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A Review on Transformer Design Optimization and Performance Analysis Using Artificial Intelligence Techniques

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Abstract: ***Transformers are the heart of electrical transmission and distribution systems. The aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer should be designed in a manner such that it is economically viable, has low weight, small size, good performance and at the same time it should satisfy all the constraints imposed by international standards. Many researchers have employed Artificial Intelligence (AI) techniques for transformer design optimization (TDO) and performance analysis. However, the true potential of AI techniques is yet to be fully explored for TDO problems. This paper conducts a brief review of research and development in the field of transformers using conventional optimization methods, artificial intelligence based optimization techniques and suggests some of the new bio-inspired AI techniques that can be employed for TDO problems***

Keywords: Transformer design optimization, Swarm Intelligence, Genetic Algorithms, Artificial Neural Networks, Artificial Intelligence Techniques

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 a magnetic core, for introducing mutual coupling between electric circuits. The transformer is an electrical machine that allows the transmission and distribution of electrical energy simply and inexpensively, as its efficiency is from 95% to 99%, i.e., the transformer operates more efficiently than most of all other electrical devices. Transformers play a key role in the interconnection of power systems at different voltage levels. Without the transformer, it would simply not be possible to use electric power in many of the ways it is used today. Consequently, transformers occupy important positions in the electric power system, being the vital links between power generating stations and points of electric power utilization. There are more than 400 published articles, 50 books and 65 standards in the domain of transformers [2], which have contributed vastly in the design improvement and performance of transformers

Transformer design is herculean task in which engineers strive to achieve the compatibility with the standards and imposed specifications, while keeping manufacturing costs low. For countries like India, modern transformer design can play a significant role in reduction of energy loss. The electricity sector in India had an installed capacity of 249.488 GW as on June 2014 [3]. India currently suffers from a major shortage of electricity generation capacity, even though it is the world's fourth largest energy consumer after United States, China and Russia. India's network losses exceeded 23.65% including non- technical losses, compared to world average of less than 15%. Better transformer design and the use of superior grade electrical steel can drastically reduce no-load loss, one of the prime components of loss in a transformer. No-load loss can be further reduced in some cases if conventional electrical steel can be replaced with amorphous metal. The amorphous metal sheet that is used for core construction is an alloy consisting of 92% iron, 5% silicon and 3% boron. It has 70% lower no-load loss than silicon steel. The thickness of amorphous metal sheet is 0.025 mm, i.e., it is about 10 times thinner than the typical thickness of silicon sheet steel [4]. With superior expertise in designing coupled with extensive R&D efforts, modern transformers are much smaller in size, lower in cost, and are able to promise a remarkable increase in efficiency and reduce lost energy.

With an aim to provide the readers about the various researches that are being conducted in the area of transformer design optimization, this paper is organized as follows: Section ‘2’ describes basic transformer design optimization problem and some of the conventional methods adopted by researchers for transformer design. Section ‘3’ describes the use of various artificial intelligence techniques for transformer design optimization and performance analysis. Section ‘4’ discusses various new AI techniques that can be employed for TDO problems. Finally, section ‘5’ concludes this paper

2. Transformer Design Optimization Problem

The problem of transformer design optimization is based on minimization or maximization of an objective function which is subjected to several constraints. Among various objective functions the commonly used objective functions are minimization of total mass, minimization of active part cost, minimization of main material cost, minimization of manufacturing cost , minimization of total owning cost or maximization of transformer rated power. With the advent of digital computers, there has been considerable reduction in the cost of computer hardware, which has provided software engineers the opportunity of automated support in transformer design process. The first transformer design was made on computer in 1955 [5]. In [6], Transformer Design Software package was developed providing a user friendly transformer design and visualization environment, while Jabr minimized total mass of transformer using geometric programming format [7]. Judd and Kressler [8] proposed a technique that begins with the assumed core geometry, which then finds the values of electrical and magnetic parameters which maximize the VA capacity or minimize loss. The transformer design optimization using multiple design method was demonstrated in [9] which considered four objectives: total owing cost, mass, total losses, cost of materials and five constraints: limits on excitation current, impedance, efficiency, no load losses and total losses. Optimal core selection to minimize core and winding losses was carried out in [10], in which design model takes into account high frequency skin and proximity effects, while [11] shows the effect of number of primary turns on price variation of transformer. Design optimization using MIP techniques was presented in [12] in which active part cost of transformer has been minimized using branch and bound techniques, while Amoiralis et. al [13] demonstrated how transformer design optimization can be achieved using decision trees. Effect of environmental constraints on distribution transformer cost evaluation was depicted in [14], while [15] demonstrated least cost choice of a distribution transformer in decentralized electric markets.

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

3. Artificial Intelligence Techniques for Transformer Design Optimization

Artificial Intelligence techniques have been extensively used in order to cope with the complex problem of transformer design optimization. This section describes the use of various AI techniques employed by researchers for TDO problems.

3.1 Genetic Algorithms

Genetic Algorithms (GAs) are based on Darwin's theory of survival of fittest. The basic concepts of GAs were developed by J.H.Holland (1975), while the practicality of using GAs for complex problems was demonstrated by De-Jong (1975) and David Goldberg (1989). Genetic algorithms have been widely for optimization in various domains including science, commerce and engineering. The primary reasons for their success are broad applicability, ease of use and global perspective.

GAs have been employed for transformer construction cost minimization [16] as well as construction and operating cost minimization [17]-[18]. GAs have also employed for the optimization of distribution transformers cooling system design [19]. Parameter identification of power transformer was suggested in [20]-[21], in which evolutionary computational model was developed using GA. Genetic Algorithms have also been used for performance optimization of cast-resin type distribution transformers [22] or toroidal core transformers [23]. Optimal design of rectifier power transformer using genetic algorithm and simulated annealing was carried out in [24]-[25] which showed effectiveness of GA as an efficient search technique for design optimization of rectifier power transformer. Georgilakis [26]-[27] dealt with transformer cost minimization problem by combining genetic algorithms with finite element method using external elitism strategy. Hybrid optimal design of a distribution transformer was presented in [28], 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 in [29] which adopted penalty function approach to process objective functions with weighted coefficients.

3.2 Artificial Neural networks

The field of 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 Neural Networks (ANN) for predicting the magnetic transformer core characteristics and core loss were employed by [30-33], which mainly focused on reduction of iron losses of assembled transformers, while cost estimation of transformer in the design stage using NN was proposed in [34-35]. Evolutionary programming combined with neural networks was explored in [36] 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 Adriano et. al [37] 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 investigated in [38], while optimization of production process of individual cores using Taguchi methods and minimization of iron losses was demonstrated in [39]. Neural network model for transformer oil's service life identification was applied by Ekonomou et. al [40] in which the developed NN model was applied on ten different operating transformers of known transformer oil's breakdown voltage. Modeling of power transformer with non-linearities was proposed in [41] 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. On line detection method of discrimination between inrush and fault currents in transformer was developed in [42], which used wavelet signals as an input for training the ANN. Incipient fault detection in a transformer using the results of dissolved gas analysis as an input for training neural networks was demonstrated in [43]-[45], while bushing fault diagnosis using ANN was carried out in [46]-[50]. Application of artificial neural networks for interpreting and classifying different types of faults was envisaged in [51] which employed separate neural network model to classify each type of fault. Detection of internal winding faults using neural networks have also been discussed in [52]-[54], while Ahadpour [55] employed electronic nose and neural networks for diagnosis of power transformers with internal faults.

3.3 Swarm Intelligence

Swarm Intelligence is the study of computational systems by collective intelligence [56]. 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. The paradigm consists of two dominant sub-fields 1) Ant Colony Optimization (ACO) and 2) Particle Swarm Optimization (PSO) which investigates probabilistic algorithms inspired by schooling, flocking or herding. Swarm intelligence algorithms are considered to be adaptive strategies and are typically applied to search and optimization problems.

Recently, there has been a growing interest among the researchers for solving TDO problems using swarm intelligence algorithms.

Optimal choice of number of turns in primary winding using ACO was carried out in [57] to minimize transformer cost, while [58] optimized the size of transformer tap changer setting in a power transmission network to improve voltage stability. ACO has also been used for optimal choice of transformer sizes to serve a forecasted load [59]. Optimal tolerance design problems for the production of power transformer was employed by [60] which maximized the effective utilization rate of sheet material for producing core columns of power transformers. Transformer owning cost calculation using conventional, GA and PSO methods [61] reveal that PSO algorithm is slightly superior as compared to other two methods. Swarm intelligence technique to train multi layer neural network for discrimination between magnetizing inrush currents and fault currents was employed in [62] which shows that particle swarm optimization technique to train the neural network is more accurate as compared to conventional back propagation method. Improved particle swarm optimization algorithm was applied in [63] for optimal design of rectifier transformer to overcome the defect of trapping in local optimum in the conventional PSO algorithm.

Another swarm based AI technique known as Bacterial Foraging Optimization Algorithm (BFOA) has been widely accepted as global optimization algorithm for optimization and control [64]-[65]. Optimal design of single phase transformer using BFOA was employed in [66] while [67] used BFOA to accurately estimate the parameters of a single phase core type transformer.

3.4 Multi-objective Optimal transformer Design using Evolutionary Algorithms

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 multi-objective optimization. Many real world search and optimization problems involve multiple objectives [68]. Multi-objective 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 [68]

The differential algorithm evolution approach based on truncated gamma probability distribution function was demonstrated in [69], while the unrestricted population size evolutionary multi-objective optimization algorithm approach combined with chaotic sequences was employed in [70] which combine the advantages of unrestricted population size and evolutionary multi-objective optimization for transformer design optimization process. Multi-objective design optimization of high frequency transformers using genetic algorithms was discussed in [71], while [72] considered maximization of efficiency and minimization of cost using particle swarm optimization. Transformer design using multi-objective evolutionary optimization was also employed in [73] for rough estimation of transformer design specifications. Multi-objective optimal design of transformer using bacterial foraging algorithm was suggested in [74] which an attempt has been made to simultaneously maximize the efficiency and minimize the cost of a 500 kVA transformer.

The authors believe that multi-objective optimal transformer design is an evolving area and multi-objective 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) can be employed for transformer design optimization problems.

Other elite preserving multi-objective optimization techniques such as Non-Dominated Sorting Genetic Algorithm (NSGA-II), Strength Pareto Evolutionary Algorithm (SPEA), Distance Pareto Genetic Algorithm, (DPGA), Thermodynamical Genetic Algorithm (TDGA), Pareto-Archived Evolution Strategy (PAES) are also suggested for solving TDO problems.

4. Modern Bio-inspired Artificial Intelligence Techniques suggested for TDO

This section describes some of the modern bio-inspired AI techniques that can be employed for transformer design optimization problems

4.1 Artificial Bee Colony (ABC) Algorithm

Artificial Bee Colony simulates the intelligent foraging behavior of a honeybee swarm. In ABC model, the colony consists of three groups of bees: employed bees, onlookers and scouts. It is assumed that there is only one artificial employed bee for each food source. Hence, the number of employed bees in the colony is equal to the number of food sources around the hive. Employed bees go to their food source and come back to hive and dance on this area. The employed bee whose food source has been abandoned becomes a scout and starts to search for finding a new food source. Onlookers watch the dances of employed bees and choose food sources depending on dances.

The performance of ABC algorithm is better or similar to other population based algorithms such as genetic algorithm, particle swarm optimization, differential evolution algorithm and evolution strategy [75]-[76]. ABC algorithm has been successfully applied for structural optimization problem [77] and real parameter optimization [78].

4.2 Bat Algorithm

The Bat Algorithm (BA) is based on echolocation behavior of bats and preliminary studies show that this algorithm is very promising [79]. In bat algorithm all bats use echolocation to discriminate between food/prey and background barriers. Each virtual bat flies randomly with a velocity 'v_i' at position (solution) 'x_i' with a varying frequency or wavelength and loudness 'A_i'. As it searches and finds its prey, it changes frequency, loudness and pulse emission rate 'r'. When a bat is near the prey, loudness decreases while pulse rate increases. Search is intensified by a local random walk. Selection of the best continues until certain stop criteria are met.

Bat algorithm has been successfully used for engineering design optimization [79] and its comparison with GA, PSO and other methods [80] conclude that BA has advantages over other algorithms.

4.3 Cuckoo Search Algorithm

Cuckoo Search (CS) is an optimization algorithm inspired by obligatory brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds [81]. In cuckoo search method, each cuckoo lays one egg at a time and dumps its egg in a randomly chosen nest. The best nests with high quality of eggs will carry over to the next generation. The number of available hosts' nests is fixed, and the egg laid by a cuckoo is discovered by the host bird with a probability $p_a \in (0,1)$. The worst discovered nests (solutions) are then removed from further calculations.

Cuckoo search has been applied for various optimization problems and it seems that it can outperform other meta-heuristic algorithms in applications [82]. Cuckoo has been applied for engineering optimization problems [83], nurse scheduling problem [84], data fusion in wireless sensor networks [85]-[86], and NP-hard combinatorial optimization problems like travelling salesman problem [87].

4.4 Firefly Algorithm

The Firefly Algorithm (FA) is a meta-heuristic algorithm inspired by flashing behavior of fireflies. The main purpose of firefly's flash is to act as a signal system to attract other fireflies [88]. In firefly algorithm all fireflies are assumed to be unisexual. The attractiveness of a particular firefly is proportional to its brightness. For any two fireflies, the less bright one will move towards brighter one, however the brightness decreases as the distance increases. If there are no fireflies, brighter than a given firefly, it will move randomly. In FA, the brightness is associated with objective function

Firefly algorithm is powerful in solving in noisy non-linear optimization problems [89]-[91] and has been successfully used for economic load dispatch problems [92], unit commitment [93] and enhancement of power quality using DSTATCOM [94]

4.5 Flower Pollination Algorithm

The Flower Pollination (FP) algorithm is inspired by the flow pollination process of flowering plants and it is found to be better than both GA and PSO [95]. In FP, biotic and cross pollination is considered as a process of global pollination process and pollen carrying pollinators move in a way according to Levy flights. For local pollination, biotic and self pollination is used. Pollinators, such as insects can develop flower constancy, which is equivalent to reproduction probability that is proportional to the similarity of two flowers involved. The switching or interaction of local and global pollination can be controlled by a switch probability $p \in [0, 1]$ with a slight bias towards local pollination

Flower pollination algorithm has been applied constrained global optimization process [96], optimization of wireless sensor network [97], economic load dispatch problems [98] and for solving large integer programming problems [99].

4.6 Shuffled Frog Leaping Algorithm (SFLA)

The shuffled frog leaping algorithm is an optimization technique that is inspired by the behavior of a group of frogs. The population consists of frogs that are partitioned into subsets known as memeplexes. The different memeplexes are then considered with as different cultures of frogs, each performing, each of which performs a local search. Within each memeplex, the individual frogs hold ideas, that can be influenced by the ideas of other frogs and evolve through a process of memetic evolution. The local search and shuffling process is carried out until the convergence criteria is satisfied [100].

SFLA was successfully employed by Afzalan et. al [101] for optimal placement and sizing of DG in radial distribution networks, while economic load dispatch with valve point effect using SFLA was addressed in [102]. SFLA has also found its application in project management [103] and continuous optimization [104].

5. Conclusion

This paper gives an overview of the literature regarding transformer design optimization using artificial intelligence techniques. Publications from various international journals and conference proceedings have been included to cover wide range of engineering methods and design considerations. A brief review of modern, bio-inspired artificial intelligence techniques that can be employed for TDO problems is also discussed. This survey provides significant information about the future trends in the field of transformer design optimization.

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