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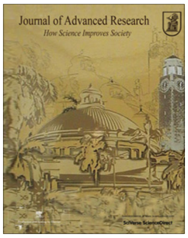

ORIGINAL ARTICLE

A performance-oriented power transformer design methodology using multi-objective evolutionary optimization

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ABSTRACT

Transformers are regarded as crucial components in power systems. Due to market globalization, power transformer manufacturers are facing an increasingly competitive environment that mandates the adoption of design strategies yielding better performance at lower costs. In this paper, a power transformer design methodology using multi-objective evolutionary optimization is proposed. Using this methodology, which is tailored to be target performance design-oriented, quick rough estimation of transformer design specifics may be inferred. Testing of the suggested approach revealed significant qualitative and quantitative match with measured design and performance values. Details of the proposed methodology as well as sample design results are reported in the paper.

Introduction

It is well known that transformers are regarded as indispensable and crucial components in power systems. Due to market globalization, and in some cases to accommodate particular specification requests, transformer manufacturers are facing an increasingly competitive environment to maintain their sales figures. This competitive environment mandates the adoption of design strategies yielding better performance at lower costs.

In the past, several power transformer design methodologies have been proposed [1–8]. Adly and Abd-El-Hafiz [1] demonstrated that feed-forward neural networks may be utilized to predict design details of power transformers after being trained using dimensional and winding details of a set of actual transformers. Alternatively, finite element analysis (FEA) coupled to an educated trial and error approach was introduced [2,3]. Furthermore, a computer-aided trial search looping algorithm aiming at minimizing transformer design cost has been demonstrated [4]. Other approaches coupling FEA to a knowledge-based design optimization strategy and genetic algorithms were presented [5–7]. Hernández and Arjona [8] proposed

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another approach that couples classical design equations to an intelligent design search algorithm.

A quick review of these methodologies reveals that a wide span of design strategies could be utilized to achieve an optimum power transformer design. For instance, analytical formulations may be utilized for the quick estimation of transformer dimensions and design details. Methodologies based upon more accurate FEA computations offer precise estimation of transformer performance measures, provided that design specifics are suggested a priori. Other methodologies, on the other hand, may utilize a hybrid strategy or even non-traditional heuristic and/or evolutionary computation approaches.

Several techniques have addressed transformer design problems using single-objective Particle Swarm Optimization (PSO). Hengsi et al. [9] demonstrated that the two objectives of minimizing power loss and leakage inductance were combined into one objective function using weighted aggregation. Single-objective evolutionary optimization was, then applied using a hybrid algorithm of PSO and differential evolution. Rashtchi et al. [10] and Jalilvand and Bagheri [11] also utilized single-objective PSO in the optimal design of protective current transformers. The objectives of making current measurements more accurate and designing more efficient current transformers in terms of both size and cost were formulated as an optimization problem to be solved by PSO. On the other hand, Du et al. [12,13] focused on improving the standard single-objective PSO algorithm and utilizing the improved version in the optimal design of rectifier transformers. The purpose of the improvement was to avoid being trapped in local optima.

The reduction of a multi-objective optimization problem to a single-objective problem is usually performed by constructing a weighted sum of the original objective functions. While such methods are easy to implement and use, it is difficult to determine the appropriate weight coefficients when enough information about the problem is not available. Another drawback of such approaches is that several runs of the algorithm are needed in order to obtain a set of optimal compromise solutions to choose from. Furthermore, some optimal solutions cannot be obtained, in some cases, regardless of the weight combinations used [14]. Hence, multi-objective PSO becomes useful as it enables finding several optimal compromise solutions in a single run of the algorithm instead of having to perform a series of separate runs as in the case of classical optimization methods.

The purpose of this paper is to present a power transformer design methodology using multi-objective evolutionary optimization. Using this methodology, which is tailored to be target performance design-oriented, quick rough estimation of transformer design specifics may be inferred. Estimated design parameters and details using the proposed methodology may also be considered for further refinement by other FEA approaches. It should be stated that while the proposed methodology is analytical in nature, some parameter range settings have utilized previously reported power transformer field computation results. Details of the proposed methodology as well as sample design results are reported in the following sections.

Performance-oriented power transformer design approach

In addition to the mandated primary line voltage V_{l1}, secondary line voltage V_{l2} and supply frequency f, a three-phase power transformer design is usually optimized to meet volt-ampere rating S, total copper losses P_{cu}, no-load losses P_{NL} and equivalent reactance X requirements. In other words, a performance-oriented design problem reduces to the proper selection of windings and dimensional details that would lead to a set of targeted performance figures. Expressions linking the above-mentioned performance figures to the windings and dimensional details of a three-phase power transformer may be deduced in a systematic way as given below (please refer, for instance, to [15–17]).

$$\frac{V_{l1}}{\sqrt{3}} = 4.44 f B K_f K_c \frac{\pi}{4} D^2 N_1, \tag{1}$$

where B is the core maximum flux density (magnetic loading), K_f is the laminations stack factor, K_c is the gross area to maximum circular area ratio, D is the core bounding diameter and N_1 is the primary winding number of turns.

It is also known that the window space factor of a three-phase transformer S_W may be expressed as:

$$S_W = \frac{2N_1 a_{c1} + 2N_2 a_{c2}}{H_w W_W}, \tag{2}$$

where N_2 is the secondary winding number of turns, H_W is the window height, W_W is the window width, while a_{c1} and a_{c2} represent the primary and secondary winding cross sectional areas, respectively.

Denoting the window height to width ratio by K_W and assuming a common current density (electric loading) J in both windings while $N_1 I_{ph1} = N_2 I_{ph2}$ (where I_{ph1} and I_{ph2} are the primary and secondary phase currents), expression (2) may be rewritten in the form:

$$S_W = \frac{4N_1 a_{c1} K_W}{H_W^2}. \tag{3}$$

It should be pointed out here that, usually, current densities in low and high voltage windings are not identical due to standard wire size availability and/or other design factor constraints. Nevertheless, the assumed current density J may be regarded as an average figure for both windings.

From expressions (1) and (3), the volt-ampere rating of a three-phase transformer may thus be expressed as:

$$\begin{aligned} S &= 3\left\{4.44 f B K_f K_c \frac{\pi}{4} D^2 N_1\right\}\left\{J \frac{S_W H_W^2}{4K_W N_1}\right\} \\ &= \left(\frac{3.33\pi K_f K_c S_W f}{4K_W}\right) J B D^2 H_W^2. \end{aligned} \tag{4}$$

Total copper losses P_{cu} may actually be regarded as a superposition of three components. Namely, these three components are the ohmic winding losses $P_{cu\text{-}ohmic}$, the eddy current losses in the windings $P_{cu\text{-}eddy}$ and the copper terminals connection losses $P_{cu\text{-}con}$. While designing a transformer to meet pre-mandated specification, maintaining the total copper losses below the threshold values becomes a must. In order to achieve this goal, accurate time consuming computations have to be carried out. Alternatively, appropriate computational safety factors may be applied to fast analytical design methodologies.

While $P_{cu\text{-}con} \leqslant 0.05 P_{cu\text{-}ohmic}$, eddy current losses in transformer windings are dependent on the window height to width ratio K_W. As previously reported by Saleh et al. [18], electromagnetic field computation results suggest that, taking $2 \leqslant K_W \leqslant 2.5$, winding eddy current losses may be estimated as $P_{cu\text{-}eddy} \leqslant 0.15 P_{cu\text{-}ohmic}$.