Optimal Design Of Transformer : A Compressive Bibliographical Survey

Ajay Khatri¹, O.P. Rahi²

¹Department of Electrical Engineering
National Institute of Technology, Hamirpur, India
¹ajaynit2004@yahoo.com, ²oprahi2k@gmail.com

Abstract:
The complexity of transformer design demands reliable and rigorous solution methods. With the fast-paced changing technologies in the power industry, new references addressing new technologies are coming to the market. A survey of current research reveals the continued interest in application of advanced techniques for transformer design optimization. This paper gives a bibliographical survey and general backgrounds of research and developments in the field of transformer design and optimization for the past 38 years, based over 126 published articles, 58 transformer books. 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. The collected literature have been divided into many section, so that new researchers do not face any difficulty for obtaining literature particularly in the area of transformer design and optimization.

Keywords: Analytical Method, Artificial Intelligence, Equivalent Circuit Models, Experimental Models, Hybrid method, Numerical Techniques, Survey, Transformer Design Optimization.

I. INTRODUCTION

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, 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.

Despite the fact that the main 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 [126].

A. Manufacturing Cost Minimization

In optimum design of transformers, the main target is to minimize the manufacturing cost as well as operating 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 [126].


In a nutshell, it is clear that the transformer design optimization problem remains an active research area. In Sept 2009, Versele et al. [47] multiobjective optimal design of high frequency transformers using genetic algorithm. In Du et al. improved PSO algorithm and its application in optimal design for rectifier transformer [48].

B. Operating Cost Minimization

Apart from the transformer manufacturing cost, In1998, Kennedy described Energy Efficient Transformers another 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 [49].

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 [126].

An important part of the transformer cost optimization research is devoted to the TOC minimization, as follows. Distribution transformer TOC optimization is analyzed. In Apr. 1992, Baranowski, Edison and Hopkinson explained an alternative evaluation of distribution transformers to achieve the lowest TOC [50]. In 2002, Hulshorst and Groeman [51] explained energy saving in industrial distribution transformers. In Nov. 2003, Merritt and Chaitkin described no load versus load losses [52]. In Jul. 2005, Merritt and Chaitkin [53] presented one from menu A-one from menu B. In 2007, Georgilakis evaluated decision support system for evaluating transformer investments in the industrial sector [54]. 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. In Feb. 1981, Nickel and Braunstein [55] proposed distribution transformer loss evaluation: I—proposed. In Feb. 1981, Nickel and Braunstein proposed distribution transformer loss evaluation: II-load characteristics and system cost parameters [56]. Furthermore, energy losses of transformers throughout their life cycle increase significantly their operational costs, resulting in TOC values much higher than their purchase price. In general, transformers with the lowest purchase price are also the ones with the highest TOC. In 1998, McConnell [57] described increasing distribution transformer efficiency: Potential for energy savings. Moreover, the external environmental costs 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. In 2003, Brussels: directorate- general for research studied external costs: research results on socio-environmental damages due to electricity and transport [58]. In 2008, Amoiralis [125] explained energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost. Last decades, the impact of transformer environmental externalities and the contribution of losses to the greenhouse gas emissions generated by the global power generation mix. In 2004, Vesterdal and Svendsen [59] presented how should greenhouse gas permits be allocated in the EU?. In 2005, Targosz et al. [60] explained the potential for global energy savings from high energy efficiency distribution transformers. In 2007 Delarue, Lamberts, and D’haeseleer [61] evaluated Simulating greenhouse gas (GHG) allowance cost and GHG emission reduction in western europe. Furthermore, ways to promote the policy to encourage the use of efficient
transformers in the Spanish market are proposed. In 2007, Frau et al. [62] proposed Consider the true cost of transformer losses, where incentives to private users and electric utilities are introduced, changing Spanish losses regulation, and allowing utilities to participate in the emissions market. Moreover, an overview of options available to distribution transformer specifies, taking advantage of the efficiency and environmental benefits. In 2002, Goudie and Chatterton [63] explained environmental and life cycle considerations for distribution and small power transformer selection and specification. However, a methodology to quantify the impact of environmental externalities on transformer TOC has not yet been developed.

In Nov. 2010, Olivares-Galván et al. [64] Comparison of three-phase distribution transformer banks against three-phase distribution transformers. In 2011, Zhang et al. presented research of transformer optimal design modeling and intelligent algorithm [65].

II. 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 [126].

A. Harmonic Modeling

The research interest on harmonic load flow studies is continuously growing, due to the increase of nonlinear devices in power systems, and a number of different approaches have been proposed in the literature [126]. In April 1997, 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 [66]. Single and three-phase equivalent circuits taking into account the non linearity of the core are presented in Apr. 2004, by Pedra et al. [67]. 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 in Apr. 2006, Mohammed et al. [68]. In Apr. 1999, Chowdhury et al. presented [69] 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 non sinusoidal operation, capable of computing derating factors in Oct. 2008, by Masoum et al. [70]. In March 2009, Di Pasquale et al. [71] shielding effectiveness for a three-phase transformer at various harmonic frequencies. In April 2011, Deoka, and Waghmare, presented impact of power system harmonics on insulation failure of distribution transformer and its remedial measures [72].

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. In April 2005, Martinez and Mork presented a review of the existing models in [73], 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 Jul. 2005, by Martinez [74].

In this type of modeling, classical methods to determine transformer magnetic circuit and windings with frequency and time domain modeling techniques.

methods to solve the system of differential equation in state space, describing the transformer transient behavior in [89], while in Jan. 2008, 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 [90]. Frequency-response analysis is used in Jan. 2006, [91] to study the transient recovery voltage associated with power transformer terminal faults. In May 2007, 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 [92] and its results are exploited in Oct. 2006, by Abeywickrama et al. [93] for high-frequency modeling of power transformers. In Mar. 1991, Wilcox [94] explains the principles of modal analysis are presented, while in Mar. 2004, Song et al. [95] 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 Jan. 1991, Mohseni [96], a model is presented for a multi winding 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 Jul. 2006, DelVecchio [97] developed applications of a multiterminal transformer model using two winding leakage inductances. In Jul. 2008, [98] a multi terminal transformer model is developed for balanced and unbalanced load. A three-phase transformer dynamic model, providing a good compromise between accuracy and excessive complexity arising in dynamic simulations is presented in Oct. 1993, by Dolinar et al. [99], while in Jul. 2006, Koley et al. explained [100] 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 Jun. 2004, by Arunkumar et al. [101]. In Jul. 1989, Stuehm et al. and Mork develop five-legged wound-core transformer models in [103]. In Oct. 1999, Mork explained [103] Five-legged wound-core transformer model: derivation, parameters, implementation and evaluation, while in Jun. 2007, 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 [104]. In Jun. 2007, Mork et al. explained hybrid transformer model for transient simulation—Part II: laboratory measurements and benchmarking [105]. In Oct. 2008, [106], 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 Oct. 1998, Fujita et al. [107] experimental investigation of high frequency voltage oscillation in transformer windings. In Oct. 2003, Popov et al. explained Computation of very fast transient over voltages in transformer windings [108]. In Jun. 2007, Popov et al. [109] described analysis of very fast transients in layer-type transformer windings. In Jan. 2007, Fujita et al. [110] Influence of VFT on shell-type transformer. In Apr. 2008, Hosseini explained comparison of transformer detailed models for fast and very fast transient studies [111]. In Jan. 2000, Mombello and Moller present a model with accurate representation of winding losses, developed for the determination of maximal stresses during resonance phenomena within transformers [112], while in Apr. 2002; Mombello performs a deep analysis of the behavior of transformer winding impedances for high frequencies by analyzing the properties of inductance matrices in [113]. In Oct. 2002, Noda et al. [114], 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 An EC based on winding resonances computed by FEM is presented in Aug. 1988, by Leohold and Silvester [115] for the simulation of winding electromagnetic oscillations. In Apr. 2006, 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 [116], in Apr. 2007, Liu et al. [117], a work which is later expanded to single-phase transformers.

Experimental methods to define models for electromagnetic transient studies are also used, as in Jan. 2004, Gustavsen explained [118], 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 Jan. 2004, by Pedra et al. [119]. In Apr. 2004, Guasch et al. [120] effects of symmetrical voltage sags on three-phase three-legged transformers. In Apr. 2005, Pedra et al. [121] symmetrical and unsymmetrical voltage sag effects on three-phase transformers. In March 2009, Yang Yu et al. explained [122] a Circuit model in a wide frequency range for power transformer and analysis of its characteristics. In 2010, Lopez-Fernandez et al. [123] proposed modeling and insulation design methodology in power transformer under fast transients. In May 2011, Shipp et al. transformer failure due to circuit breaker induced switching [124].

III. 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. Highlighting a list of 58 books in the domain of transformers [126].


The paper presents exhaustive overviews of the transformer design optimization and compassing from introduction of transformer to latest state of art in transformer design. The paper based on many research articles published since last 40 years. In addition, various literatures available in the form of books has also been cited. Therefore, in nutshell.

IV. CONCLUSION

The paper presents exhaustive overviews of the transformer design optimization and compassing from introduction of transformer to latest state of art in transformer design. The paper based on many research articles published since last 40 years. In addition, various literatures available in the form of books has also been cited. Therefore, in nutshell.

V. REFERENCES


