are two different technologies for stacking the sheets of the magnetic material of the core, providing a further distinction to a) stack-core transformers, where the layers of the sheets of the magnetic material are placed one over the other and the vertical and the horizontal layers are over lapped, and b) wound-core transformers, where the magnetic circuit is of shell type and the sheets are wound. Multi-winding transformers, as well as poly-phase transformers, can be made in either shell or core type designs, with a magnetic circuit that consists of five (in shell-type transformers) or three legs (in core-type transformers), respectively.

B. Transformer Survey Structure

Transformer design must take into account numerous performance parameters and technical constraints. The research in the relevant literature may deal with each one of these parameters separately, or concern the overall transformer optimization. Fig. 4 presents the main categories of the literature survey, which define the structure of the survey overview presented in the next Sections.

III. RESEARCH DEDICATED TO SPECIFIC TRANSFORMER CHARACTERISTICS

The numerous computational methods and engineering models proposed for transformer analysis and the accurate prediction of their characteristics can be roughly categorized into six main groups: 1) numerical techniques (NT) that consist of some of the most widely used tools for transformer simulation. Among the proposed techniques of this group, the finite-element method (FEM) is the most prevalent one; 2) improved versions of the transformer equivalent circuit (EC), in order to include semiempirical descriptions of the core and winding characteristics that affect the accuracy of calculations. The use of the EC is still common in the manufacturing industry, due to its simplicity and its ability to provide reliable results, especially in cases of standardized geometries; 3) analytical methods (AM), employing analytical formulas for the representation of the transformer electromagnetic field as well as other operational characteristics (such as the current distribution), providing alternative modeling with less computational complexity compared to numerical methods; 4) stochastic methods, including artificial-intelligence (AI) techniques, such as genetic algorithms (GAs), which have seen increased usage in the transformer design area over the last few years; 5) experimental methods (EM), combining data provided by measurements with analytical or other methods, in order to provide efficient models for the accurate representation of certain transformer characteristics; 6) hybrid methods (HM) (i.e., combinations of one or more of the methods listed before).

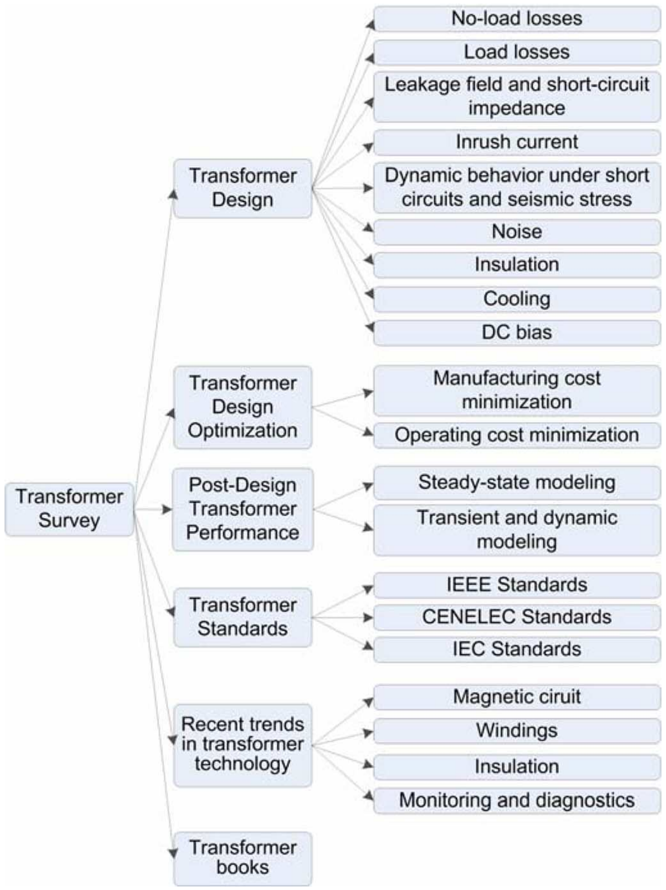

Fig. 4. Transformer survey structure.

Table I illustrates an overview of the references presented in Sections III-A–III-I, sorted by the subject and methodological approach (based on the six categories defined before). Further details on each reference or group of references are included in the following paragraphs, providing the necessary background for their classification. Since several papers were not entirely dedicated to a single transformer characteristic or methodological approach, their classification was based on the main axes of the proposed methodology or the basic aspects of the addressed research problems. The observation of Table I not only facilitates researchers in the field to categorize previous works but

TABLE I
CLASSIFICATION OF REFERENCES PRESENTED IN SECTION III BY SUBJECT AND METHODOLOGICAL APPROACH

	NT	EC	AM
No-load losses	[7]-[38], [44], [45]	[47], [56]-[62]	[40], [43]
Load losses	[83]-[101]		[80]-[82]
Leakage field	[107]-[123]	[124], [125]	[126]- [129]
Inrush current	[134], [136]	[133], [135], [137]-[146], [148]-[151], [154]	[152], [153]
Dynamic behavior	[155]-[158], [160], [161], [167], [168]		[163]-[166]
Noise	[180], [188]	[185]-[187]	[181], [184]
Insulation	[189]-[191]	[192]-[197]	
Cooling	[215]-[218], [223]	[241]-[244], [247]-[254]	[229]-[240]
DC bias	[271]-[275]	[276]-[280]	

	AI	EM	HM
No-load losses	[48]-[54]	[39], [41], [42], [46], [63]-[79]	[55]
Load losses		[102]-[104]	
Leakage field	[130]	[105], [106], [131], [132]	
Inrush current	[147]		
Dynamic behavior		[169]	[159], [162]
Noise		[170]-[179], [182], [183]	
Insulation		[199]-[214]	[198]
Cooling	[260]-[264]	[265]-[269]	[219]-[222], [224]-[228], [245], [246], [255]-[259]
DC bias		[270], [281]-[283]	

also reveals fields that have not yet been covered, proposing further research areas.

A. No-Load Losses

No-load losses are the continuous losses of a transformer, regardless of load, namely, they exist whenever the unit is energized [6]. No-load losses are also called iron or core losses because they are mainly a function of the core materials. The two main components of no-load losses are eddy currents and hysteresis. Hysteresis describes the memory of a magnetic material. More force is necessary to demagnetize magnetic material than it takes to magnetize it; the magnetic domains in the material resist realignment. Eddy current losses are small circulating currents in the core material. The steel core is a conductor that carries an alternating magnetic field, which induces circulating currents in the core. These currents through the resistive conductor generate heat and losses. Cores are typically made from cold-rolled, grain-oriented silicon steel laminations. A third component of core loss is also present, that cannot be directly attributed to eddy current or hysteresis phenomena, and is often called stray, extra or anomalous loss.

FEM has been extensively employed in the no-load losses prediction problem. The application of two-dimensional (2-D) FEM in the calculation of transformer core losses is realized in [7] and [8], where tools for the calculation of stray and eddy losses are developed, while in [9]–[11], hysteresis models are developed. Detailed modeling of the core magnetic properties based on measurements is presented in [12]–[16], while in [17], eddy current loss in transformers operated by pulsewidth-modulated inverters is presented. Magnetic anisotropy models for use in 2-D numerical analysis are developed in [18]–[20]. Igarashi *et al.* propose a 2-D FEM method which reduces the number of unknowns in the finite-element analysis of steel laminations in [21]. A numerical method for the calculation of the power losses of nonlinear laminated ferromagnetic cores is developed in [22], performing a two-step analysis (the first step considers the anisotropic conductivity of the material, while the second one introduces its inhomogeneous permeability) and employs FEM models as a tool for the correction and refinement of results provided by the first step. Anisotropic magnetic material properties in conjunction with 2-D FEM are used for the analysis of transformer magnetic material properties frequency dependence [23]. 2-D FEM modeling combined with 2-D and 3-D calculations is carried out in [24] in order to derive a dedicated model of dynamic hysteresis and extra losses in transformer soft magnetic materials. Excessive core losses and temperature rises due to the half-turn effect (the phenomenon where the winding leads are taken out from the different sides of the core leading to an additional half-turn in one of the core windows in a single-phase transformer) are studied through 2-D FEM in [25]. Virtual air gaps created in a transformer core by a change in core permeability in the vicinity of auxiliary windings carrying direct current (dc) are also investigated by 2-D FEM in [26]. In order to achieve more detailed analysis and computation of the transformer magnetic field, the 3-D analysis becomes necessary, as proposed in [27]–[31]. Moreover, Koppikar *et al.* [32] describe details of statistical analysis used in conjunction with 2-D FEM for quantifying the effect of various factors affecting flitch plate loss along with the results of 3-D FEM simulations carried on slotted and laminated flitch plates. To reduce the computational complexity of 3-D FEM, a practical modeling method of core lamination modeling is investigated in [33]. Nakata *et al.* investigate the influence of transformer core step lap joints on its loss in [34]. Furthermore, a rigorous analytical study using the finite difference method for magnetic-field calculation is performed by several authors in the literature in order to understand the role of joints in determining the performance of cores of power and distribution transformers [35] and to accurately calculate the 3-D spatial distribution, components, and total core losses in power transformer stacked cores [36], [37]. A dynamic core loss model to estimate core loss in soft ferromagnetic and power ferrite materials with arbitrary flux waveforms, for application in 2-D and 3-D transient finite-element analysis is proposed in [38].

In addition, various studies [39]–[46] explore the local flux distribution in transformer cores as a function of joint design and its relevance for power loss and noise. It is worth noting that although transformer joint air gaps have been well studied using FEM, they are seldom taken into account in circuit models [47].

The application of AI in loss evaluation is addressed in [48] and [49], where the no-load losses as a function of core design parameters are predicted by means of artificial neural networks (ANNs). Georgilakis *et al.* [50], [51] also used ANNs to reduce the iron losses of assembled transformers while optimizing the production process of individual cores using Taguchi methods. In addition, a combination of three AI methods is presented in [52] and [53], namely, ANNs, decision trees (DTs), and GAs, in order to minimize iron losses during manufacturing of wound-core distribution transformers. In [54], the differential evolution method is applied to determine the magnetically nonlinear characteristics of transformers. Hybrid methods, combining AI techniques with numerical methods, have been employed for the calculation and minimization of core losses, as in [55], where a 3-D permeability tensor FEM is combined with simulated annealing in order to define appropriate design variables of wound cores constructed by a combination of standard and high magnetization grade steel.

Accurate calculation of losses is also provided by the development of improved equivalent circuits, as proposed in [56], where a circuit that is able to predict losses under different operating conditions is presented. Moreover, a final EC of sufficient accuracy, combining hysteresis and eddy current losses contributions, is proposed in [57]. In addition, Adly [58] presented an analytical investigation of the various transformer losses resulting from semirotating flux excitation. The main feature of this analysis is that core magnetic properties are accurately represented and simulated using recently developed vector Preisach-type models of hysteresis. Reference [59] introduces an accurate Preisach-type model of the hysteretic inductor to represent a single-phase transformer for the investigation of the ferroresonance phenomenon, while [60] introduces an accurate transformer core model, using the Preisach theory, to represent the core magnetization characteristic in order to simulate ferroresonance in voltage transformers. An improved magnetic anisotropy model, by use of tensor reluctivity, to accurately express the phase difference between the magnetic flux density and the magnetic-field intensity is developed in [61]. Guerra and Mota present a nonlinear electric circuit to describe the behavior of magnetic cores in low-frequency applications in [62].

Experimental methods, combining data provided by measurements with analytical or other methods, in order to provide efficient models for the accurate representation of hysteresis and power losses in the laminations of power transformers, are proposed in [63] and [64], based on data supplied from the steel manufacturer. Moses [65] reported results in which localized flux density and losses have been measured experimentally in model cores and compared with data obtained from an FEM analysis of the same core geometry. In addition, Girgis *et al.* [66] carried out an analytical study in an attempt to determine the magnitude of the effects of a number of core production attributes. Albach *et al.* [67] present a practical method for predicting the core losses in magnetic components for an arbitrary shape of the magnetizing current. Furthermore, Dolinar [68] determined a magnetically nonlinear iron core model of a three-phase three-limb transformer and compared it with the classical saturated iron core model [69]. In [70], an experimental investigation of the factors that influence the harmonic content of magnetizing current (namely the flux density, the degree of saturation and the core stacking technique) is performed.

Many researchers have studied rotational iron losses over the years and a number of techniques for making measurements have been described in the literature. Stranges and Findlay [71] described an apparatus capable of determining iron losses due to rotational flux. In addition, Findlay *et al.* [72] and Davies and Moses [73] have carried out experiments on various samples in order to test the hypothesis that different stacking patterns of grain oriented silicon steel laminations, cut at small angles to the rolling direction, can reduce the iron core losses in power transformers. Fiorillo *et al.* have experimentally investigated the magnetic variables of grain oriented alloys, in order to derive models of magnetization curve, hysteresis loops, and losses in any direction [74]. In addition, Marketos and Meydan [75] introduced a novel method of fabricating consolidated stacks of electrical steel into single-phase transformer cores, which can considerably speed up the time required to build the cores by attempting to further reduce the amount of flux that deviates from the rolling direction at the corners of transformer cores. Experimental study of harmonic flux effects in transformer ferromagnetic materials is realized in [76], while a method for predicting the core losses under the sinusoidal conditions with an adequate accuracy from the test results obtained with the real nonsinusoidal voltage waveform is proposed in [77]. Anisotropic behavior of transformer core loss material is experimentally studied and interpreted in [78]. Finally, the silicon steel complex permeability at high frequencies is experimentally determined in [79].

B. Load Losses

Load losses result from load currents flowing through the transformer [6]. Load losses are also called copper or wire or winding losses. The two components of the load losses are the Joule losses (deriving from the product I^2R, where symbol I stands for the winding current and symbol R represents the winding resistance) and the stray losses. I^2R losses are based on the measured dc resistance, the bulk of which is due to the winding conductors, and the current at a given load. The stray losses are a term given to the accumulation of the additional losses experienced by the transformer, which includes winding eddy losses and losses due to the effects of leakage flux entering internal metallic structures. Auxiliary losses refer to the power required to run auxiliary cooling equipment, such as fans and pumps, and are not typically included in the total losses.

A review of about 50 papers were conducted by Kulkarni and Khaparde [80], which have dealt with one or more components of stray loss from the point of view of estimation and reduction. In this case, stray losses include eddy and circulating current loss in windings, losses in flitch plate, core edge loss, loss due to high current field, and frame and tank losses.

Moreover, a short methodological survey is carried out by Krawczyk and Turowski [81], showing the need of eddy current analysis in electric devices. Robert provides a theoretical discussion about the layer copper factor used in winding loss calculation in [82], focusing on a review of the relevant technical literature.

The FEM analysis is quite commonly used for the eddy loss calculations [83], [84]. Pern and Yeh [85] are engaged in the formulation of a finite-element method based on vector magnetic potential formulation to simulate the electromagnetic field and current distribution in the windings of power transformers with non-negligible circulating current. In addition, the foil-winding eddy loss is estimated by Ram [86], and his model is afterwards exploited for the study of the variation of transformer sheet winding eddy current loss with frequency [87]. Furthermore, the eddy current field due to both windings and heavy current leads in large power transformers is analyzed in [88] by using an improved FEM method based on scalar magnetic potential formulation. This formulation is also employed in [89] for the calculation of three-dimensional distributions of eddy-current densities and loss densities in metals near heavy current leads in a large transformer. On the other hand, vector magnetic potential is used to determine the magnetic field distribution in transformer windings considering inhomogeneous current distribution in [90] and time-periodic nonlinear magnetic fields with eddy currents in [91]. A numerical analysis of losses generated in the tank-wall surrounding the high-current bushings of pad-mounted transformers using a 3-D FEM is conducted in [92]. A special type of finite element is developed in [93] for the calculation of eddy current losses in transformer tank shields. 3-D eddy current calculation is also conducted by means of integral equation method in [94], which, as opposed to 3-D FEM, provides less computational complexity. Analytical representations of the electromagnetic field are also used for the prediction of eddy current losses in transformer tank covers in [95], an investigation that is expanded in [96] by 1) an analytical formulation; 2) a three-dimensional finite-element method; 3) from measured values of the initial temperature rise; and 4) from measured values of the steady-state temperature rise. Eddy losses due to high current leads in transformers are calculated by analytical methods as well as 2-D and 3-D FEM in [97]. In [98], an accurate 3-D formulation to study the boundary eddy current field arising from the heavy winding and terminal lead currents in a compact power transformer is developed. The 3-D reluctance network method is also proposed for transformer load loss prediction in [99] as a fast low cost tool for obtaining power and hottest-spot output data. The same method is employed for the assessment of the effectiveness of a laminated flux collector in controlling the power losses of the transformer in [100]. Finally, FEM has been employed for the investigation of proximity effects on conductor losses in [101].

Experimental study of load losses is also encountered in the relevant literature. When a three-phase three-limb core type transformer is subjected to the load-loss measurement test, it is found that the losses and currents of the phases are asymmetrical (and unequal). Reference [102] attempts to give a comprehensive explanation for the asymmetry in the loss values of the three phases during the load-loss test. Moreover, eddy current losses are experimentally determined in order to analyze the derating of single-phase transformers under nonlinear loads in [103], [104].

C. *Leakage Field and Short-Circuit Impedance*

The calculation of transformer leakage flux is a prerequisite to the calculation of reactance, short-circuit impedance, short-circuit forces, and eddy current losses. A review of the most common winding arrangements in dual voltage transformers (i.e., in transformers with primary or/and secondary windings that can be reconnected in order to produce different operating voltages) and their impact on short-circuit strength is carried out in [105]. A further analysis on transformers with tap changers, resulting to variable volts per turn, is carried out in [106], focusing not only to the leakage field but on losses, noise and weight as well.

The finite-element method has been extensively employed in transformer leakage field evaluation. The first research attempts, presented over three decades ago [107], [108], focused on 2-D modeling, due to the restricted performance abilities provided by the early development of personal computers. 2-D FEM remains an efficient tool for leakage field and short-circuit impedance evaluation and more recent developments in the prediction of these parameters are presented in the literature [109]–[111]. Although the 2-D modeling is convenient and useful in some design problems, it can be found insufficient for detailed analysis and computation of the transformer magnetic field, and therefore the 3-D solution, initially proposed by Demerdash *et al.* at the beginning of 1980 [112], becomes necessary [113]–[117]. In this context, formulas for the exploitation of 3-D FEM model results in winding flux linkage are proposed in [118]. The boundary-element method is another numerical technique extensively used for electromagnetic problems [119]. The main attraction of this method is the simplicity of the data required to solve these problems, along with the high accuracy obtained with boundary elements. Moreover, the combination of boundary and finite elements is another widely used numerical field analysis technique presenting significant advantages in transformer leakage field modeling [120]–[123].

To overcome the main numerical techniques drawback, namely the complexity of the required mesh size, especially in 3-D configurations, alternative leakage field evaluation models have been proposed, with the use of a 3-D reluctance network method [124], [125], falling into the category of EC representation. An alternative method of transformer leakage field calculation is based on simplified analytical formulas, as in [126], where the calculation of self and mutual impedances between sections of transformer windings is performed or [127], where analytical calculations are carried out using Maxwell's differential equations and introducing the vector potential, for the components of the magnetic induction in two-dimensional field space. Analytical methods are often employed by transformer manufacturers in order to simplify the time and complexity of the calculations required in automated design process. Tomczuk and Zakrewski and Tomczuk propose the integral equation method for the calculation of magnetic leakage fields in [128] and [129], respectively.

Stochastic methods are also employed for solving problems of this category, as by Thilagar and Rao [130], who suggested an exact EC model for the estimation of all impedance parameters of three-winding transformers, with the use of GAs. The suggested method also estimates geometrically a complex parameter, that is, mutual leakage between secondary and tertiary windings.

In terms of leakage reactance experimental investigation, the influence of the test circuit (involving low voltage and single-phase excitation) on the respective measurements is presented in [131]. The effects of aluminum magnetic shielding and mild steel magnetic shunts on the leakage flux in the steel tank of a single-phase transformer are experimentally examined in [132].

D. *Inrush Current*

Transformer inrush currents are high-magnitude, harmonic-rich currents generated when transformer cores are driven into saturation during energization. These currents have undesirable effects, including potential damage or loss-of-life to the transformer and reduced power quality on the system [133]. Moreover, a significant impact on transformer winding mechanical stress may be observed [134]. It is also shown that under special conditions, the currents observed after transformer switching on do not contain enough restraining information (e.g., second harmonic), resulting in protective relay misoperation and posing a great problem for protective relaying of power transformers [135]. Inrush current prediction is therefore another important issue during transformer design and various approaches to deal with it are present in the technical literature.

Numerical techniques are present in the above context of inrush current prediction, as in [134] and [136], where 2-D and 3-D FEM is applied to three-legged power transformers for the evaluation of forces on the windings due to inrush current and their comparison to the respective short-circuit forces. However, the majority of the methods used for inrush current simulations are based on the derivation of appropriate equivalent circuits, taking into account the core geometry [137] and structural characteristics [138], the core material nonlinear characteristics [139], [140], using real-time measurements [141], [142], adopting proper parameters for the core magnetic hysteresis Jiles–Atherton model [143] or by proper simulation of the voltage sags caused by inrush currents [144]. Other models take into account the effect of transformer energization to other parallel connected transformers [145]. Frequency domain solution techniques have also been proposed for the simulation of inrush current variation, in order to overcome numerical problems due to the transient nature of the phenomenon [146]. Artificial neural networks have also been employed for the computation of inrush current and the resultant forces on the transformer windings [147].

Practical methods of elimination of transformer inrush current are also proposed in the relevant bibliography as in [148], where proper control strategies of circuit breakers that control transformer switching are presented, or in [149]–[151], by means of sequential phase energization (i.e., by energizing each phase of the transformer in sequence). Other methods may be applied during the design stage, by modifying the winding configuration [152], [153].

Inrush current phenomena may be exploited to estimate transformer performance as in [154] where they are used as a criterion to assess core saturation characteristics.

E. Dynamic Behavior Under Short Circuits and Seismic Stress

The short-circuit current in a transformer creates enormous forces on the turns of the windings. The short-circuit currents in a large transformer are typically 8 to 10 times larger than rated and in a small transformer 20 to 25 times larger than rated. The forces on the windings due to the short-circuit current vary as the square of the current, so whereas the forces at rated current may be only a few newtons, under short-circuit conditions these forces can be tens of thousands of newtons. These mechanical and thermal stresses on the windings must be taken into consideration during the design of the transformer. Transformer behavior under short circuits or internal faults is one of the major concerns during their design, since the ability to overcome the resulting stresses and currents without significant consequences on their operation is a requirement often present in the international technical standards. The accurate representation of this behavior is mainly realized through numerical techniques due to their prevalence in the transformer detailed magnetic field calculation: In [155], 2-D and 3-D FEM are compared in terms of accurate prediction of exerted forces on shell-type transformers under short circuit. In [156], a method was developed to apply 2-D FEM to calculate the parameters for an EC of the transformer with an internal short-circuit fault, while in [157] the method is expanded, representing in detail winding insulation deterioration. Winding internal faults are also modeled by 3-D FEM in [158] and by coupling the finite-element transformer's physical model with external electric circuit equations in [159]. 3-D FEM based on scalar and vector magnetic potential formulation is used for transient eddy current and short-circuit forces estimation, in [160] and [161], respectively.

Equivalent circuit approaches are also employed, although their application is usually coupled to some detailed calculation, often based on numerical methods [162], in order to ensure better representation of the phenomena occurring during short circuits.

Analytical models based on the theory of symmetrical components are also used for the simulation of transformer faults [163], while the stability of continuously transposed cable windings under axial short-circuit forces is investigated through analytical formulas in [164] and the vibration analysis of faulted transformers helical windings is performed in [165]. Analytical methods are proposed in [166] for the calculation of the power flow during transformer internal faults.

Seismic stress is another transient phenomenon with particular interest to transformer engineers, as it can cause severe damage including anchorage failure ripping the transformer case and oil leakage, as well as fracture of porcelain bushings. Therefore, seismic qualification of transformers, focusing on high voltage bushings, is another design consideration that is explored in [167], [168] by means of 3-D FEM analysis, and in [169] by a specially developed experimental setup.

F. Noise

Transformers located near a residential area should have sound level as low as possible. Techniques for power transformer noise control have been proposed over four decades ago [170]–[173] mainly through experimental study and statistical analysis of measurements used to determine the principal factors affecting transformer performance. The sound intensity method for power transformer noise measurements is described and results of its application are demonstrated in [174], while methods based on this technique are also developed in [175] and [176]. In [177] and [178], appropriate conditions for accurate outdoors and indoors measurement of transformer noise are derived and the inherent inaccuracies in the measurements are determined, resulting to the proposition of modifications to the existing IEC and IEEE industry standards of measuring transformer noise.

Since the core magnetic properties and structure are the major factors influencing transformer noise, a lot of research focusses on the analysis and improvement of the core attributes with regard to transformer noise: A simple technique of measuring the dynamic magnetostriction is used to illustrate the effects of improving the stress sensitivity of steel and reducing core vibration by a suitable bonding technique which can also reduce transformer noise in [179]. 3-D FEM structural dynamic analysis is used for the examination of the influence of core lamination upon transformer noise in [180], while vibro-acoustic modelling is also proposed for further analysis. Finally, the relevance of the core magnetic properties for the generation of audible noise in transformer cores is analytically and experimentally investigated in [181].

Methods of noise level reduction are also proposed in the bibliography, through the addition of equipment in transformer substations [182], [183]. More recent approaches perform noise level optimization by means of a reverse calculation method and Linear Programming using an empirical formula for estimating noise levels at the boundary points around the substation premises [184]. The design and the manufacture of a transformer with low sound level require indepth analysis of noise sources. Core, windings and cooling equipment are three main factors of noise, with the first factor the paramount one. To determine a method for the optimum design of the noise-reduction transformer, noise attenuation of a simple structured prototype transformer that utilizes C-cores is quantitatively discussed based on the EC analysis [185], [186]. Similar work is presented in [187]. A recently developed calculation scheme for the computer modelling of the load-controlled noise of liquid-insulated three-phase power transformers is presented in [188]. This modelling scheme allows the precise and efficient computation of the coupled electromagnetic, mechanical and acoustic fields. The equations are solved by using the FEM as well as the boundary-element method (BEM).

G. Insulation

The insulation of a transformer is linked to its ability to withstand surge phenomena and overvoltages likely to occur during its operation. For this purpose, the related work may deal with the analysis of such phenomena, so as to design an adequate transformer insulation system. Other factors that affect transformer insulation life are vibration or mechanical stress, repetitive expansion and contraction, exposure to moisture and other contaminants, and electrical and mechanical stress due to overvoltage and short-circuit currents.

Numerical methods are more scarcely applied for the simulation of the aforementioned phenomena, and are mainly used for the calculation of the transformer electric field [189]–[191]. On the other hand, the majority of research is based on EC representation for transformer analysis under overvoltages, with respect to their geometrical characteristics [192], their dynamic behavior [193], their frequency-response characteristics [194] or the characteristics of the network where they are connected [195]. Other attempts to model the insulation structure of transformers and the quantitative analysis of its dielectric response are also encountered [196], [197]. Hybrid methods, combining finite-element simulations for the derivation of EC parameters have also been proposed [198].

Finally, the exploitation of measurements and the experience from the impact of the operational characteristics on the insulation life assessment is often one of the main methods to design an insulation system and predict its ability to withstand any transient phenomena during the transformer life [199].

Insulation condition assessment is a widely covered topic, and various published works deal with this subject. A theoretical discussion on the aging of oil-impregnated paper in power transformers is carried out in [200], while [201]–[203] and [204] present experimental methods to determine cellulose and oil aging. Transformer oil breakdown is experimentally and theoretically analyzed in [205]. Effects of moisture and aging on the oilpaper insulation of transformers are investigated by return voltage measurements (i.e., the voltage that is built up between the electrodes on a dielectric after the application of direct voltage for a long period of time) in [206]. An analytical model establishing the time to failure of the insulation of transformers given their operating history is developed in [207], based on hourly load and ambient temperature measurements that extract the operating profile of the equipment and IEEE life consumption models to assess the consumed life of insulation. Partial discharge measurements are used to determine dielectric characteristics of transformer oils in [208], [209] and [210]. Frequency response of oil-impregnated pressboard and paper are used for estimating moisture in transformer insulation in [211] and [212]. Experimental investigation of bushing insulation is analyzed in [213]. Methods to overcome the insulating materials degradation with time in service are also proposed, as in [214], where the use of synthetic minerals for the absorption of moisture in paper insulation is discussed.

H. Cooling

Transformer cooling is one of the most important parameters governing a transformer's life expectancy. The total temperature is the sum of the ambient and the temperature rise. The temperature rise in a transformer is intrinsic to that of a transformer at a fixed load. The design of the cooling system is based on the hottest-spot temperature value, and different methods for its prediction are proposed in the literature, along with the overall temperature distribution prediction, according to the transformer cooling method. Furthermore, the improved knowledge of transformer thermal characteristics can allow transformer engineers to achieve enhanced designs and manufacturers are particularly interested in its accurate prediction.

The finite difference method is proposed by Pierce [215] for hottest-spot temperature prediction in dry-type transformers. 2-D FEM thermal calculation is proposed in [216] for the calculation of core hottest-spot temperature in power and distribution transformers. Moreover, it is employed to model the effect of harmonic currents in the winding temperature [217] and to perform heat transfer analysis and obtain the steady state and the transient temperature distribution of SF_6 gas cooled-insulated power transformers [218]. Most recent trends in thermal modeling employ coupled electromagnetic-thermal finite-element models [219], [220]. In [221] a 3-D FEM model using a magnetic scalar potential formulation is combined with a mixed analytical and numerical form of the electrical circuit equation to take into account the skin and proximity effects in the windings, resulting to current densities that are used as inputs to a steady state thermal FEM. In [222] a method that relies on the combination of analytical calculations, 2-D thermal and 3-D electromagnetic FEM is presented for transformer thermal modeling. Rosas *et al.* propose the finite volume method as a means of predicting the improvement of the cooling process of liquid-immersed electrical transformers using heat pipes [223]. For the proper representation of the cooling medium circulation, which affects the transformer thermal performance, thermal FEM is often coupled to computational fluid dynamics (CFD), in 2-D [224], [225] or 3-D models [226], [227]. Coupled fluid flow, heat transfer and electromagnetic numerical analysis is also encountered in the relevant litterature [228], further enhancing the accuracy in the prediction of transformer temperature.

Transformer thermal performance is usually predicted through analytical formulas that use approximations and constants derived from experimental results. Significant research effort is focusing on the improvement of these formulas and the derivation of more efficient calculation methods. In [229] the authors present analytical methods for estimating the temperature and its distribution at different points of the transformer, while in [230] they extend this work, taking into account the thermal inhomogeniety of the windings. This method is later employed to perform an elapsed life assessment study by acquiring insulation-aging data under accelerated thermal stresses in [231]. Calculation methodologies of top oil temperatures and hottest-spot temperatures are evaluated in [232] by comparison to respective measured values in power transformers. Two different thermal analytical models to predict temperature rises in an OFAF transformer at OFAN cooling mode in service are presented and experimentally investigated in [233]. In [234], new thermal loading guides are proposed, based on test results in factories and measured data in the field that are used to determine parameters of thermal differential equations. A mathematical model of the winding hottest-spot response to step changes in the load current of power transformers is presented in [235]. Ryder presents an analytical model to predict winding temperature gradient in power transformers, based on electrical analogy in [236]. The analytical assessment of the impact of ambient temperature rise, as a result of climate change, to distribution transformer loss of life is performed in [237]. In [238] and [239], four top-oil thermal models that require only parameters available from heat-run data and need only measurements utilities routinely monitor are presented and compared. Finally, a short review of developments in analytical thermal models is presented in [240].

Different kinds of equivalent thermal circuits are encountered in the literature, dependent on the geometry of the core and windings and the type of cooling. Appropriate equivalent circuits are developed in [241] for the core rise temperature calculation and power transformer thermal distribution [242]–[244]. In [245] and [246], the parameters of the proposed liquid-immersed transformer thermal model are derived with the use of GAs. Dynamic thermal models are also proposed in the literature [247]–[249], taking proper account of oil viscosity changes and loss variation with temperature, while in [250] a reliability analysis of various dynamic thermal models is carried out. Since transformer cooling is dependent on the hydrodynamic properties of oil, hydraulic models for mass flow distribution have been proposed in the literature, so as to provide detailed representation of the oil flow and pressure in ONAN transformers, as a function of the number and configuration of the cooling ducts [251], [252]. Hydraulic models are combined with heat convection models in [253] and [254].

The variation of transformer loading directly affects its thermal performance and must be correlated to the transformer time constants in order to derive safe conclusions for the resulting thermal loading. Therefore, several works have focused on developing proper load models, suitable for adoption in transformer thermal studies. In [255], a probabilistic model is presented by using load profiles, where variance and covariance are included. A methodology for specifying the winter and summer peak-load limits for substation transformers that carry a temperature-sensitive load, taking into account the random nature of load and ambient temperature as well as their correlation is presented in [256]. Residential loading profiles are extracted in [257], through statistical processing of measured data, proposing a methodology for sizing the transformers to serve these kinds of loads. In [258] a risk-based probabilistic method is presented to assess transformer loading capability, taking into account the probabilistic nature of time-varying loads and ambient temperature. Finally, a method for the evaluation of cyclic loading of power transformers is presented in [259].

Particle swarm method, neural networks, and neurofuzzy networks are also encountered in the relevant research field [260]–[263]. Monte Carlo methods are also used for sensitivity analysis of transformer hottest-spot and equivalent aging in [264].

Experimental investigation of thermal distribution of cast-resin and liquid-filled transformers is carried out in [265] and [266], respectively. Experimental data are used for the improvement of analytical equations that predict thermal distribution of liquid-filled transformers in [267] and [268]. Transformer oil characteristics before and after modifications of the forced-oil cooling system are experimentally studied in [269].

I. DC Bias

DC current can flow in alternating-current (ac) power lines if a dc potential difference exists between the various grounding points. Such a difference can be caused by a geomagnetic storm [geomagnetically induced current (GIC)] or the injection of dc current by one of the ground electrodes of a dc link [270]. DC flowing through the earthed neutrals of transformer windings causes a dc component in the magnetising current. Owing to nonlinearity, the waveform of this current is strongly distorted. The prediction and impact of this phenomenon has been studied with finite-element method [271]–[275] and equivalent magnetic circuits [276]–[280]. The experimental study of the phenomenon has also been performed, by field tests in a power and distribution transformer in [281] and [282], respectively, and by reactive power measurements in various distribution transformer ratings in [283].

TABLE II
Classification of References Presented in Section IV by Problem Type and Problem Name

Problem type	Problem name	References
Manufacturing cost minimization	Transformer design software	[284]-[298]
	Transformer design optimization using Deterministic methods	[3], [299]-[305]
	Transformer design optimization using Artificial Intelligence	[3], [306]-[310]
	Transformer design optimization imposing certain technical specifications	[121], [311]-[314]
Operating cost minimization	Energy efficient transformers	[3], [315]-[323]
	Energy efficient transformers taking into account environmental externalities	[3], [324]-[329]

IV. Transformer Design Optimization

Transformer manufacturers use cost optimization techniques during the design phase to minimize material costs and satisfy the utility's loss evaluation requirement. The difficulty in achieving the optimum balance between the transformer cost and performance is a complicated task, and the techniques that are employed for its solution must be able to deal with the design considerations of Section III, so as to provide a design optimum, while remaining cost-effective and flexible. The research associated with design optimization is therefore more restricted involving different mathematical optimization methods.

Whatever the chosen optimization method is, there is also the question of how much detail to include in the problem description. Despite the fact that the goal is to find the lowest cost, one might wish that the solution should provide sufficient information so that an actual design could be produced with little additional work. However, it would be unrealistic to expect that the optimum cost design for a transformer would automatically satisfy all of the mechanical, thermal, and electrical constraints that require sophisticated design algorithms to evaluate. Based on these, our main goal is to present the transformer design optimization techniques that deal with the minimization of the manufacturing as well as operating cost. These techniques are summarized in Table II according to the category of the addressed optimization problem and they are discussed in the forthcoming subsections.

A. Manufacturing Cost Minimization

In optimum design of transformers, the main target is to minimize the manufacturing cost. Therefore, the objective function is a cost function with many terms, including material costs, labor costs, and overhead costs. These component costs, as well as the constraint functions, must be expressed in terms of a basic set of design variables.

In order to compete successfully in a global economy, transformer manufacturers need design software capable of producing manufacturable and optimal designs in a very short time. Traditionally, the transformer design problem has been surrounded by much transformer designer art. The first transformer design was made on computer in 1955 [284]. Later on, more research in transformer design using computers was pioneered by [285]–[290]. Several design procedures for low-frequency and high-frequency transformers have appeared in the literature after the 70's. Judd and Kressler [291] presented a technique for designing transformers with given size and type of structure to have maximum volt-ampere (VA) output while at the same time insuring the satisfaction of a number of design constraints. The resulting design technique eliminates overdesign problems in that the smallest physical size structure will result consistent with the design objectives. An improved solution of the described problem was presented by Hurley *et al.* [292]. Poloujadoff *et al.* [293] show the variation in the price of the transformer depending on the primary turns, which is an approximately hyperbolic function. Also cost curves of the transformer against the magnetic flux density and against the current density are presented. Jeweel [294] does a functional proposal with students in electrical engineering, in which the student designs, builds and tests a 10-VA transformer. Grady *et al.* [295] deal with the teaching of design of dry type transformers, based on a computer program, where the user optimizes its design based on trial and error. Furthermore, Rubaai [296] describes a computer program yielding an optimal design of a distribution transformer based on user input data (classified in given, independent and dependent). The author includes design transformer formulas used by the program. Andersen [297] presented an optimizing routine, Monica, based on Monte Carlo simulation. Basically, his routine uses random numbers to generate feasible designs from which the lowest cost design is chosen. Hernandez and Arjona [298] develop an object-oriented knowledge-based distribution transformer design system, in conjunction with FEM, which is used as a tool for design performance validation.

Deterministic methods provide robust solutions to the transformer design optimization problem. In this context, the deterministic method of geometric programming has been proposed in [299] in order to deal with the design optimization problem of both low frequency and high frequency transformers. Furthermore, the complex optimum overall transformer design problem, which is formulated as a mixed-integer nonlinear programming problem, by introducing an integrated design optimization methodology based on evolutionary algorithms and numerical electromagnetic and thermal field computations, is addressed in [3], [300]. However, the overall manufacturing cost minimization is scarcely addressed in the technical literature, and the main approaches deal with the cost minimization of specific components such as the magnetic material [301], the no-load loss minimization [302], [303] or the load loss minimization [304]. Techniques that include mathematical models employing analytical formulas, based on design constants and approximations for the calculation of the transformer parameters are often the base of the design process adopted by transformer manufacturers [305].

Apart from deterministic methods, Artificial Intelligence techniques have been extensively used in order to cope with the complex problem of transformer design optimization, such as GAs that have been used for transformer cost minimization [306], performance optimization of cast-resin distribution transformers with stack-core technology [307] or toroidal core transformers [308]. Neural network techniques are also employed as a means of design optimization as in [3], [309] and [310], where they are used for winding material selection and prediction of transformer losses and reactance, respectively.

Another aspect of transformer design optimization consists in providing design solutions in order to maintain certain aspects of transformer performance within the limits imposed by the technical specifications. In this context, the maintenance of short-circuit impedance and losses within the acceptable tolerance is often addressed, as in [121], [311], [312], and [313], [314], respectively.

In a nutshell, it is clear that the transformer design optimization problem remains an active research area.

B. Operating Cost Minimization

Apart from the transformer manufacturing cost, another criterion used for transformer evaluation and optimization is the total owning cost (TOC) taking into account the cost of purchase as well as the cost of energy losses throughout the transformer lifetime [315].

The TOC technique is the most widely used transformer evaluation method for determining the cost-effectiveness of energy-efficient transformers, providing a balance between cost of purchase and cost of energy losses. The TOC evaluation method has been developed as a handy tool to reflect the unique financial environment faced by each electric utility when purchasing distribution transformers. According to this method, the variability of the cost of electric energy, capacity and financing costs is expressed through two evaluation factors, called A and B factors, corresponding to the unit cost of no-load and load losses, respectively. It is important to note that the method that defines these two factors varies according to the role of the transformer purchaser in the energy market (two major categories can be considered: electric utilities and industrial users) and the depth of the analysis (depending on the accuracy of the representation of the transformer loading characteristics). It is important to recognize that the perspective of the electric utility is different from the perspective of the industrial and commercial users of transformers. The transformer loss evaluation procedure for the electric utility involves understanding and assessing the total cost of generation, transmission, and distribution transformer losses, while the transformer loss evaluation procedure for an industrial and commercial user requires an understanding and assessment of the electric rates they pay to the electric utility.

An important part of the transformer cost optimization research is devoted to the TOC minimization, as follows. Distribution transformer TOC optimization is analyzed in [316]–[320]. Since the load losses are directly linked to the type of the considered load and the specific details of the network at the transformer installation point, a number of versatile factors should be incorporated in the TOC analysis. Such an analysis is performed in depth in [321], [322].

Furthermore, energy losses of transformers throughout their life cycle increase significantly their operational costs, resulting in TOC values much higher than their purchase price. For the above reason, the decision for what transformer to purchase should not be based only on its purchase price. In general, transformers with the lowest purchase price are also the ones with the highest TOC. Therefore, in order to choose the most economical transformer in the long term, the TOC value during the lifespan of the transformer should be taken into account [323]. Moreover, the external environmental costs [3], [324] should be taken into consideration as well (i.e., the costs that are associated with various types of emissions resulting from the combustion of fossil fuels) so as to compensate for transformer losses.

Recently, the impact of transformer environmental externalities and the contribution of losses to the greenhouse gas emissions generated by the global power generation mix has been addressed [325]–[327]. Furthermore, ways to promote the policy to encourage the use of efficient transformers in the Spanish market are proposed by Frau *et al.* [328], where incentives to private users and electric utilities are introduced, changing Spanish losses regulation, and allowing utilities to participate in the CO_2 emissions market. Moreover, an overview of options available to distribution transformer specifiers, taking advantage of the efficiency and environmental benefits, has been provided [329]. However, a methodology to quantify the impact of environmental externalities on transformer TOC has not yet been developed.

V. Post-Design Transformer Performance

The main incentive of the research presented in the previous sections was to develop models for transformer simulation and adopt methodologies that were able to optimize their performance according to their constructional characteristics, providing several criteria for transformer design optimization. The works presented in this section do not focus on the prediction and evaluation of transformer characteristics during the design stage, but the derivation of proper models for given performance characteristics, to be included in power system studies or other engineering studies, where transformers are involved. The relevant research can be divided into two major categories: models suitable for harmonic load flow studies and models for electromagnetic transient studies. Table III lists the relevant publications by category, further classifying them according to their methodological approach. The acronyms NT, AM, EM, and HM of Table III correspond to the categories defined in Section III (and included in Table I). It must be noted that the majority of the articles concern the derivation of transformer equivalent circuits; therefore, they are all included in the category EC (equivalent circuits) defined in Section III, a classification that is not explicitly denoted in Table III.

A. Harmonic Modeling

The research interest on harmonic load flow studies is continuously growing, due to the increase of nonlinear devices in power systems. Since transformers are key elements in these systems, their modeling is an important subject in harmonic load-flow studies and a number of different approaches have been proposed in the literature. Stensland *et al.* develop a transformer model where the iron and copper losses under low frequency voltage harmonics may be determined either analytically or by FEM, suitable for power system studies [330]. Single and three-phase equivalent circuits taking into account the non-

TABLE III
CLASSIFICATION OF REFERENCES PRESENTED IN SECTION V BY SUBJECT AND METHODOLOGICAL APPROACH

	NT	AM	EM	HM
Harmonic modeling	[330]	[331], [333], [334]		[332]
Transient and dynamic modeling	[354], [355], [377]-[379]	[335], [336], [338]-[353], [356]-[365], [370], [371], [373]-[376]	[369], [372], [380]-[383]	[337], [366]-[368]

linearity of the core are presented in [331]. Mohammed *et al.* implement a transformer transient FEM coupled to external electric circuits and the wavelet packet transfer algorithm for the analysis of harmonic behavior of the transformer currents and the dc load current [332]. In [333], a complete analytical model is developed to calculate the time domain waveform and the harmonic components of the transformer excitation current. Masoum *et al.* develop a nonlinear transformer modeling technique for steady-state operation under unbalanced, asymmetric, and nonsinusoidal operation, capable of computing derating factors in [334].

B. Transient and Dynamic Modeling

One of the weakest components of modern transient simulation software is the transformer model. Many opportunities exist to improve the simulation of its complicated behaviors, which include magnetic saturation of the core, frequency-dependency, capacitive coupling, and topological correctness of core and coil structure [335]. Martinez and Mork present a review of the existing models in [335], providing an overview of their main developments, while Martinez *et al.* provide guidelines for the estimation of transformer model parameters for low- and mid-frequency transient simulations in [336].

In this type of modeling, classical methods to determine transformer magnetic circuit and windings such as the ones described in Section III are combined with frequency and time domain modeling techniques, as presented in the following.

Woivre *et al.* propose a model for shell-type transformer overvoltage study, where the main R, L, and C parameters are calculated with analytical and numerical methods, while transient overvoltages of the transformer are calculated from frequency response by Fourier transform [337]. Reduction techniques of linear and nonlinear lumped parameters models are proposed by Gutierez *et al.* [338] and Degeneff *et al.* [339], respectively. De Leon and Semlyen introduce a simple dynamic hysteresis loss model in [340] and the calculation of transformer EC elementary parameters (namely leakage inductance and capacitance) on a turn-to-turn basis in [341] which are used to derive a winding model suitable for transformer transients in [342]. Moreover, they investigate time domain modeling of eddy currents for electromagnetic transients study in [343] and propose techniques for time step reduction in electromagnetic transient simulation in [344], while in [345], a complete three-phase transformer model is proposed based on their previous works in [341]–[343]. This model is improved in [346] to include the capacitive effects between turns or sections of a winding. An alternate model for low-frequency electromagnetic transients is proposed in [347] and its more simplified version is presented in [348]. Papadias *et al.* present three-phase transformer models for the study of switching fast electromagnetic transients in [349]. Distributed equivalent magnetic and electric circuits are introduced in transformer transient analysis in [350]. Tokic *et al.* develop numerical methods to solve the system of differential equations in state space, describing the transformer transient behavior in [351], while Tokic and Uglesic develop an original method of modeling nonlinear elements, for the elimination of overshooting effects and suppression of numerical oscillations in transformer transient calculations in [352]. Frequency-response analysis is used in [353] to study the transient recovery voltage associated with power transformer terminal faults. Abeywickrama *et al.* present a 3-D model of electromagnetic (EM)-field distribution in a power transformer at high frequencies for use in frequency-response analysis in [354] and its results are exploited in [355] for high-frequency modeling of power transformers. In [356], the principles of modal analysis are presented, while in [357], modal analysis is used to consider frequency-dependent effects of internal capacitance, inductance, and resistance of windings in order to analyze the transient characteristics of a transformer. In [358], a model is presented for a multiwinding multiphase transformer developed by the nodal inverse inductance matrix, which can be used for transient and steady-state analysis in complicated winding arrangements and network configurations, while in [359] and [360] a multiterminal transformer model is developed for balanced and unbalanced load, respectively. A three-phase transformer dynamic model, providing a good compromise between accuracy and excessive complexity arising in dynamic simulations is presented in [361], while in [362] frequency-dependent time-varying resistance of the transformer winding is considered during modeling the response to lightning impulse wave. A model reference approach for classification of faults that can occur during impulse tests on power transformers is proposed in [363]. Stuehm *et al.* and Mork develop five-legged wound-core transformer models in [364], [365], while Mork *et al.* propose a hybrid transformer model based on four typically available sources of information: factory test reports, design data, basic ratings and direct laboratory measurements [366], [367]. In [368], Mork *et al.* detail the parameter estimation methods developed for the five-legged core of the aforementioned hybrid model. Very fast transient voltage analysis is performed in [369]–[373]. Mombello and Moller present a model with accurate representation of winding losses, developed for the determination of maximal stresses during resonance phenomena within transformers [374], while Mombello performs a deep analysis of the behavior of transformer winding impedances for high frequencies by analyzing the properties of inductance matrices in [375]. In [376], a model that reproduces not only the impedance characteristics seen from each terminal of a core-type distribution transformer but also the surge-transfer characteristics between the primary and secondary sides in a wide range of frequencies is presented.

The coupling of numerical methods with other transient modeling techniques is proposed by other researchers in the field.

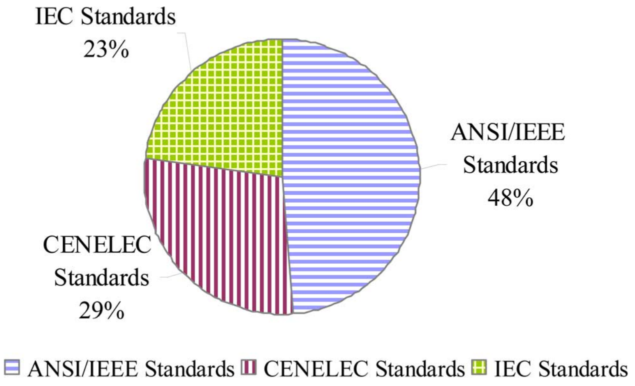

Fig. 5. Percentage participation of IEEE, CENELEC, and IEC standards in the overall amount of standards survey.

An EC based on winding resonances computed by FEM is presented in [377] for the simulation of winding electromagnetic oscillations. Mohammed *et al.* use a circuit coupled FEM analysis under sinusoidal waveforms to derive inductances as a function of the amplitude of ac flux as well as its phase angle during a complete ac cycle for three-phase transformer modeling [378], a work which is later expanded to single-phase transformers [379].

Experimental methods to define models for electromagnetic transient studies are also employed, as in [380], which describes the measurement setup for the extraction of a frequency dependent model of a two winding transformer. A three-phase transformer model including saturation and based on experimental parameters is developed in [381], for the examination of symmetrical and unsymmetrical voltage sag effects on three-legged transformers in [382] and [383], respectively.

VI. TRANSFORMER STANDARDS

A number of transformer relevant standards are listed in this section. These standards are issued by the three institutions: ANSI/IEEE, CENELEC, and IEC (Fig. 5).

IEEE stands for The Institute of Electrical and Electronics Engineers, Inc. IEEE standards are national standards prepared and issued in the United States of America by the IEEE Societies. The use of these standards is wholly voluntary, and it becomes mandatory only when specified in a contractual relationship or when required by a duly constituted legal authority. The IEEE clearly indicates that the existence of an IEEE Standard does not imply that there are no other ways to deal with matters related to the scope of the IEEE standard.

CENELEC stands from Comité Européen de Normalisation Electrotechnique (in English: European Committee for Electrotechnical Standardization). It was created in 1973. CENELEC standards (EN standards) are international standards prepared by working groups and approved by weighted voting among countries being members of the European Union (EU) and other countries included in the European Economic Area Agreement. Furthermore, CENELEC has issued a number of Harmonization Documents (HD), and their formal status is practically the same as that of the EN standards. CENELEC has decided to phase out the Harmonization Documents and replace them by EN standards.

IEC stands for International Electrotechnical Commission, which was officially founded in 1906 in London. The use of IEC standards is a voluntary matter. Technical committee number 14 (TC14) deals with power transformers. The IEC standards do not prescribe how to design and produce transformers. Therefore, it would be meaningless or it would at least be imprecise use of language to say that a transformer shall be or is designed and produced according to IEC standards. The IEC transformer standards establish a series of performance, safety, application, selection and other requirements to be satisfied by the equipment, including performance tests for their certification. In this context, they define certain tests the transformers shall be subjected to before delivery from the factory and state the acceptance criteria. The purpose of the tests is that transformers that have passed these tests shall have good prospects of a long life and high service reliability, when adequately protected and maintained.

It is important to note that between the standards that are issued by these three institutions, there are some basic differences which are not in the scope of this work to emphasize. However, IEC and IEEE have expressed the intention gradually to decrease or remove these basic differences between their standards. It is envisaged that a closer co-operation between these organizations will make the future standardization work more cost efficient.

A. ANSI/IEEE Standards

IEEE Std. C57.12.00-2006—IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers;
IEEE Std. C57.12.01-2005—IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers, Including Those with Solid-Cast and/or Resin Encapsulated Windings, Revision of C57.12.01-1998;
IEEE Std. C57.12.10-1997—American National Standard for Transformers—230 kV and Below 833/958 through 8333/10 417 kVA, Single-Phase, and 750/862 through 60 000/80 000/100 000 kVA, Three-Phase Without Load Tap Changing; and 3750/4687 through 60 000/80 000/100 000 kVA with Load Tap Changing-Safety Requirement;
IEEE STD C57.12.20-2005—IEEE standard for overhead-type distribution transformers, 500 kVA and smaller: high voltage, 34 500 V and below; low voltage, 7970/13 800y V and below;
IEEE Std. C57.12.21-1992—American National Standard Requirements for Pad-Mounted, Compartmental-Type Self-Cooled, Single-Phase Distribution Transformers with High Voltage Bushings; High-Voltage, 34500 GRYD/19920 Volts and Below; Low-Voltage, 240/120 Volts; 167 kVA and Smaller;
IEEE Std. C57.12.22-1993—American National Standard for Transformers—Pad-Mounted, Compartmental-Type, Self-Cooled Three-Phase Distribution Transformers With High-Voltage Bushings, 2500 kVA and Smaller: High Voltage, 34 500 Grd Y/19 920 Volts and Below; Low Voltage, 480 Volts and Below, Reaffirmed 1998;
IEEE Std. C57.12.23-2002—IEEE Standard for Underground Type, Self-Cooled, Single-Phase, Distribution

Transformers with Separable Insulated High-Voltage Connectors; High Voltage 25 000 V and Below; Low Voltage 600 V and Below; 167 kVA and Smaller Revision of C57.12.23-1992;
IEEE Std. C57.12.24-2000 Withdrawn—American National Standard for Transformers Underground-Type Three-Phase Distribution Transformers, 2500 kVA and Smaller; High Voltage, 34 500 GrdY/19 920 Volts and Below; Low Voltage, 480 Volts and Below Requirements;
IEEE Std. C57.12.25-1990—American National Standard for Transformers—Pad-mounted, Compartmental-type, Self-cooled, Single-phase Distribution Transformers with Separable Insulated High-voltage Connectors; High Voltage, 34 500 Grdy/19 920 Volts and Below; Low Voltage, 240/120 Volts; 167 kVA and Smaller Requirements;
IEEE Std. C57.12.26-1992—IEEE Standard for Pad-mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors (34 500 Grd Y/19 920 V and Below, 2500 kVA and Smaller);
IEEE Std. C57.12.28-2005—IEEE Std. C57.12.28—2005 IEEE Standard for Pad-Mounted Equipment—Enclosure Integrity;
IEEE Std. C57.12.29-2005—IEEE Standard for Pad-Mounted Equipment—Enclosure Integrity for Coastal Environments;
IEEE Std. C57.12.31-2002—IEEE standard for Pole Mounted Equipment—Enclosure Integrity;
IEEE Std. C57.12.32-2002—IEEE Standard for Submersible Equipment—Enclosure Integrity, Reaffirmed 2008;
IEEE Std. C57.12.34-2004—IEEE Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, three-phase distribution transformers (2500 kVA and smaller)—High-voltage: 34 500 GrdY/19 920 volts and below; low-voltage: 480 volts and below;
IEEE Std. C57.12.35-2007—IEEE Standard for Bar Coding for Distribution Transformers and Step-Voltage Regulators, Revision of C57.12.35-1996;
IEEE Std. C57.12.36-2007—IEEE Standard Requirements for Liquid-Immersed Distribution Substation Transformers;
IEEE Std. C57.12.37-2006—IEEE Standard for the Electronic Reporting of Distribution Transformer Test Data, Revision of 1388-2000;
IEEE Std. C57.12.40-2006—IEEE Standard Requirements for Secondary Network Transformers, Subway and Vault Types (Liquid Immersed);
IEEE Std. C57.12.44-2005—IEEE Standard Requirements for Secondary Network Protectors, Revision of C57.12.44-2000;
IEEE Std. C57.12.50-1981—American National Standard Requirements for Ventilated Dry-Type Distribution Transformers, 1 to 500 kVA, Single-Phase, and 15 to 500 kVA, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 120 to 600 Volts;
IEEE Std. C57.12.51-1981—American National Standard Requirements for Ventilated Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts;
IEEE Std. C57.12.52-1981—American National Standard Requirements for Sealed Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 to 34 500 Volts, Low-Voltage 208Y/120 to 4160 Volts;
IEEE Std. C57.12.55-1987—American National Standard for Transformers—Used in Unit Installations, Including Unit Substations-Conformance Standard;
IEEE Std. C57.12.56-1986—IEEE standard Test Procedure for Thermal Evaluation of Insulation Systems for Ventilated Dry-Type Power and Distribution transformers;
IEEE Std. C57.12.58-1991—IEEE Guide for conducting a transient voltage analysis of a dry-type transformer coil, Reaffirmed 1996, 2002, 2008;
IEEE Std. C57.12.59-2001—IEEE Guide for dr-type transformer through-fault current duration, Reaffirmed 2006;
IEEE Std. C57.12.60-1998—IEEE Guide for test procedures for thermal evaluation of insulation systems for solid-cast and resin-encapsulated power and distribution transformers;
IEEE Std. C57.12.70-2000—IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers;
IEEE Std. C57.12.80-2002—IEEE Standard Terminology for power and distribution transformers, Revision of C57.12.80-1978;
IEEE Std. C57.12.90-2006—IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers;
IEEE Std. C57.12.91-2001—IEEE Standard Test Code for Dry-Type Distribution and Power Transformers;

B. *CENELEC Standards*

EN 60076-1:1997/A12:2002—Part 1: General;
EN 60076-2:1997—Part 2: Temperature rise;
EN 60076-3:2001—Part 3: Insulation levels, dielectric tests and external clearances in air;
EN 60076-4:2002—Part 4: Guide to the lightning impulse and switching impulse testing—Power transformers and reactors;
EN 60076-5:2006—Part 5: Ability to withstand short circuit;
EN 60076-6:2008—Part 6: Reactors;
EN 60076-10:2001—Part 10: Determination of sound levels;
EN 60076-11:2004—Part 11: Dry-type transformers;
EN 60076-13:2006—Part 13: Self-protected liquid-filled transformers;
EN 50216-1:2002—Part 1: General;
EN 50216-2:2002—Part 2: Gas and oil actuated relay for liquid immersed transformers and reactors with conservator;
EN 50216-3:2002—Part 3: Protective relay for hermetically sealed liquid-immersed transformers and reactors without gaseous cushion;

EN 50216-4:2002—Part 4: Basic accessories (earthing terminal, drain and filling devices, thermometer pocket, wheel assembly);

EN 50216-5:2002—Part 5: Liquid level, pressure and flow indicators, pressure relief devices and dehydrating breathers;

EN 50216-6:2002—Part 6: Cooling equipment—removable radiators for oil-immersed transformers;

EN 50216-7:2002—Part 7: Electric pumps for transformer oil;

HD 428.1 S1:1992/A1:1995 Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV—Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV;

HD 428.3 S1:1994 Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA, with highest voltage for equipment not exceeding 36 kV—Part 3: Supplementary requirements for transformers with highest voltage for equipment equal to 36 kV;

HD 428.1 S1:1992 Three-phase oil-immersed distribution transformers 50 Hz, from 50 to 2500 kVA with highest voltage for equipment not exceeding 36 kV—Part 1: General requirements and requirements for transformers with highest voltage for equipment not exceeding 24 kV.

C. IEC Standards

IEC 60076-1 (2000-04) Power transformers—Part 1: General;

IEC 60076-2 (1993-04) Power transformers—Part 2: Temperature rise;

IEC 60076-3 (2000-03) Power transformers—Part 3: Insulation levels, dielectric tests and external clearances in air;

IEC 60076-4 (2002-06) Power transformers—Part 4: Guide to the lightning impulse and switching impulse testing—power transformers and reactors;

IEC 60076-5 (2006-02) Power transformers—Part 5: Ability to withstand short circuit;

IEC 60076-6 (in process) Power transformers—Part 6: Reactors;

IEC 60076-7 (2005-12) Power transformers—Part 7: Loading guide for oil-immersed power transformers;

IEC 60076-8 (1997-11) Power transformers—Part 8: Application guide;

IEC 60076-10 (2005-07) Power transformers—Part 10: Determination of sound levels;

IEC 60076-10-1 (2005-10) Power transformers—Part 10-1: Determination of sound levels—Application guide;

IEC 60076-11 (2004-05) Power transformers—Part 11: Dry-type transformers;

IEC 60076-12 (in process) Power transformers—Part 12: Loading guide for dry-type power transformers;

IEC 60076-13 (2006-05) Power transformers—Part 13: Self-protected liquid-filled transformers;

IEC/TS 60076-14 (2004-11) Power transformers—Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials;

IEC 60076-15 (in process) Power transformers—Part 15: Gas-filled power transformers;

TABLE IV
CLASSIFICATION OF REFERENCES PRESENTED IN SECTION VII BY PROBLEM TYPE AND PROBLEM NAME

Problem type	Problem name	References
Magnetic circuit	Core losses	[384]-[388]
Windings	Superconducting transformers	[389]-[397]
Insulation	Mineral oil	[398]
	Natural esters or vegetable oils	[399]-[403]
	Accelerated Aging Tests	[404]-[405]
	Mixtures of inslulated liquids	[406]-[408]
	Gas insulated transformers	[409]-[410]
Monitoring and diagnostics	Transformer fault diagnosis	[411]-[417]
	Winding deformation identification	[418]
	Gas analysis	[419]-[421]
	Others	[422]-[425]

VII. RECENT TRENDS IN TRANSFORMER TECHNOLOGY

In the last decade, rapid changes and developments have been made in the field of transformer design. The phenomenal growth of power systems has put tremendous responsibilities on the transformer industry to supply reliable and cost-effective transformers. This section identifies the recent trends in research and development in materials, insulations systems, accessories, and diagnostic techniques, by quoting keyworks that address them, giving pointers to readers desirous of pursuing research in transformers. The references of this Section are summarized in Table IV and they are discussed in further detail in the forthcoming subsections.

A. Magnetic Circuit

There has been a steady development of core steel material in the last century. The trend of reduction in transformer losses in the last few decades is related to a considerable increase in energy costs. One of the ways to reduce the core losses is to use better and thinner grades of core steels, but their price is higher. However, continuous efforts are directed at developing improved electrical steels with lower iron losses for energy-efficient transformers. It is well known that low magnetic losses of amorphous material are attributable to the material's amorphous condition and small thickness of the ribbon [384], [385]. The core losses can be limited by insulating coatings [386], and various types of coatings have been developed for application to both fully processed and semiprocessed electrical steels. In addition, Matsuura *et al.* [387] and Ezure *et al.* [388] presented long-term property reliability for iron-based amorphous alloy for use in liquid-immersed transformer cores.

B. Windings

The advent of high-temperature superconducting (HTS) materials has renewed interest in research and development of superconducting transformers. The principal advantages of HTS transformers are: much lower winding material content and losses, higher overload capacity and possibility of coreless design. Some considerations from design point of view are discussed in [389], [390], while in [391] new perspectives of HTS transformer design are introduced. The development of technology based on liquid nitrogen at temperatures up to 79 K has reduced the complexity and cost of superconducting transformers [392], [393]. A development of a three-phase 100-kVA superconducting transformer with amorphous core has been reported in [394]. A high-superconducting coil that simulated the inner secondary winding of a high-superconducting traction transformer is presented in [395], [396]. Moreover, the magnetization losses in HTS pancake windings according to the operating temperature, is discussed in [397].

C. Insulation

Transformers in electric power distribution and transmission systems are expected to function reliably and efficiently in the long term. The quality of the oil in a transformer plays an important role in performing this function, and the characteristics of transformer oil have been examined and reported on for decades. The majority of transformers use mineral oil in order to meet their cooling demands, due to the fact that mineral oil has not only a low price but also very good electrical insulating properties [398]. However, nowadays, the mineral oil performance cannot meet the modern needs of transformers.

Numerous activities have been initiated to try to improve the properties of mineral oil or to find other substitute liquids Alternatively to conventional mineral oils, natural esters or vegetable oils have been used successfully as transformer dielectric coolants [399]–[403]. Their application offers some advantages, such as safety against a fire incident, environmental friendliness and improved transformer performance.

The results of Accelerated Aging Tests are discussed in length in [404] while in [405] these results suggest that the use of natural esters extends the life of the insulating paper.

Furthermore, mixtures consisting of mineral oil and two other kinds of insulating liquids (namely silicon and synthetic ester oils) are investigated in [406], [407]. Moreover, the "retro-filling" application (i.e., replacing mineral oil with natural esters) is also presented, as a method to extend the remaining thermal life of an aging transformer [408].

Last but not least, there is a considerable progress in the technology of gas immersed transformers in the last decade. Unlike the liquid-immersed transformers, they have SF_6 gas for the insulation and cooling purposes [409], [410].

D. Transformer Monitoring and Diagnostics

Despite the fact that monitoring and diagnostics are not part of the transformer design process, they are relevant to the main design considerations. For this purpose, an overview of some key works dealing with the characteristics presented in the previous Sections is provided in the present Section.

AI techniques and stochastic methods are prevailing in the present category. Neural networks are encountered in the majority of the research dealing with transformer fault diagnosis [411]–[415]. They are also employed for liquid-immersed distribution transformer monitoring in [416]. Furthermore, Stochastic Petri Nets are used for the simulation of the fault diagnosis process of liquid-immersed transformers and the definition of the actions followed to repair the transformer [417]. The particle swarm method is used for winding deformation identification in [418] and dissolved gas analysis in [419]. Finally, fuzzy systems and expert systems are proposed in [420] and [421] for the gas analysis and insulation monitoring, respectively. Significant research effort has focused on discrimination between fault and inrush current in transformers, and various methods are evolving [422]. Monitoring methods are also based on vibro-acoustic measurements [423], oil temperature [424] or spectral thermography have also been developed. A review of transformer condition assessment methods is provided in [425].

VIII. TRANSFORMER BOOKS

It is necessary to make a brief presentation of transformer books, giving to the reader a convenient starting point. This kind of review will be extremely helpful and handy not only to undergraduate and postgraduate students but also to the transformer industrial engineers. The thorough treatment of all-important aspects of transformer engineering given will provide the reader all the appropriate background to pursue research and development activities in the field of transformers. Bibliography on transformer books is inspired by the IEEE Power Engineering Society (PES) Transformer Committee (http://www.transformerscommittee.org), highlighting a list of 52 books in the domain of transformers.

- James H. Harlow, *Electric Power Transformer Engineering, 2nd Edition*, CRC Press, New York, 2007.
- Giorgio Bertagnolli, *Short—Circuit Duty of Power Transformers 3rd Revised Edition*, ABB Management Services Ltd. Transformers, Zurich, Switzerland, 2006.
- ABB Transformer and Engineering Services North America, S*ervice Handbook for Power Transformers*, ABB, USA, 2006.
- ABB Power Technologies Management Ltd. *Transformer Handbook*, ABB, Switzerland, 2004.
- ABB Business Area Power Transformers, *Testing of Power Transformers*, ABB, Zurich, 2003.
- Hydroelectric Research and Technical Services Group, *Transformers: Basics, Maintenance, and Diagnostics*, US Department of the Interior, Bureau of Reclamation, Government Printing Office, April 2005.
- Bharat Heavy Electricals Ltd., *Transformers*, McGraw-Hill, New York, 2005.
- S. V. Kulkarni, S. A. Khaparde, *Transformer Engineering Design & Practice*, Marcel Dekker, Inc., New York, 2004.
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- Kenneth L. Gebert, Kenneth R. Edwards, *Transformers Principles and Applications 2nd Edition*, American Technical Publishers, Inc., Illinois, 1974.
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- Petter I. Fergestad, *Transient Oscillations in Transformer Windings*, Naper Boktrykkeri, Kragero, Norway, 1972.
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IX. CONCLUSION

In this paper, an overview of the literature concerning transformer design has been undertaken, focusing on the progress realized in the past four decades. Relevant publications from international journals have been selected, covering a broad range of engineering methods and design considerations. Moreover, the most important international standards governing transformer performance and qualification requirements have been presented. In addition, a brief presentation of transformer books has been introduced. The difficulties to include and categorize the majority of the research in such a vast field were overcome by a convenient survey structure, taking into account various design considerations. This survey provides important information on the main directions of the considered research and the future trends in the field of transformer design.

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