

# The state of the art in engineering methods for transformer design and optimization: a survey

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The complexity of transformer design demands reliable and rigorous solution methods. Survey of current research reveals the continued interest in application of advanced techniques for transformer design optimization. This paper summarizes some of the most important developments in this research area. The main purpose is to provide a synthesis of the published research in this field and stimulate further research interests and efforts in the respective topics.

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## 1. Introduction

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 MHz), 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 application of various computational methods for transformer design, based on an extensive number of published papers. The review is divided into two major sections: research efforts focusing on the prediction and/or optimization of specific transformer characteristics (mainly losses and short-circuit impedance) and techniques adopted for global transformer design optimization, taking into account all the relevant performance parameters.

The paper is organized as follows: Section 2 describes the various transformer types that are present in the relevant bibliography as well as the main considerations during the transformer design process. Section 3 includes the survey overview of research dedicated to transformer characteristics, while Section 4 provides an overview of the research conducted on transformer design optimization. Finally, Section 5 concludes the paper.

## 2. Transformer design

A transformer has been defined by ANSI/IEEE [3] 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.

### 2.1 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. Power transformers may be further classified according to their scope of application, according to the followings. 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. 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 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 oil-immersed or dry type transformers. In oil-immersed transformers, the insulating medium is oil while in dry type transformers, the cooling is implemented with natural air circulation. The identification of oil-immersed transformers according to the cooling method is expressed by a four-letter code. The first letter expresses the internal cooling medium in contact with the windings. The second letter identifies the circulation mechanism for internal cooling medium. The third letter expresses the external cooling medium. The fourth letter identifies the circulation mechanism for external cooling medium. For example, if the internal cooling medium is mineral oil, which is circulated with natural flow, and the external 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, four cooling methods exist: ONAF (Oil Natural Air Forced), OFAN (Oil Forced Air Natural) (OFAN Oil Forced Air Forced) and OFWF (Oil Forced Water Forced). Combinations like ONAN/ONAF, ONAN/OFAN or ONAN/OFAF are also applicable [4].

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 overlapped, 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.

## 2.2 Transformer design considerations

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. 1 presents the main categories of the literature survey, which define the

structure of the survey overview presented in the next Sections.

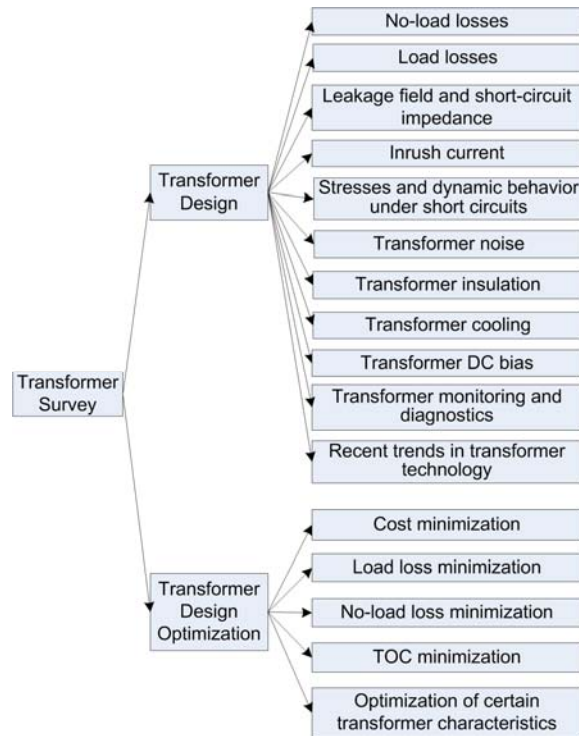


Fig. 1. Transformer survey structure.

## 3. 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 four main groups:

1. **Numerical techniques** that consist 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. **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.
3. Improved versions of the transformer **equivalent circuit**, in order to include semi-empirical descriptions of the core and winding characteristics that affect the accuracy of calculations. Its use is still common in the manufacturing industry, due to its simplicity and its ability to provide reliable results, especially in cases of standardized geometries.
4. **Experimental methods**, combining data provided by measurements with analytical or other methods, in order to provide efficient models for the accurate representation of certain transformer characteristics.

### 3.1 No-load losses

*No-load losses* are the continuous losses of a transformer, regardless of load, namely they exist whenever the unit is energized [5]. 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.

The FEM has been extensively employed in the no-load losses prediction problem. The application of two-dimensional (2D) FEM in the calculation of transformer core losses is realized in [6,7], where tools for the calculation of stray and eddy losses, and hysteresis are developed. Detailed modeling of the core magnetic properties based on measurements are presented in [8-12]. In order to achieve more detailed analysis and computation of the transformer magnetic field, the three-dimensional (3D) analysis becomes necessary, as proposed in [13]. Moreover, Koppikar et al. [14] 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 results of 3-D FEM simulations carried on slotted and laminated flitch plates. 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 [15] and to accurately calculate the 3D spatial distribution, components, and total core losses in power transformer stacked cores [16,17].

In addition, various studies [18-25] 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 [26].

The application of AI in loss evaluation is addressed in [27,28], where the no-load losses as a function of core design parameters are predicted by means of Artificial Neural Networks (ANNs). Georgilakis et al. [29,30] 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 [31], namely ANNs, Decision Trees (DTs) and GAs, in order to minimize iron losses during manufacturing of wound-core distribution transformers.

Accurate calculation of losses is also provided by the development of improved equivalent circuits, as proposed in [32], which is able to predict losses under any circumstances. Moreover, a final equivalent circuit of sufficient accuracy, combining both hysteresis and eddy current losses contributions is proposed in [33]. In

addition, Adly [34] presented an analytical investigation of the various transformer losses resulting from semi-rotating 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.

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 [35,36], based on data supplied from steel manufacturer. Mosses [37] reported results in which localised flux density and losses have been measured experimentally in model cores and compared with data obtained from a FEM analysis of the same core geometry. In addition, Girgis et al. [38] 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. [39] present a practical method for predicting the core losses in magnetic components for an arbitrary shape of the magnetizing current. Furthermore, Dolinar [40] determined a magnetically nonlinear iron core model of a three phase three-limb transformer and compared it with the classical saturated iron core model [41].

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 [42] described an apparatus capable of determining iron losses due to rotational flux. In addition, Findlay et al. [43] and Davies and Moses [44] 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. In addition, Marketos and Meydan [45] 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.

### 3.2 Load losses

Load losses result from load currents flowing through the transformer [5]. *Load losses* are also called *copper* or *wire* or *winding losses*. The two components of the load losses are the *IR losses* 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 [46], 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 [47], showing the need of eddy current analysis in electric devices.

The FEM analysis is quite commonly used for the eddy loss calculations [48,49]. Pern and Yeh [50] are engaged in the formulation of an A-V finite element method 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 [51]. Furthermore, the eddy current field due to both windings and heavy current leads in large power transformers is analyzed in [52] by using the improved T- $\Omega$  method.

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 [53] attempts to give a comprehensive explanation for the asymmetry in the loss values of the three phases during the load-loss test. A three-phase transformer has been analyzed using a comprehensive 3-D time-harmonic FEM analysis.

### 3.3 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.

The finite element method has been extensively employed in transformer leakage field evaluation. The first research attempts, presented over three decades ago, [54], focused on 2D modeling, due to the restricted performance abilities provided by the early development of personal computers. 2D 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 [55]. Although the 2D 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 three-dimensional (3D) solution becomes necessary [56-60]. The boundary-element method is another numerical technique extensively used for electromagnetic problems [61]. 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 [62,63].

To overcome the main numerical techniques drawback, namely the complexity of the required mesh size, especially in 3D configurations, alternative leakage field evaluation models have been proposed, with the use of a 3D reluctance network method [64], falling into the category of equivalent circuit representation. An alternative method of transformer leakage field calculation is based on simplified analytical formulas [65,66], a method often employed by transformer manufacturers in

order to simplify the time and complexity of the calculations required in automated design process.

Stochastic methods are also employed for solving problems of this category, as by Thilagar and Rao [67], who suggested an exact equivalent circuit model for the estimation of all impedance parameters of three winding transformers, with the use of GA. The suggested method also estimates geometrically a complex parameter, that is, mutual leakage between secondary and tertiary windings.

### 3.4 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, protective relay misoperation, and reduced power quality on the system [68]. 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 [69], where 2D 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 [70] and structural characteristics [71], the core material nonlinear characteristics [72] or using real-time measurements [73]. Artificial neural networks have also been employed for the computation of inrush current and forces [74].

### 3.5 Stresses and dynamic behavior under short circuits

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 are 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 is one of the major concerns during their design, since the ability to overcome the resulting stresses and currents for external or internal faults of a certain time duration 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, [75-80]. Equivalent circuit approaches are also employed, although their application is usually coupled to some

detailed calculation, often based to numerical method [81], in order to ensure better representation of the phenomena occurring during short-circuits.

### 3.6 Transformer noise

Transformers located near a residential area should have sound level as low as possible. The design and the manufacture of a transformer with low sound level require in-depth 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 equivalent circuit analysis [82,83]. Similar work is presented in [84]. Finally, a recently developed calculation scheme for the computer modelling of the load-controlled noise of oil-insulated three-phase power transformers is presented in [85]. This modelling scheme allows the precise and efficient computation of the coupled electromagnetic, mechanical and acoustic fields. The equations are solved using the FEM as well as the boundary element method (BEM).

### 3.7 Transformer 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 over-voltage and short-circuit currents.

Numerical methods are more scarcely applied for the simulation of the above phenomena, and are mainly used for the calculation of the transformer electric field [86]. On the other hand, the majority of research is based on equivalent circuit representation for transformer analysis under overvoltages, respective to their geometrical characteristics [87], their dynamic behavior [88], their frequency response characteristics [89] or the characteristics of the network where they are connected [90]. Other attempts to model the insulation structure of transformers and the quantitative analysis of its dielectric response are also encountered [91,92]. 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 [93].

### 3.8 Transformer 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 transformer at a fixed load. The design of the cooling system is based on the hot-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.

The finite difference method is proposed by Pierce [94] for hot-spot temperature prediction in dry-type transformers. 2D FEM thermal calculation is proposed in [95] for the calculation of core hot-spot temperature in power and distribution transformers. Most recent trends in thermal modeling employ coupled electromagnetic-thermal finite element models [96,97].

Appropriate equivalent circuits are developed in [98] for the core rise temperature calculation and power transformer thermal distribution [99-101]. In [102] and [103] the parameters of the proposed oil-immersed transformer thermal model derive with the use of genetic algorithms. Dynamic thermal models are also proposed in the literature [104-106], taking proper account of oil viscosity changes and loss variation with temperature.

Particle swarm method and neural networks are also encountered in the relevant research field [107,108].

Experimental investigation of thermal distribution of cast-resin and oil-filled transformers is carried out in [109] and [110], respectively. Experimental data are used for the improvement of analytical equations that predict thermal distribution of liquid filled transformers in [111].

Last but not least, in order to improve power transformer reliability, a special focus has been carried out on insulating materials and especially on insulating oils. The most commonly used liquid in power transformers is mineral oil due to its low price and its good properties [112]. However, the performance of mineral oil starts to be limited. Numerous activities have been initiated to try to improve the properties of mineral oil or to find other substitute liquids. Natural esters or vegetable oils have been used successfully as transformer dielectric coolants, alternatively to conventional mineral oils [113-117]. Their application offers some advantages, such as safety against a fire incident, environmental friendliness and improved transformer performance. Moreover, mixtures consisting of mineral oil and two other kinds of insulating liquids (namely silicon and synthetic ester oils) are investigated in [118,119]. Finally, the "retrofilling" application, in this case replacing mineral oil with natural esters, is also presented in [120], as a method to extend the remaining thermal life of an aging transformer.

### 3.9 Transformer DC bias

Direct Current (DC) 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 or the injection of DC current by one of the ground electrodes of a DC link [121]. Direct current flowing through the earthed neutrals of transformer windings causes a DC component in the

magnetising current. Owing to non-linearity, the waveform of this current is strongly distorted. The prediction and impact of this phenomenon has been studied with finite element method [122-124] and equivalent magnetic circuits [125,126].

### 3.10 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 [127-131]. They are also employed for oil-immersed distribution transformer monitoring in [132]. Furthermore, Stochastic Petri Nets are used for the simulation of the fault diagnosis process of oil-immersed transformers and the definition of the actions followed to repair the transformer [132]. Particle swarm method is used for winding deformation identification in [133]. Finally, fuzzy systems and expert systems are proposed in [135] and [136] for the gas analysis and insulation monitoring, respectively.

### 3.11 Recent trends in transformer technology

In the last decade, rapid changes and developments have been made in the field of the transformer design.

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 [137,138]. The core losses can be limited by insulating coatings [139], and various types of coatings have been developed for application to both fully processed and semiprocessed electrical steels. In addition, Matsuura et al. [140] presented long-term property reliability for iron-based amorphous alloy for use in oil-immersed transformer cores.

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 [141,142], while in [143] new perspectives of HTS transformer design are introduced. The development of technology based on liquid nitrogen at temperature up to 79°K has reduced the complexity and cost of the superconducting transformers [144,145]. A development of three-phase 100 kVA superconducting transformer with amorphous core has been reported in [146]. A high-

superconducting coil that simulated the inner secondary winding of a high-superconducting traction transformer is presented in [147,148]. Moreover, the magnetization losses in HTS pancake windings according to the operating temperature, is discussed in [149].

There is a considerable progress in the technology of gas immersed transformers in the last decade. Unlike the oil-immersed transformers, they have SF6 gas for the insulation and cooling purposes [150,151].

## 4. Transformer design optimization

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 3, 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.

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 [152]. Artificial Intelligence techniques have been extensively used in order to cope with the complex problem of transformer design optimization, such as genetic algorithms (GAs) that have been used for transformer cost minimization [153], performance optimization of cast-resin distribution transformers with stack core technology [154] or toroidal core transformers [155]. Neural network techniques are also employed as a means of design optimization as in [156] and [157], where they are used for winding material selection and prediction of transformer losses and reactance, respectively. Deterministic methods may also provide robust solutions to the transformer design optimization problem. In this context, the deterministic method of geometric programming has been proposed in [158] in order to deal with the design optimization problem of both low frequency and high frequency transformer. 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 [159] or certain performance parameters as the output power [160], the load loss minimization [161,162] or the no-load loss minimization [163].

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 [164]. An important part of the transformer cost optimization research is devoted to the *TOC* minimization, as follows. Distribution transformer *TOC* optimization is analysed in [165-168]. 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 [169,170].

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 [171,172] and [173,174], respectively.

## 5. Conclusion

In the present paper, an overview of the literature concerning transformer design has been undertaken, focusing on the progress realized in the past two decades. Relevant publications from international journals have been selected, covering a broad range of engineering methods and design considerations. 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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