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A REVIEW OF INTELLIGENT BASED OPTIMIZATION TECHNIQUES IN POWER TRANSFORMER DESIGN

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ABSTRACT

One of the major components of power system which reliability depends on is the transformer which plays major role in power generation, transmission and distribution system. The voltage transformation of any transformer is dependent on the complexity of the design. However, with the fast-paced changing technologies in the power industry, new references addressing new technologies that satisfy constraints imposed on international standards, low weight, small size and good performances for economic viability are coming to the market. Current research of transformer design reveals the continued interest in the use of intelligent techniques for transformer design optimization. This paper gives a bibliographical study and general backgrounds of research and developments in the field of transformer design and optimization using intelligent based techniques for the past 42 years, based on over 80 published articles. The benefit of this work is to provide reference point for educational development on recent published research in this field and stimulate further research interests.

1. INTRODUCTION

A transformer has been defined by ANSI/IEEE [1] as a static electric device consisting of two or more windings, with or without magnetic core, for producing mutual coupling between electric circuits. As an electrical machine, transformers are vital links in power system which has made possible power generated at lower voltage to be transmitted over long distances at higher voltage and subsequently reduced to smaller voltage at the point of electric power utilization [2]. This unique function of transformers in power system network in most times results to its failure in power supply that requires expensive repairs.

Transformer manufacturers' therefore uses cost optimization techniques at design phase to minimize material costs and satisfy utility loss evaluation requirement. The difficulty in achieving optimum balance between transformer cost and performance is herculean in nature, and techniques employed for these solution must be able to deal with design considerations, so as to provide a design optimum, while remaining cost-effective and flexible. Research associated with intelligent based optimization is therefore more restricted involving different mathematical optimization methods [3]-[4].

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 optimum cost design for a transformer would automatically satisfy all of mechanical, thermal, and electrical constraints that require sophisticated design algorithms to evaluate [5]-[6]. In Nigeria, modern transformer design can play a significant role in reduction of energy

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loss. The electricity sector in Nigeria had an installed capacity of 8.664GW as at August 2013 [7]. Nigeria currently suffers from a major shortage of electricity generation capacity, despite full implementation of electricity power sector reform, a road map for improvement and massive investment for energy supply. Nigeria's network losses exceeded 35% including non-technical losses, compared to world average of less than 15%. Better transformer design, use of superior grade electrical steel and superior expertise in designing coupled with extensive research and development efforts can drastically reduce no-load loss, one of the leading components of losses in transformers, reduce lost energy and bring a remarkable increase in efficiency [8].

Based on these, our main goal is to present intelligent based optimization techniques that deal with minimization of manufacturing as well as operating cost in the design of transformer. This paper is arranged as follows: Section '2' describes specific transformer design optimization problem and some methods adopted by researchers for transformer design. Section '3' discusses use of intelligent based optimization techniques for transformer design. Section '4' discusses various recent trends in transformer design technology. Finally, Section '5' concludes this paper.

2. SPECIFIC TRANSFORMER DESIGN OPTIMIZATION PROBLEM

Power transformers are possibly the single most expensive asset within an electrical transmission and distribution network in [9], and that alone justifies the requirement of developing appropriate reliable systems that can ensure their availability and reliability.

Transformer design optimization is mainly determined by minimizing the overall transformer cost comprising of materials cost and the labour cost and system losses cost which takes into consideration constraints connected to international technical specifications and transformer user needs. It seeks a constrained minimum cost solution by optimally setting the transformer geometry parameters and the relevant electrical and magnetic quantities by [10].

Similarly, in optimum design of transformers, the target is to minimize the manufacturing cost as well as operating cost whose 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, are expressed in terms of a basic set of design variables. In order to compete successfully in a global economy, transformer manufacturers use design software capable of producing manufacturable and optimal designs in a very short time. The normal practice in transformer design is to rely on an earlier design that has been used in manufacturing transformers with similar main characteristics such as voltage ratio, rated power, etc. Another method is to start a trial and error process by varying some of the design variables until achieving the required new specifications. Starting from scratch could lead to the same design but with more effort and time. Although the above two methods are extensively used to get designs as per IEC and ANSI international standards, they do not guarantee an efficient optimized product.

A survey of literatures on systematic transformer design and optimization procedures will be briefly presented here. The work of [11] summarized a thermal model for the design of rectangular layer windings for transformers. The model calculates thermal gradients across layers, to and from the core, and from the no-duct region under the core iron to the ducted region. The model evaluates the effects of cooling duct quantity, location, and size on the thermal performance. The predicted data of transformer thermal model was not compared with the test data. Similar work by [12] proposed a single-phase transformer design. In his work, the transformer designed was based on some practical philosophy rather than on design optimization of cost. Two simple examples of transformer design were presented while the scope of work covered only low rating and low voltage transformers. However, many practical factors that contributed to transformer design were not considered or highlighted. Another design optimization procedure for transformer analysis that involved only routine calculation was presented by [13]. In this paper, a considerable amount of creativity, resourcefulness, initiative and good judgment was used to identify various alternatives and to choose between them. A few criteria for the "optimum" design was inferred but were not clearly stated.

In [14] a computer based optimization design of single phase transformers which utilizes a routine to guide the choice of the independent variables in such a way that the final design usually has the lowest cost was proposed. In essence, the routine does self-optimize its design by simply entering some input variables in a program which provides a design. However, there were no examples presented with regards to the software approach and the design of independent variables was that of width and depth of the core leg and the current density, while the current density was set equal for the two windings. A PC-based transformer design and analysis program developed by [15] which did attempt to automatically optimize an objective function and was limited to the design of dry type transformer. [16] described a single-phase transformer design suitable for classroom training. The design did not include effect of transformer design variables other than the core and coils while a recent study by [17] used a methodology that allows application of artificial neural networks in some specific stages of transformer design. The paper did not consider transformer cost. Two other different design procedures of large power transformers were analyzed and discussed by [18]. In the first procedure, the losses were not a fixed priori by the customer, and the designer must keep the cost of both the no load and load losses into account, i.e. free losses. The second procedure, the designer was required to respect assigned values of the losses, i.e. fixed losses. The design of mathematical formulation was performed using trial and error method rather than using any optimization methodology. In the study application, the transformer had high MVA rating (63 MVA) and high primary voltage (132 kV). In [19] an Improved Genetic Algorithm (IGA) optimization method applied to the power transformer design problem was represented. The method used Simple Genetic Algorithm (SGA) to overcome common transformer design problems limited to the use of rectangular copper strip in primary and secondary windings. None of the reported work formulated the transformer design problem as an optimization function that includes the transformer losses cost in the objective function.

In recent book published by [20], the work of power transformer cost minimization was done using a branch of optimization theory called geometric programming. In this study, the developed work appears to be suited to the needs of distribution transformers rather than power transformers. The cost function includes weight of primary and secondary windings' materials. No Load Loss and Load loss were included in the cost function. [21] explained minimum weight of EI core and pot core inductor to transformer designs. The main approach dealt with minimization of cost to magnetic material while [22] only considered optimization on the shape of windings for minimum losses. The application of geometric programming to transformer design optimization problem of both low frequency and high frequency transformers was presented by [10] and was limited to low and high frequency transformer. [23] used a heuristic solution for transformer manufacturing cost optimization problem and techniques that included mathematical models employing analytical formulas, based on design constants and approximations for the calculation of the transformer parameters based on the design process adopted by transformer manufacturers. Similar work by [24] explained energy savings in electric power systems by development of advanced uniform models for the evaluation of transformer manufacturing and operating cost and [25] later presented a parallel mixed integer programming-finite element method technique for global design optimization of power transformers. [26] presented the selection of copper against aluminum windings for distribution transformers while [27] presented optimal design of single phase transformer using bacterial foraging algorithm.

Optimal core selection to minimize core and winding losses in [28] made design model using high frequency skin and proximity effects, while [29] showed the effect of number of primary turns on price variation of transformer. Design optimization using MIP techniques was presented by [30] in which active part cost of transformer was minimized using branch and bound techniques while in [31] a demonstration of transformer design optimization was achieved using decision trees. Effect of environmental constraints on distribution transformer cost evaluation has been depicted and demonstrated using least cost choice of a distribution transformer in decentralized electric markets by [32].

Whatever the chosen optimization method is, the herculean task of achieving optimum balance between transformer performance and cost is complicated, and it would be unrealistic to expect that optimum cost design would satisfy all mechanical, thermal and electrical constraints. Therefore, the researchers have resorted to Intelligent based technique in pursuit of the same

3. Intelligent Based Optimization Techniques

Intelligent based optimization technique in power transformer optimization is one of the numerous modern methods and engineering models proposed for transformer design and accurate prediction of its characteristics [33]. Intelligent based optimization technique includes Stochastic Method, ***Neural and Artificial Neural Network (ANN), Genetic Algorithm (GA)***, ***Swarm Intelligence***, Simulated Annealing, Evolutionary Algorithm, Tabu Search, Decision Tree, and Hybrid System using a combination of one or more of the later methods have seen increased usage in transformer design area over the last few years [34]-[36].

3.1. Genetic Algorithms

Genetic Algorithm (GA) is a search algorithm based on the speculation of natural selection and genetics [37]. Firstly, the features of genetic algorithm are multi-path that searches many peaks in parallel, and hence reducing the possibility of local minimum trapping. Secondly, GA works with a coding of parameters instead of parameters themselves helping the genetic operator to evolve the current state into the next state with minimum computations. Thirdly, GA evaluates the fitness of each string to guide its search instead of the optimization function. The genetic algorithm only needs to evaluate objective function to guide its search and required no derivatives or other auxiliary knowledge for computation of derivatives or other auxiliary functions [33], [38]. The basic concepts of GAs were developed by [39] using formalized framework to predict the quality of the next generation in cellular automia while practical application of GAs to complex problems was demonstrated by [40] to solve gas pipeline optimization problem proving that GAs are not really function optimizers.

Genetic algorithms have been widely used for optimization in various domains including bioinformatics, phylogenetic, computational science, engineering, economics, chemistry, manufacturing, mathematics, physics, pharmacometrics and other fields in [41] due to its broad applicability, ease of use and global perspective. Similarly application of Gas to practical problems includes a multi-objective optimization technique comprising of simple genetic and improved genetic algorithm has been employed to transformer construction cost minimization and excellent solution for the first time in [42] which was limited to S9-1000/10KV power transformer. In [43], the team narrowed it research to transformer electromagnetic calculation optimization using genetic algorithm with chaos, a mixed genetic algorithm to successfully show popularization and application of genetic algorithm to transformer optimal design problem. GAs has also been employed in optimization of distribution transformers cooling system design [44]. Parameter identification of power transformer was suggested also in [45], in which evolutionary computational model was developed using GA. [46] presented an effective method to reduce the iron losses of wound core distribution transformers based on a combined neural network-genetic algorithm approach. The originality of the work presented in this paper was that it tackled the iron loss reduction problem during the transformer production phase, while previous works concentrated on the design phase. More specifically, neural networks effectively use measurements taken at the first stages of core construction in order to predict the iron losses of the assembled transformers, while genetic algorithms was used to improve the grouping process of the individual cores by reducing iron losses of assembled transformers. The proposed method was tested on a transformer manufacturing industry whose results demonstrated the feasibility and practicality of this approach. Significant reduction of transformer iron losses was observed in comparison to the current practice leading to important economic savings for the transformer manufacturer.

Genetic Algorithms have also been used for performance optimization of cast-resin type distribution transformers [47] or toroidal core transformers in [48]. [49] described rectifier power transformer design using genetic algorithm (GA) and simulated annealing (SA) methods for locating global minimum and optimal design parameters of a rectifier power transformer. A closed form of expression for actual phase current waveform of the rectifier transformer was derived and comparison was made with the approximate waveform normally considered for fixing the transformer rating. The optimal results demonstrated by an example showed potential for implementation of GA as an efficient search technique for design optimization of rectifier power transformers. Similar study conducted by [50] explained recursive genetic algorithm-finite element method technique for finding solution of transformer manufacturing cost minimization and global transformer optimization problem using evolutionary design and numerical field computation. This study was limited to the use of an innovative recursive GA with a novel external elitism strategy associated with variable crossover and mutation rates to compute no-load loss, impedance and global optimum design before [51] presented Hybrid optimal design of a distribution transformer which combined 2-D finite element, genetic algorithm and a deterministic algorithm to find the final solution. Optimal transformer design based on total owning cost using simple genetic algorithm was demonstrated also in [52], which adopted penalty function approach to process objective functions with weighted coefficients.

3.2. Neural and Artificial Neural Networks

The field of Neural and Artificial Neural Networks is concerned with the investigation of computational models inspired by theories and observation of the structure and function of biological networks of neural cells in the brain. They are generally designed as models for addressing mathematical, computational and engineering problems. Artificial neurons were first proposed in 1943 by a neurophysiologist and a logician in [53]. Thereafter Firouzfar et al., in [54] described estimation of weight of main material for 63/20kV transformers with artificial neural network (ANN). The work by [55] presented cost analysis of transformer's main material weight with artificial neural network (ANN).

Artificial neural networks has predicted magnetic transformer core characteristics, core loss and reduction of iron losses of assembled transformers while cost estimation of transformer in the design stage using NN was proposed in [56]. Evolutionary programming combined with neural networks was later explored in [57] to improve the quality of wound core distribution transformers. Using the information available from daily load curve, evaluation of losses in distribution transformer using NN was carried out by [58] in which utility does not need to perform measurements to evaluate load profile for all type of consumers. Evaluation of iron losses under unbalanced supply state using neural networks was also investigated in [59], while optimization of production process of individual cores using Taguchi methods and minimization of iron losses was demonstrated by [60]. Neural network model for transformer oil's service life identification has been applied by [61] on ten different operating transformers to test known transformer oil's breakdown voltage. Modeling of power transformer with non-linearities was proposed by [62] using the approach based on complex valued open recurrent neural networks. Artificial neural networks have also been used extensively for detecting abnormal conditions in transformers and to predict the resultant forces on transformer windings due to inrush current an important factor usually considered during transformer design [63]. On line detection method of discrimination between inrush and fault currents in transformer was also developed in [64], which used wavelet signals as an input for training ANN. Incipient fault detection in a transformer using the results of dissolved gas analysis as an input for training neural networks was demonstrated in [65]. Application of artificial neural networks for interpreting and classifying different types of faults, and diagnosis of power transformers with internal faults has been envisaged in [66].

3.3. Swarm Intelligence and Particle Swarm Optimization

Swarm Intelligence is the study of computational systems by collective intelligence [67]. Collective intelligence emerges through co-operation of large numbers of homogenous agents in the environment. Examples include flock of birds, school of fish or colonies of ants.

Particle swarm optimization is an exciting new methodology in evolutionary computation that is somewhat similar to a genetic algorithm in that the system is initialized with population of random solutions. Unlike other algorithms, however, each potential solution (called a particle) is also assigned a randomized velocity and then flown through the problem hyperspace. [33]

Swarm intelligence algorithms and Particle swarm optimization has been found to extremely effective in solving a wide range of engineering and optimization problems.

Recently, there has been a growing interest among researchers for solving TDO problems using swarm intelligence algorithms. Optimal choice of number of turns in primary winding using Ant Colony Optimization (ACO) has been carried out in [68] to minimize transformer cost while the work by [69] optimized size of transformer tap changer setting in a power transmission network to improve voltage stability and optimal choice of transformer sizes to serve a forecasted load in [70]. In [71] optimal tolerance design problems for the production of power transformer has been employed to maximized effective utilization rate of sheet material for producing core columns of power transformers. Transformer owning cost calculation using conventional, GA and PSO methods by [72] revealed that PSO algorithm is slightly superior as compared to other two methods. Swarm intelligence technique has been used to train multi layer neural network for discrimination between magnetizing inrush currents and fault currents in [73] which showed application of particle swarm optimization technique to train the neural network to be more accurate as compared to conventional back propagation method. Improved particle swarm optimization algorithm was later applied in [74] for optimal design of rectifier transformer to overcome the defect of trapping in local optimum in the conventional PSO algorithm.

3.4. Hybrid Method

When an optimization problem involves only one objective, the task of finding optimal solution is known as single objective optimization. However, when optimization problem involves more than one objective, the task of finding one or more optimum solutions is known as hybrid method or multi-objective optimization. Hybrid methods of optimization using evolutionary algorithms have gained popularity as population of solutions is processed in every generation. This feature gives evolutionary algorithms a tremendous advantage for its use in multi-objective optimization problems [75]. Differential algorithm evolution approach based on truncated gamma probability distribution function and unrestricted population size evolutionary hybrid optimization algorithm approach combined with chaotic sequences has been employed in [76] for transformer design optimization process. Hybrid design optimization of high frequency transformers using genetic algorithms considered maximization of efficiency and minimization of cost using particle swarm optimization for rough estimation of transformer design specifications in [77] while [78]

using bacterial foraging algorithm made an attempt to simultaneously maximize the efficiency and minimize the cost of a 500 kVA transformer.
Several authors accept as true that optimization algorithms such as Vector Evaluated Genetic Algorithms (VEGA), Weight Based Genetic Algorithm (WBGA), Multiple Objective Genetic Algorithm (MOGA), Non dominated Sorting Genetic Algorithms (NSGA) Niched Pareto Genetic Algorithm (NPGA) employed for transformer design optimization problems are evolving area of hybrid optimization algorithms while other best preserving multi-objective optimization techniques such as Non-Dominated Sorting Genetic Algorithm (NSGA-II), Strength Pareto Evolutionary Algorithm (SPEA), Distance Pareto Genetic Algorithm, (DPGA), Thermo-dynamical Genetic Algorithm (TDGA), Pareto-Archived Evolution Strategy (PAES) are also suggested for solving TDO problems [79].

4. Recent Trends in Transformer Technology

In the last decade, rapid changes and developments have been made in the field of transformer design. The phenomenal growth of power systems has put tremendous responsibilities on the transformer industry to supply reliable and cost-effective transformers [80].

This section describes some of the recent intelligent based techniques that can be employed for transformer design optimization problems.

4.1. Artificial Bee Colony Algorithm (ABCA)

The Artificial Bee Colony Algorithm (ABC) is an optimization algorithm based on the intelligent foraging behaviour of honey bee swarm which has been employed in structural optimization in 2010 by [81]. Artificial Bee Colony (ABC) algorithm has equally been used for nanoelectronic based Phase-Locked Loop (PLL) optimization by O. Garitselov, S. P. Mohanty, and E. Kougianos to speedup physical design optimization in [82]

4.2. Bees Algorithm (BA)

Bees Algorithm is a population-based search algorithm which was developed in 2005 by [83]. It mimics the food foraging behaviour of honey bee colonies which performs a kind of neighbourhood search combined with global search, and can be used for both combinatorial optimization and continuous optimization. Several studies of Bees Algorithms and it applications to solving optimization problem include optimization of classifiers/clustering systems], manufacturing, Controls, bioengineering, and multi-objective optimization by [84].

4.3. Reactive Search Optimization (RSO)

This is a heuristics optimization algorithm that automatically adjusts their working parameters during the optimization phase. RSO methods have been described as root of Learning and Intelligent Optimization (LION) approach that combines machine learning and optimization [85]. Several applications of reactive search optimization published in recent years includes quadratic assignment, training neural nets and control problems, vehicle-routing, structural acoustic control, special-purpose graph partitioning, electric power distribution, maximum efficiency, constraint satisfaction, optimization of continuous functions, traffic grooming in optical networks, maximum clique, real-time dispatch of trams in storage yards, roof truss design, increasing internet capacity, improving vehicle safety and aerial reconnaissance simulations[86].

4.4. Memetic Algorithms (MA)

Memetic Algorithm is a recent growing area of research in evolutionary computation. This term MA is now widely used as a synergy of evolutionary or any population-based approach with separate individual learning or local improvement procedures for problem search. MA is commonly referred to in the literature as Baldwinian Evolutionary Algorithm (BEA) or Hybrid Genetic Algorithms (HGA) [87].

Recent application of MA that has successfully been applied to a multitude of real-world problems include training of artificial neural networks, pattern recognition, robotic motion planning, beam orientation, circuit design, electric service restoration, medical expert systems, single machine scheduling, automatic timetabling, manpower scheduling, nurse roistering optimization, processor allocation, maintenance scheduling of an electric distribution network, multidimensional knapsack, clustering of gene expression profiles, feature/gene selection, and multi-class multi-objective feature selection [88].

5. CONCLUSION

This work covers review on introduction to transformer design, factors to consider to maximally optimize transformer design. Intelligent based optimization techniques such as SWARM intelligent and particle SWARM optimization, Neural and Artificial Neural Networks, generic algorithm and hybrid methods (combination of two or more intelligent techniques) was also reviewed. Summary of transformer design optimization using intelligent techniques in transformer design was also studied. The paper is based on many research articles published since last 42 years, modern optimization techniques and various literatures available were reviewed. This research work provides formidable ground for researchers in the field of transformer design optimization.

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