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# Optimal Design Of Transformer : A Compressive Bibliographical Survey

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***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 May 1954, The first transformer design was made on computer, Williams and Abetti given how digital computers aid transformer designer [1]. In 1956, Williams, Abetti, and Magnusson described application of digital computers to transformer design [2]. In 1958, Sharpley and Oldfield given the digital computer applied to the design of large power transformers [3]. In 1959, Williams, Abetti, and Mason explained complete design of power transformers with a large size digital computer [4]. In Jun. 1967, Andersen [5] present optimum design of electrical machines. In Mar. 1970, Wu and Adams present [6] transformer design using time-sharing computer. In Jan. 1974, Odyssey given transformer design by computer [7]. Several design procedures for low-frequency and high-frequency transformers have appeared in the literature after the 70's. In Jul. 1977 ,Judd and Kressler [8] presented design optimization of small low-frequency power transformer .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 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. In Nov. 1986, Poloujadoff and Findlay presented a procedure for illustrating the effect variations of parameters on optimal transformers design [9]. In May 1990, Jewell described [10] transformer design in the undergraduate power engineering laboratory. In Jan. 1991, Andersen [11] 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. In May 1992, Grady *et al*. [12] 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, In Aug. 1994, Rubaai [13] explained computer aided instruction of power transformer design in the undergraduate power engineering class. In Jul. 1998, Hurley [14] presented optimized transformer design: inclusive of high-frequency effects for improved solution of the described problem. In 2008, Amoiralis explained energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost [3]. In oct.2008, Hernandez [15] presented object-oriented knowledge-based system for distribution transformer design. In oct.2010, Amoiralis [16] developed development of power transformer design and simulation methodology integrated in a software platform. In 2011, Amoiralis et al. developed a complete software package for transformer design optimization and economic evaluation analysis [17].

Transformer design optimization problem by using deterministic methods . In Sep. 1980, Wu and Lee [18] explained minimum weight EI core and pot core inductor and transformer designs and the main approaches deal with the cost minimization of specific components such as the magnetic material. In Sept. 1996 Pham *et al.* explained shape optimization of windings for minimum losses [19]. In 2002. Doulamis *et al* described [20] a synergetic neural network-genetic scheme for optimal transformer construction. In Oct. 2002, Doulamis and Doulamis presented [21] optimal distribution transformers assembly using an adaptable neural network-genetic algorithm scheme. In Nov. 2005, Jabr presented application of geometric programming to transformer design has been proposed in [22] in order to deal with the design optimization problem of both low frequency and high frequency transformers. In 2007, Georgilakis [23] given a heuristic solution to the transformer manufacturing cost optimization problem and 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. In 2008, Amoiralis [3] explained energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost. In June 2008, Amoiralis *et al.* [24] presented a parallel mixed integer programming-finite element method technique for global design optimization of power transformers. In 2008, Rao and Hasan described rectifier power transformer design by [25] intelligent optimization techniques. In Jan 2009, Georgilakis [26] explained recursive genetic algorithm-finite element method technique for the solution of transformer manufacturing cost minimization problem. In Mar. 2009, Amoiralis, *et al.* [27] presented global transformer optimization method using evolutionary design and numerical field computation. In June 2009, Olivares-Galva´n [28] presented selection of copper against aluminium windings for distribution transformers. In April 2011, Subramanian and Padma [29] presented optimal design of single phase transformer using bacterial foraging algorithm.

Apart from deterministic methods, artificial intelligence techniques have been extensively used in order to cope with the complex problem of transformer design optimization. In 2001, Hui *et al*. [30] presented application research based on improved genetic algorithm for optimum design of power transformers. In 2002, Geromel and Souza [31] given the applications of intelligent systems in power transformer design. In 2004, Tutkun and Moses explained design optimization of a typical strip-wound toroidal core using genetic algorithms [32]. In 2006, Elia explained [33] design of cast-resin distribution transformers by means of genetic algorithms. In Apr. 2007, Amoiralis *et al.* described artificial intelligence combined with hybrid FEM-BE techniques for global transformer optimization and neural network techniques are also employed as a means of design optimization as in [34], where they are used for winding material selection and prediction of transformer losses and reactance, respectively. 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. In 2009, Jingying Zhao given research on application of genetic algorithm in optimization design of transformer [35]. In 2009, Zhang *et al* described application of chaos genetic algorithm to transformer optimal design [36]. In June 2010 Firouzfar *et al.* described estimating the weight of main material for 63/20kV transformers with artificial neural network (ANN) [37]. In 2010, Yadav *et al.* cost analysis of transformer's main material weight with artificial neural network (ANN) [38]. In 2010, Georgilakis [39] proposed an innovative method combining genetic algorithm (GA) and finite element method (FEM) for the solution of TDO problem.

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, In Jul. 2000, Takahashi *et al.* [40] described optimal design of tank shield model of transformer. In Aug. 2001, Rizzo, Savini and Turowski explained [41] dependence of forces, eddy current and stray losses on screening in power transformers. In Jul. 2003, Olivares *et al.* [42] given reducing losses in distribution transformers. In 2005, Tsili [43] presented development of mixed finite element-boundary element numerical techniques for the design of power transformers. In May 2005, Tsili *et al.* presented geometry optimization of magnetic shunts in power transformers based on a particular hybrid finite-element boundary-element model and sensitivity analysis [44]. In April 2010, Rama Rao *et al.* [45] optimal parameters of rectifier power transformer by intelligent techniques. In aug.2010, Arjona presented [46] hybrid optimum design of a distribution transformer based on 2-D FE and a manufacturer design methodology.

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.

In Jan. 1993, 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 over voltages of the transformer are calculated from frequency response by Fourier transform [75]. Reduction techniques of linear and nonlinear lumped parameters models are proposed by in Apr. 1995, Gutierez *et al.* [76] and in Apr. 1995, Degeneff *et al.* presented nonlinear, lumped parameter transformer model reduction technique [77], respectively. In Jan. 1995, De Leon and Semlyen introduce a simple dynamic hysteresis loss model in [78] and the calculation of transformer EC elementary parameters (namely leakage inductance and capacitance) on a turn-to-turn basis in Jan. 1992, by Leon and Semlyen Jan. 1992,by Leon and Semlyen [79] which are used to derive a winding model suitable for transformer transients in Jan. 1992, [80]. Moreover, they investigate time domain modeling of eddy currents for electromagnetic transients study in Jan. 1993 ,[81] and in Aug. 1993, [82] propose techniques for time step reduction in electromagnetic transient simulation, while in Jan. 1994, Leon and Semlyen presented [83] complete transformer model for electromagnetic transients. In Apr. 1994, detailed modeling of eddy current effects for transformer transients [84]. In Aug.1994, Narang and Brierley presented topology based magnetic model for steady-state and transient studies for three-phase core type transformers [85]. In Apr. 1997, Chen and Venkata explained a three-phase three winding core-type transformer model for low-frequency transient studies [86]. In Apr. 1994, Papadias *et al.* present three-phase transformer models for the study of switching fast electromagnetic transients in [87]. Distributed equivalent magnetic and electric circuits are introduced in transformer transient analysis in Sep. 1994, by Haydock and Holland [88]. In Oct. 2005,Tokic *et al.* develop numerical 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. 2008, by Abeywickrama *et al*. [93] for high-frequency modeling of power transformers. In Mar. 1991, Wilcox [94] explained 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].

- Omer Mahmood Butt, asfand ali ,*Practical Transformer Design*, Lambert Academic Publishing, 2010.
- Slawomir Wiak, *Computational Methods for the Innovative Design of Electrical Devices*, Springer, 2010.
- Pavlos S. Georgilakis, *Spotlight on Modern Transformer Design*, Springer, 2009.
- Still Alfred, *Principles of Transformer Design*, BiblioLife, 2009.
- Alfred H. Avery ,*Auto-Transformer Design - A Practical Handbook for Manufacturers, Contractors and Wiremen*, Lightning Source Inc, 2009 - Technology & Engineering.
- Martin J. Heathcote, *J & P Transformer Book*, Newnes, 2007.
- H. M. Hobart ,*Design of Static Transformers*, Josephs Press, 2007.
- K B Raina, *Electrical Design Estimating And Costing*, New Age International, 2007.
- 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*, Mc- Graw-Hill, New York, 2005.
- S. V. Kulkarni, S. A. Khaparde, *Transformer Engineering Design & Practice*, Marcel Dekker, Inc., New York, 2004.
- M. Horning, J. Kelly, S. Myers, R. Stebbins, *Transformer Maintenance Guide, Third Edition*, Transformer Maintenance Institute, S. D. Myers Inc., 2004.
- Indrajit Dasgupta, *Design of Transformers*, Tata McGraw-Hill Publishing Co. Ltd., New Delhi, 2002.
- John J. Winders Jr., *Power Transformers Principles and Applications*, Marcel Dekker, Inc., New York, 2002.
- Robert M. Del Vecchio, Bertrand Poulin, Pierre T. Feghali, Dilip kumar M. Shah, Rajendra Ahuja, *Transformer Design Principles—With Application to Core-Form Power Transformers*, Gordon and Breach Science Publishers, Canada, 2001.
- Alexander Publications, editor, *Distribution Transformer Handbook*, Alexander Publications, Newport Beach, California, 2001.
- Axel Krämer, *On-Load Tap-Changers for Power Transformers, Operation Principles, Applications and Selection*, MR-Publication, Regensburg, Germany, 2000.
- Martin Heathcote, *J & P Transformer Book 12th Edition*, Butterworth-Heinemann Ltd. Great Britain, 1998.
- Barry W. Kennedy, *Energy Efficient Transformers*, Mc-Graw-Hill Companies, Inc., New York, 1998.
- Alfred Berutti, P.E., *Practical Guide to Applying, Installing and Maintaining Transformers*, Intertec Publishing Corporation, EC&M Books, Overland Park, Kansas, 1998.
- Stephen L. Herman, Donald E. Singleton, *Delmar's Standard Guide to Transformers*, Delmar Publishers, New York, 1996.
- Eric Lowden, *Practical Transformer Design Handbook 2nd Edition*, Tab Books Inc. Pennsylvania, 1989.
- H. P. Moser, V. Dahinden, *et al. Transformer board II*, H. AG, Rapperswil, Switzerland, 1987.
- K. Karsai, D. Kerenyi, L. Kiss, *Large Power Transformers*, (Studies in Electrical and Electronic Engineering, Vol. 25), Elsevier Co., New York, 1987.
- Bernard Hochart, editor, *Power Transformer Handbook*, Butterworths & Co. Ltd., London, 1987.
- A. W. Goldman, C. G. Pebler, Volume 2 *Power Transformers*, Electric Power Research Institute, Palo Alto, California, 1987.
- William M. Flanagan, *Handbook of Transformer Design & Applications—2nd Edition*, McGraw-Hill Book Co., New York, 1986.
- H. P. Moser, V. Dahinden, *et al.*, *Transformerboard*, H. AG, Rapperswil, Switzerland, 1979.
- R. Feinberg, editor, *Modern Power Transformer Practice*, Halsted Press, 1979.
- Colonel Wm. T. McLyman, *Transformer and Inductor Design Handbook*, Marcel Dekker, Inc., New York, 1978.
- Kenneth L. Gebert, Kenneth R. Edwards, *Transformers Principles and Applications 2nd Edition*, American Technical Publishers, Inc., Illinois, 1974.
- Power Transformer Department, L. F. Blume, A. Boyajian, *Transformer Connections*, General Electric, Schnectady, New York, 1970.
- Petter I. Fergestad, *Transient Oscillations in Transformer Windings*, Naper Boktrykkeri, Kragero, Norway, 1972.
- M. Waters, *The Short-Circuit Strength of Power Transformers*, Macdonald & Co., London, 1966.
- R. L. Bean, N. Chacken, Jr, H. R. Moore, E. C. Wentz, *Transformers for the Electric Power Industry*, McGraw- Hill Book Co., New York, 1959.
- L. F. Blume, A. Boyajian, G. Camilli, T. C. Lennox, S. Minneci, V. M. Montsinger, *Transformer Engineering— 2nd edition*, John Wiley & Sons, Inc., New York, 1951.
- J. B. Gibbs, *Transformer Principles & Practice*, McGraw-Hill Book Co., New York, 1950.
- Eric E. Wild, *Transformers*, Blackie & Son, 2nd Edition, London, 1948.

- Carl H. Dunlap, W. A. Siefert, Frank E. Austin, *Transformers Principles and Applications*, American Technical Society, Chicago, 1947.
- W. C. Sealey, *Transformers Theory and Construction*, International Textbook Co., Scranton, Pennsylvania, 1946.
- Members of the Staff of the Department of Electrical Engineering Massachusetts Institute of Technology, *Magnetic Circuits and Transformers*, John Wiley & Sons, Inc., New York, 1943.
- J. Rosslyn, *Power Transformers*, Chemical Publishing Co. Inc., New York, 1941.
- L. H. Hill, *Transformers 149C*, International Textbook Co., Scranton, Pennsylvania, 1937.
- David D. Coffin, *Transformers 149B*, International Textbook Co., Scranton, Pennsylvania, 1935
- G. Camilli, *the Testing of Transformers*, General Electric Co., 1929–1930.
- William T. Taylor, *Electricity Supply Transformer Systems and Their Operation*, Charles Griffin and Co. Ltd., London, 1929.
- Emerson G. Reed, *Transformer Construction and Operation*, McGraw-Hill Co., Inc., New York, 1928
- Emerson G. Reed, *Essentials of Transformer Practice—Theory, Design and Operation*, D Van Nostrand Co., Inc., New York, 1927.
- Alfred Still, *Principals of Transformer Design*, John Wiley & Sons, Inc., New York, 1919.
- William T. Taylor, *Transformer Practice, Manufacture, Assembling, Connections, Operation and Testing*, McGraw-Hill Book Co., Inc. New York, 1913.
- Frederick Bedell, *the Principals of the Transformer*, The Macmillian Co., New York, 1896.
- Fleming J. A., *The Alternate Current Transformer in Theory and Practice, Volume 1, The Induction of Electric Currents*, New Edition, The Electrician Printing and Publishing Co. Ltd., London, 1896.
- Fleming J. A., *The Alternate Current Transformer in Theory and Practice, Volume I1, The Utilization of Induced Currents*, New Edition, The Electrician Printing and Publishing Co. Ltd., London, 1892.
- Caryl D. Haskin, *Transformers*, Bubier Publishing Co., Lynn, Mass., 1892.
- Friedrich Uppenborn, *History of the Transformer*, original translated from German, E & F.N. Spon, New York, 1889. (Reprint available from Kessinger Publishing, Montana.)

## IV. CONCLUSION

The paper presents exhuastic 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

[1] S. B. Williams, P. A. Abetti, and E. F. Magnesson, "How digital computers aid transformer designer," in *Gen. Elect. Rev.*, vol. 58, pp. 24–25 May 1955.

[2] S. B.Williams, P. A. Abetti, and E. F. Magnusson, "Application of digital computers to transformer design," *AIEE Trans. Power App. Syst.*, vol. 75, pt. III, pp. 728–735, 1956.

[3] W. Sharpley and J. V. Oldfield, "The digital computer applied to the design of large power transformers," *Proc. Inst. Elect. Eng.*, vol. 105, pp. 112–125, 1958.

[4] S. B. Williams, P. A. Abetti, and H. J. Mason, "Complete design of power transformers with a large size digital computer," *AIEE Trans. Power App. Syst.*, vol. 77, pt. III, pp. 1282–1291, 1959.

[5] O. W. Andersen, "Optimum design of electrical machines," *IEEE Trans. Power App. Sys.*, vol. PAS-86, no. 6, pp. 707–711, Jun. 1967.

[6] H. H.Wu and R. Adams, "Transformer design using time-sharing computer," *IEEE Trans. Magn.*, vol. MAG-6, no. 1, p. 67, Mar. 1970.

[7] P. Odessey, "Transformer design by computer," *IEEE Trans. Manuf. Technol.*, vol. 3, no. 1, pp. 1–17, Jan. 1974.

[8] F. F. Judd and D. R. Kressler, "Design optimization of small low-frequency power transformer," *IEEE Trans. Magn.*, vol. MAG-13, no. 4, pp. 1058–1069, Jul. 1977.

[9] M. Poloujadoff and R. D. Findlay, "A procedure for illustrating the effect variations of parameters on optimal transformers design," *IEEE Trans. Power Syst.*, vol. PWRS-1, no. 4, pp. 202–205, Nov. 1986.

[10] W. T. Jewell, "Transformer design in the undergraduate power engineering laboratory," *IEEE Trans. Power Sys.*, vol. 5, no. 2, pp. 499–505, May 1990.

[11] O. W. Andersen, "Optimized design of electric power equipment," *IEEE Comput. Appl. Power*, vol. 4, no. 1, pp. 11–15, Jan. 1991.

[12] W. M. Grady, R. Chan, M. J. Samotyj, R. J. Ferraro, and J. L. Bierschenk, "A PC-based computer program for teaching the design and analysis of dry-type transformers," *IEEE Trans. Power Syst.*, vol. 7, no. 2, pp. 709–717, May 1992.

[13] A. Rubaai, "Computer aided instruction of power transformer design in the undergraduate power engineering class," *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp. 1174–1181, Aug. 1994.

[14] W. G. Hurley, W. H.Wolfle, and J. G. Breslin, "Optimized transformer design: Inclusive of high-frequency effects," *IEEE Trans. Power Electron.*, vol. 13, no. 4, pp. 651–659, Jul. 1998.

[15] C. Hernandez, M. A. Arjona, and S.-H. Dong, "Object-oriented knowledge- based system for distribution transformer design," *IEEE Trans. Magn.*, vol. 44, no. 10, pp. 2332–2337, Oct. 2008.

[16] Eleftherios I. Amoiralis1, Marina A. Tsili, Antonios G. Kladas, "Development of power transformer design and simulation methodology integrated in a software platform", ARWtr,2010,pp 1-6.

[17] Eleftherios I. Amoiralis, Pavlos S. Georgilakis , Marina A. Tsili, Antonios G. Kladas and Athanassios T. Souflaris, "A complete software package for transformer design optimization and economic evaluation analysis", *Materials Science Forum* ,Vol. 670,pp 535-546,2011.

[18] C. J. Wu and F. C. Lee, "Minimum weight EI core and pot core inductor and transformer designs," *IEEE Trans. Magn.*, vol. 16, no. 5, pp. 755–757, Sep. 1980.

[19] T. H. Pham, S. J. Salon, and S. R. H. Hoole, "Shape optimization of windings for minimum losses," *IEEE Trans. Magn.*, vol. 32, no. 5, pp. 4287–4289, Sept. 1996.

[20] N. D. Doulamis, A. D. Doulamis, P. S. Georgilakis, S. D. Kollias, and N. D. Hatziargyriou, "A synergetic neural network-genetic scheme for optimal transformer construction," *Integr. Comput.-Aided Eng.*, vol. 9, pp. 37–56, 2002.

[21] N. D. Doulamis and A. D. Doulamis, "Optimal distribution transformers assembly using an adaptable neural network-genetic algorithm scheme," in *Proc. IEEE Int. Conf. Systems, Man Cybernetics*, Oct. 2002, vol. 5, pp. 6.

[22] R. A. Jabr, "Application of geometric programming to transformer design," IEEE Trans. Magn., vol. 41, no. 11, pp. 4261–4269, Nov. 2005.

[23] P. S. Georgilakis, M. A. Tsili, and A. T. Souflaris, "A heuristic solution to the transformer manufacturing cost optimization problem," J. Mat.Process. Technol., vol. 181, pp. 260–266, 2007.

[24] Eleftherios I. Amoiralis1, Marina A. Tsili2, Pavlos S. Georgilakis1, Antonios G. Kladas2, and Athanassios T. SouflarisA , "Parallel Mixed Integer Programming-Finite Element Method Technique for Global Design Optimization of Power Transformers", *IEEE Trans. Magn.*, VOL. 44, NO. 6,pp 1022 -1025, JUNE 2008.

[25] K.S Rama Rao and Khairul Nisak Md Hasan, "Rectifier Power Transformer Design by Intelligent Optimization Techniques", *IEEE Electrical Power & Energy Conference*, 2008.

[26] P.S. Georgilakis,"Recursive genetic algorithm-finite element method technique for the solution of transformer manufacturing cost minimization problem", *IET Electr. Power Appl.*, Vol. 3, pp. 514–519,2009.

[27] E. I. Amoiralis, P. S. Georgilakis, M. A. Tsili, and A. G. Kladas, "Global transformer optimization method using evolutionary design and numerical field computation," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1720–1723, Mar. 2009.

[28] J.C. Olivares-Galva´n ,F. de Leo´n ,P.S. Georgilakis ,R. Escarela-Pe´rez, "Selection of copper against aluminium windings for distribution transformers", *IET Electr. Power* Vol. 4, pp. 474–485 ,Appl., 2010,.

[29] S.Subramanian, S.Padma, "optimal design of single phase transformer using bacterial forgaging algorithm", *IJEST*, Vol. 3, No. 4,pp 267-2684,April 2011.

[30] L. Hui, H. Li, H. Bei, and Y. Shunchang, "Application research based on improved genetic algorithm for optimum design of power transformers," in *Proc. 5th Int. Conf. Electrical Machines and Systems*, vol. 1, pp. 242–245, 2001.

[31] L. H. Geromel and C. R. Souza, "The applications of intelligent systems in power transformer design," in *Proc. IEEE Canadian Conf. Electrical and Computer Engineering*, vol. 1, pp. 285–290,2002.

[32] N. Tutkun and A. Moses, "Design optimization of a typical strip-wound toroidal core using genetic algorithms," *J. Magn. Magn. Mater.*, vol. 277, no. 1–2, pp. 216–220, 2004.

[33] S. Elia, G. Fabbri, E. Nistico, and E. Santini, "Design of cast-resin distribution transformers by means of genetic algorithms," in *Proc. Int. Symp. Power Electronics, Electrical Drives, Automation and Motion*, 2006, pp. 1473–1477.

[34] E. I. Amoiralis, P. S. Georgilakis, T. D. Kefalas, M. A. Tsili, and A. G. Kladas, "Artificial intelligence combined with hybrid FEM-BE techniques for global transformer optimization," *IEEE Trans. Magn.*, vol. 43, no. 4, pp. 1633–1636, Apr. 2007.

[35] Jingying Zhao, Fang Yao, Haitao Wang, Yanzhi Mi, Yabin Wang, "Research on Application of Genetic Algorithm in Optimization Design of Transformer", *DRPT*,pp,955-958, july 2011.

[36] Shuang Zhang, Qinghe Hu, Xingwei Wang, Zhiliang Zhu, "Application of Chaos Genetic Algorithm to Transformer Optimal Design", *International Workshop on Chaos-Fractals Theories and Applications*,pp 108-111, 2009.

[37] Mohammad Firouzfar, Peyman Salah, Seyed Siavash Karimi Madahi, "Estimating the Weight of Main Material for 63/20kV Transformers with Artificial Neural Network (ANN)", *PEOCO*, pp 358-362, June 2010.

[38] Amit Kr. Yadav,Akhilesh Singh , Hasmat Malik,Abdul Azeem ,"Cost Analysis of Transformer's Main Material Weight with Artificial Neural Network (ANN)", *International Conference on Communication Systems and Network Technologies*, 2011.

[39] P. Georgilakis , "An innovative method combining genetic algorithm (GA) and finite element method (FEM) for the solution of TDO problem", 2010,

[40] N. Takahashi, T. Kitamura, M. Horii, and J. Takehara, "Optimal design of tank shield model of transformer," *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 1089–1093, Jul. 2000.

[41] M. Rizzo, A. Savini, and J. Turowski, "Dependence of forces, eddy current and stray losses on screening in power transformers," in *Proc. 5th Int. Conf. Electrical Machines and Systems*, vol. 1, pp. 182–185, Aug. 2001.

[42] J. C. Olivares, Y. L. Jose, M. Canedo, R. Escarela-Pérez, J. Driesen, and P. Moreno, "Reducing losses in distribution transformers," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 821–826, Jul. 2003.

[43] Tsili ," development of mixed finite element-boundary element numerical techniques for the design of power transformers", 2005.

[44] M. A. Tsili, A. G. Kladas, P. S. Georgilakis, A. T. Souflaris, and D. G. Paparigas, "Geometry optimization of magnetic shunts in power transformers based on a particular hybrid finite-element boundary-element model and sensitivity analysis," *IEEE Trans. Magn.*, vol. 41, no. 5, pp. 1776–1779, May 2005.

[45] K. S. Rama Rao, K. N. Md Hasan and M. N. Karsiti, "Optimal Parameters of Rectifier Power Transformer by Intelligent Techniques", *OJEEE*,Vol. (1) ,No. (1), pp 15-19.

[46] M. A. Arjona, C. Hernandez, and M. Cisneros-Gonzalez , "Hybrid Optimum Design of a Distribution Transformer Based on 2-D FE and a Manufacturer Design Methodology", *IEEE Trans. Magn.*, VOL. 46, NO. 8, pp 2864-2867, AUGUST 2010.

[47] Versele, C.Deblecker, O.Lobry, "Multiobjective Optimal Design of High Frequency Transformers Using Genetic Algorithm",*EPE,* pp 1-10,Sept 2009.

[48] Jiang Du, Peng Li, Guowei Wu, Huizhen Bail, Juhua Shen, "Improved PSO Algorithm and Its Application in Optimal Design for Rectifier Transformer", pp 605-608.

[49] B. Kennedy, *Energy Efficient Transformers*. New York: Mc- Graw-Hill, 1998.

[50] J. F. Baranowski, T. A. Edison, and P. J. Hopkinson, "An alternative evaluation of distribution transformers to achieve the lowest TOC," *IEEE Trans. Power Del.*, vol. 7, no. 2, pp. 614–619, Apr. 1992.

[51] W. T. J. Hulshorst and J. F. Groeman, "Energy saving in industrial distribution transformers," 2002, KEMA Rep..

[52] S. Y. Merritt and S. D. Chaitkin, "No load versus load losses," *IEEE Ind. Appl. Mag.*, vol. 9, no. 6, pp. 21–28, Nov. 2003.

[53] S. Y. Merritt and S. D. Chaitkin, "One from menu A—One from menu B," *IEEE Ind. Appl. Mag.*, vol. 11, no. 4, pp. 66–71, Jul. 2005.

[54] P. S. Georgilakis, "Decision support system for evaluating transformer investments in the industrial sector," *J. Mat. Process. Technol.*, vol. 181, pp. 307–312, 2007.

[55] D. L. Nickel and H. R. Braunstein, "Distribution transformer loss evaluation: I—Proposed techniques," *IEEE Trans. Power App. Sys.*, vol. PAS-100, no. 2, pp. 788–797, Feb. 1981.

[56] D. L. Nickel and H. R. Braunstein, "Distribution transformer loss evaluation: II-Load characteristics and system cost parameters," *IEEE Trans. Power App. Syst.*, vol. 100, no. 2, pp. 798–811, Feb. 1981.

[57] B. W. McConnell, "Increasing distribution transformer efficiency: Potential for energy savings," *Proc. IEEE Power Eng. Rev.*, vol. 18, no. 7, pp. 8–10, 1998.

[58]"External costs: Research results on socio-environmental damages due to electricity and transport, 2003, Eur. Comm., 2003, Brussels: Directorate-General for Research, Study 20198.

[59] M. Vesterdal and G. T. Svendsen, "How should greenhouse gas permits be allocated in the EU?," *Energy Policy*, vol. 32, pp. 961–968, 2004.

[60] R. Targosz, R. Belmans, J. Declercq, H. De Keulenaer, K. Furuya, M. Karmarkar, M. Martinez, M. McDermott, and I. Pinkiewicz, "The potential for global energy savings from high energy efficiency distribution transformers," 2005, *Leonardo Energy, Eur. Copper Inst*.

[61] E. Delarue, H. Lamberts, and W. D'haeseleer, "Simulating greenhouse gas (GHG) allowance cost and GHG emission reduction in Western Europe," *Energy*, vol. 32, pp. 1299–1309, 2007.

[62] J. Frau, J. Gutierrez, and A. Ramis, "Consider the true cost of transformer losses," *Transm. Distrib. World*, vol. 1, pp. 50–55, 2007.

[63] J. L. Goudie and W. J. Chatterton, "Environmental and life cycle considerations for distribution and small power transformer selection and specification," *Proc. IEEE Int. Symp. Electrical Insulation*, 2002, pp. 354–358.

[64] Juan C. Olivares-Galván, Pavlos S. Georgilakis, Ernesto Vázquez-Martínez, Jesús A. Mendieta-Antúnez, "Comparison of Three-Phase Distribution Transformer Banks Against Three-Phase Distribution Transformers",*Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion*, November 2010, pp 1-6.

[65] Shuang Zhang, Qinghe Hu, Xingwei Wang, Dingwei Wang, "Research of Transformer Optimal Design Modeling and Intelligent Algorithm", *CCDC*, pp 213-218,2011.

[66] T. Stensland, E. F. Fuchs, W. M. Grady, and M. T. Doyle, "Modeling of magnetizing and core-loss currents in single-phase transformers with voltage harmonics for use in power flow," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 768–774, Apr. 1997.

[67] J. Pedra, F. Córcoles, L. Sainz, and R. López, "Harmonic nonlinear transformer modeling," *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 884–890, Apr. 2004.

[68] O. A. Mohammed, N. Y. Abed, and S. Liu, "Investigation of the harmonic behavior of three phase transformer under nonsinusoidal operation using finite element and wavelet packets," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 967–970, Apr. 2006.

[69] A. H. Chowdhury, W. M. Grady, and E. F. Fuchs, "An investigation of the harmonic characteristics of transformer excitation current under non sinusoidal supply voltage," *IEEE Trans. Power Del.*, vol. 14, no. 2, pp. 450–458, Apr. 1999.

[70] M. A. S. Masoum, P. S.Moses, and A. S. Masoum, "Derating of asymmetric three-phase transformers serving unbalanced nonlinear loads," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2033–2041, Oct. 2008.

[71] A. Di Pasquale G. Antonini A. Orlandi "Shielding effectiveness for a three-phase transformer at various harmonic frequencies*", IET Sci. Meas. Technol.*, Vol. 3, Iss. 2, pp. 175–183,2009.

[72] Sanjay A. Deoka, Dr. Laxman M. Waghmare, "Impact of Power System Harmonics on Insulation Failure of Distribution Transformer and its Remedial Measures",*ICECT*,vol no.3,pp 136-140, April 2011.

[73] J. A. Martinez and B. A. Mork, "Transformer modeling for low- and mid-frequency transients—A review," *IEEE Trans. Power Del.*, vol. 20, no. 2, pt. 2, pp. 1625–1632, Apr. 2005.

[74] J. A. Martinez, R. Walling, B. A. Mork, J. Martin-Arnedo, and D. Durbak, "Parameter determ. for modeling system transients— Part III: Transf.," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 2051–2062, 2005.

[75] V. Woivre, J. P. Arthaud, A. Ahmad, and N. Burais, "Transient overvoltage study and model for shell-type power transformers," *IEEE Trans. Power Del.*, vol. 8, no. 1, pp. 212–222, Jan. 1993.

[76] M. Gutierrez and R. C. Degeneff, "Linear, lumped parameter transformer model reduction technique," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 853–861, Apr. 1995.

[77] R. C. Degeneff, M. Gutierrez, and M. Vakilian, "Nonlinear, lumped parameter transformer model reduction technique," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp. 862–868, Apr. 1995.

[78] F. de Leon and A. Semlyen, "A simple representation of dynamic hysteresis losses in power transformers," *IEEE Trans. Power Del.*, vol. 10, no. 1, pp. 315–321, Jan. 1995.

[79] F. de Leon and A. Semlyen, "Efficient calculation of elementary parameters of transformers," *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 376–383, Jan. 1992.

[80] F. de Leon and A. Semlyen, "Reduced order model for transformer transients," *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 361–369, Jan. 1992.

[81] F. de Leon and A. Semlyen, "Time domain modelling of eddy current effects for transformer transients," *IEEE Trans. Power Del.*, vol. 8, no. 1, pp. 271–279, Jan. 1993.

[82] F. de Leon and A. Semlyen, "Comput. of electro-magnetic transients using dual or multiple time steps," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 1274–1281, 1993.

[83] F. de Leon and A. Semlyen, "Complete transformer model for electromagnetic transients," *IEEE Trans. Power Del.*, vol. 9, no. 1, pp. 231–239, Jan. 1994.

[84] F. de Leon and A. Semlyen, "Detailed modeling of eddy current effects for transformer transients," *IEEE Trans. Power Del.*, vol. 9, no. 2, pp. 1143–1150, Apr. 1994.

[85] A. Narang and R. H. Brierley, "Topology based magnetic model for steady-state and transient studies for three-phase core type transformers," *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp. 1337–1349, Aug. 1994.

[86] X. Chen and S. S. Venkata, "A three-phase three-winding core-type transformer model for low-frequency transient studies," *IEEE Trans. Power Del.*, vol. 12, no. 2, pp. 775–782, Apr. 1997.

[87] B. C. Papadias, N. D. Hatziargyriou, J. A. Bakopoulos, and J. M. Prousalidis, "Three phase transformer modelling for fast electromagnetic transient studies," *IEEE Trans. Power Del.*, vol. 9, no. 2, pp. 1151–1159, Apr. 1994.

[88] L. Haydock and S. A. Holland, "Transient analysis of power transformers using magnetic and equivalent circuits," *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 2996–2999, Sep. 1994.

[89] A. Tokic, V. Madzarevic, and I. Uglesic, "Numerical calculations of three-phase transformer transients," *IEEE Trans. Power Del.*, vol. 20, no. 4, pp. 2493–2500, Oct. 2005.

[90] A. Tokic and I. Uglesic, "Elimination of overshooting effects and suppression of numerical oscillations in transformer transient calculations," *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 243–251, Jan. 2008.

[91] W. Hribernik, L. Graber, and J. H. Brunke, "Inherent transient recovery voltage of power transformers—A model-based determination procedure," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 129–134, Jan. 2006.

[92] K. G. N. B. Abeywickrama, A. D. Podoltsev, Y. V. Serdyuk, and S. M. Gubanski, "Computation of parameters of power transformer windings for use in frequency response analysis," *IEEE Trans. Magn.*, vol. 43, no. 5, pp. 1983–1990, May 2007.

[93] N. Abeywickrama, Y. V. Serdyuk, and S. M. Gubanski, "High-frequency modeling of power transformers for use in frequency response analysis (FRA)," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2042–2049, Oct. 2008.

[94] D. J. Wilcox, "Theory of transformer modelling using modal analysis," *Proc. Inst. Elect. Eng., Gen. Transm. Distrib.*, vol. 138, no. 2, pp. 121–128, Mar. 1991.

[95] S. Song, H. S. Kim, T. K. Chung, and S. Y. Hahn, "Modal analysis for the transient internal voltage of a transformer," *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 581–584, Mar. 2004.

[96] H. Mohseni, "Multi-winding multi-phase transformer model with saturable core," *IEEE Trans. Power Del.*, vol. 6, no. 1, pp. 166–173, Jan. 1991.

[97] R. M. DelVecchio, "Applications of a multiterminal transformer model using two winding leakage inductances," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1300–1308, Jul. 2006.

[98] R. M. D. Vecchio, "Multiterminal three phase transformer model with balanced or unbalanced loading," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1439–1447, Jul. 2008.

[99] D. Dolinar, J. Pihler, and B. Grcar, "Dynamic model of a three-phase power transformer," *IEEE Trans. Power Del.*, vol. 8, no. 4, pp. 1811–1819, Oct. 1993.

[100] C. Koley, P. Purkait, and S. Chakravorti, "Time-frequency representation of resistance for modeling of transformer winding under impulse test," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1367–1374, Jul, 2006.

[101] S. Arunkumar, V. Sandeep, S. Shankar, M. Gopalakrishnan, K. Udayakumar, and V. Jayashankar, "Impulse testing of power transformers—A model reference approach," *Proc. Inst. Elect. Eng., Sci. Meas. Technol.*, vol. 151, no. 1, pp. 25–30, Jun. 2004.

[102] D. L. Stuehm, B. A. Mork, and D. D. Mairs, "Five-legged core transformer equivalent circuit," *IEEE Trans. Power Del.*, vol. 4, no. 3, pp. 1786–1793, Jul. 1989.

[103] B. A. Mork, "Five-legged wound-core transformer model: Derivation, parameters, implementation and evaluation," *IEEE Trans. Power Del.*, vol. 14, no. 4, pp. 1519–1526, Oct. 1999.

[104] B. A. Mork, F. Gonzalez, D. Ishchenko, D. L. Stuehm, and J. Mitra, "Hybrid transformer model for transient simulation—Part I: Development and parameters," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 248–255, Jun. 2007.

[105] B. A. Mork, F. Gonzalez, D. Ishchenko, D. L. Stuehm, and J. Mitra, "Hybrid transformer model for transient simulation—Part II: Laboratory measurements and benchmarking," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 256–262, Jun. 2007.

[106] B. Mork, D. Ishchenko, F. Gonzalez, and S. D. Cho, "Parameter estimation methods for five-limb magnetic core model," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2025–2032, Oct. 2008.

[107] S. Fujita, N. Hosokawa, and Y. Shibuya, "Experimental investigation of high frequency voltage oscillation in transformer windings," *IEEE Trans. Power Del.*, vol. 13, no. 4, pp. 1201–1207, Oct. 1998.

[108] M. Popov, L. van der Sluis, G. C. Paap, and H. De Herdt, "Computation of very fast transient overvoltages in transformer windings," *IEEE Trans. Power Del.*, vol. 18, no. 4, pp. 1268–1274, Oct. 2003.

[109] M. Popov, L. van der Sluis, R. Peter, P. Smeets, and J. L. Roldan, "Analysis of very fast transients in layer-type transformer windings," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 238–247, Jun. 2007.

[110] S. Fujita, Y. Shibuya, and M. Ishii, “Influence of VFT on shell-type transformer,” *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 217–222, Jan. 2007.

[111] S. M. H. Hosseini, M. Vakilian, and G. B. Gharehpetian, “Comparison of transformer detailed models for fast and very fast transient studies,” *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 733–741, Apr. 2008.

[112] E. E. Mombello and K. Möller, “New power transformer model for the calculation of electromagnetic resonant transient phenomena including frequency-dependent losses,” *IEEE Trans. Power Del.*, vol. 15, no. 1, pp. 167–174, Jan. 2000.

[113] E. E. Mombello, “Impedances for the calculation of electromagnetic transients within transformers,” *IEEE Trans. Power Del.*, vol. 17, no. 2, pp. 479–488, Apr. 2002.

[114] T. Noda, H. Nakamoto, and S.Yokoyama, “Accurate modeling of coretype distribution transformers for electromagnetic transient studies,” *IEEE Trans. Power Del.*, vol. 17, no. 4, pp. 969–976, Oct. 2002.

[115] J. Leohold and P. P. Silvester, “Calculation of transformer winding resonances by a specialized finite element method employing substructures,” *IEEE Trans. Power Syst.*, vol. 3, no. 3, pp. 1385–1389, Aug. 1988.

[116] O. A. Mohammed, Z. Liu, S. Liu, and N. Y. Abed, “Finite-elementbased nonlinear physical model of iron-core transformers for dynamic simulations,” *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 1027–1030, Apr. 2006.

[117] Z. Liu, S. Liu, and O. A. Mohammed, “A practical method for building the FE-based phase variable model of single phase transformers for dynamic simulations,” *IEEE Trans. Magn.*, vol. 43, no. 4, pp. 1761–1764, Apr. 2007.

[118] B. Gustavsen, “Wide band modeling of power transformers,” *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 414–422, Jan. 2004.

[119] J. Pedra, L. Sainz, F. Córcoles, R. López, and M. Salichs, “PSpice computer model of a nonlinear three-phase three-legged transformer,” *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 200–207, Jan. 2004.

[120] L. Guasch, F. Corcoles, J. Pedra, and L. Sainz, “Effects of symmetrical voltage sags on three-phase three-legged transformers,” *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 875–883, Apr. 2004.

[121] J. Pedra, L. Sainz, F. Corcoles, and L. Guasch, “Symmetrical and unsymmetrical voltage sag effects on three-phase transformers,” *IEEE Trans. Power Del.*, vol. 20, no. 2, pt. 2, pp. 1683–1691, Apr. 2005.

[122]Yang Yu ; Wang Zanji ; Shao Chong, “A Circuit Model in a Wide Frequency Range for Power Transformer and Analysis of Its characteristics”, APPEEC, march 2009,pp 1-5.

[123] Xose. M. Lopez-Fernandez, C. Alvarez-Mariño, D. Couto, R. Lopes, A. Jacomo-Ramos, “Modeling and Insulation Design Methodology in Power Transformer under Fast Transients”,*ICEM* ,2010

[124] David D. Shipp, Thomas J. Dionise, Visuth Lorch, Bill G MacFarlane, “transformer failures due to circuit breaker induced swithing transients”,*I&CPS*, 2011,pp 1-10.

[125] E. I. Amoiralis, “Energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost” (in Greek) Ph.D. dissertation, Tech. Univ. Crete, Greece, 2008. [Online]. Available: http://www.library. tuc.gr/artemis/PD2009-0001/PD2009-0001.pdf.

[126] Eleftherios I. Amoiralis, Marina A. Tsili and Antonios G. Kladas, “Transformer Design and Optimization: A Literature Survey”, *IEEE Trans. Power Del.*, vol. 19, no. 1, pp 1999-2024,Oct. 2009.