Design optimization of Rectifier Transformers

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***Abstract*— Optimization refers to finding one or more feasible solutions, which correspond to extreme values of one or more objectives. The need for finding such optimal solutions in a problem comes mostly from the extreme purpose of either designing a solution for minimum possible cost of fabrication, or for maximum possible reliability, or others. Because of such extreme properties of optimal solutions, optimization methods are of great importance in practice, particularly in engineering design, scientific experiments and business decision-making. Rectifier transformers deserve extensive treatment in the field of research and production, due to the fact that the electric energy undergoes several transformations on its way from generators to the consumers i.e. rectifiers. In this paper, an effective application of the population based search Differential Evolution algorithm is proposed with the aim of minimizing the cost of the active part of wound core rectifier transformers. The constraints resulting from international specifications and customer needs are taken into account. The Objective Function that is optimized is a minimization dependent on multiple input variables. All constraints are normalized and modeled as inequalities.**

Keywords— Optimization, Rectifier transformer, Design optimization methodology, Differential Evolution algorithm, Optimization methods, Wound core type rectifier transformer.

I. INTRODUCTION

When using any population based search algorithm in general and DE in particular to optimize a function, an acceptable trade-off between convergence rate and robustness must generally be determined. Convergence rate implies a fast convergence although it may be to a local optimum. On the other hand, robustness guarantees a high probability of obtaining the global optimum. Because of the software design approach and the ease of making multiple iterations of the same design layout, it is easy to optimize the rectifier transformer using a minimal set of expensive materials. The difficulty in resolving the optimum balance between the cost of rectifier transformer and its performance is becoming even more complicated nowadays, as the main materials to produce (copper or aluminum for windings and steel for magnetic circuit) are stock exchange commodities and their prices vary daily. One area of great importance that can benefit from the effectiveness of such algorithms is Rectifier equipment systems.

The work in this paper introduces the use of an evolutionary algorithm, titled Differential Evolution (DE) in conjunction with the penalty function approach to minimize the rectifier transformer cost while meeting international standards and customer needs. A simple additive penalty function approach is used in order to convert the constrained problem into an unconstrained problem.

The method is applied to the design of a rectifier transformer and the results are compared with a heuristic transformer design optimization methodology, resulting in cost savings.

II. RELATED WORK

In this paper, a single-objective differential evolution algorithm, which combines several features (penalty function) of previous evolutionary algorithms (EAs) in a unique manner, is proposed for the design of a Rectifier transformers.

Several applications have been recently proposed in the scientific literature. In [17], [20], [21] the DE algorithm has been applied by combining two of the various possible implementing strategies for this evolutionary approach. In particular, the DE/1/best/bin version [17] is used until the cost function has reached a predefined value; successively, the DE/1/rand/bin strategy [17] is applied. It has been found that the DE/1/best/bin strategy is quite able to rapidly locate the “attraction basin” of a minimum, but, since it uses the best individual of the population to perform the mutation, it can sometimes be trapped in a local minimum. This drawback is overcoming by switching, after a predefined threshold, to the DE/1/rand/bin strategy, which is able to explore more efficiently the search space, without modifying the previous best solution if it is inside the correct attraction basin. Concerning the choice of the control parameters, F has been chosen in the range [0.5,1.0], whereas good reconstructions have been obtained with $CR = 0.8$. In [16], the DE method has been used to suppress the sideband radiation patterns in time modulated linear array antennas. The DE algorithm has been found to be a very effective tool in optimizing the static excitation amplitudes and the “switch-on” time intervals of each element. In this application, the DE algorithm has been applied to optimize 32 variables. Moreover, the authors of [16] have found the DE method to be “more powerful” than the standard GA for the present application.

III. THE DIFFERENTIAL EVOLUTION (DE) ALGORITHM

Differential Evolution (DE) algorithm was introduced by Ken Price and Rainer Storn [5], [6] as a population-based stochastic method for global optimization problems over continuous domains. Unlike simple GA that uses binary coding for representing problem parameters, Differential Evolution (DE) uses real coding of floating point numbers. Among the DE's advantages are its simple structure, ease of use, speed and robustness. The way in which the DE is applied to these Rectifier transformers problems is schematized in Fig. 1.

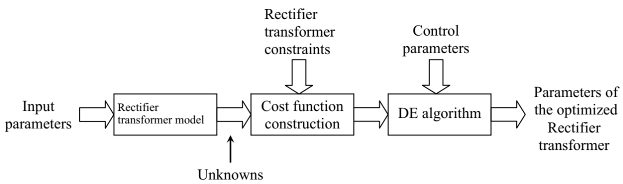

Fig.1 Schematic representation of the application of the DE algorithm to a Rectifier transformer

In all, just three factors control evolution under DE, the population size, *NP*; the weight applied to the random differential, *F*; and the crossover constant, *CR*. A notation the various DE-variants is defined by DE/x/y/z where *x* denotes the base vector, *y* denotes the number of difference vectors used, and z representing the crossover method. Price and Storn [5] gave the working principle of DE with single strategy [6]. They suggested ten different strategies for DE. The following are the ten different working strategies: 1. DE/best/1/exp, 2. DE/rand/1/exp, 3. DE/rand-to-best/1/exp, 4. DE/best/2/exp, 5. DE/rand/2/exp, 6. DE/best/1/bin, 7. DE/rand/1/bin, 8. DE/rand-to-best/1/bin, 9. DE/best/2/bin, 10. DE/rand/2/bin. However, strategy-7 (DE/rand/1/bin) appears to be the most successful and the most widely used strategy.

IV. RECTIFIER TRANSFORMER

A rectifier transformer(RT) is a transformer which includes diodes or thyristors in the same tank. Voltage regulation may also be included. Rectifier transformers are used for industrial processes which require a significant direct current (DC) supply. Typical processes would include DC traction, electrolysis, smelting operations, large variable speed drive trains, etc. The application for which the transformer is used, will drive the design considerations including: bridge type connection of the thyristors for higher voltages, interphase connection for low voltage - high current applications, number of pulses (6, 12 and higher with phase shifting), and eddy current and harmonic issues. Voltage regulation is achieved with no-load or on-load tap changers on the high voltage side. Fine levels of voltage regulation can be achieved using saturable reactors on the secondary side. Regulation units may be built in or separate.

The twelve pulses AC to DC converter are also popularly known as three-phase twelve pulse rectifier. As the number of pulses per cycle is increased, the output DC waveform gets improved. So, with twelve pulses per cycle, the quality of output voltage waveform would definitely be improved with low ripple content

One can actually increase the number of secondary windings to reduce the Total Harmonic Distortion(THD) of the Input Supply (Caused due to Rectification process), but this would increase the cost and number of pulses required in the rectifiers. They are combined with a diode or thyristors rectifier. The comparison of different multi pulse converter has been shown in the Fig.2.

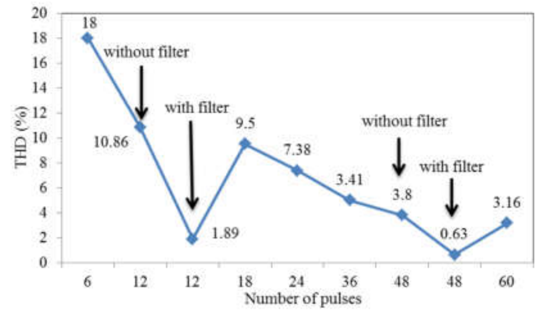

Fig.2 Performance comparison of multi-pulse converters

Regulating and rectifier transformer combinations that are applied to primary aluminum production (smelters) are commonly known as 'rectiformers'. A typical aluminum potline is built as a 60-pulse system with five parallel 12-pulse rectiformers, each with different phase-shift windings; a 60-pulse system can be achieved by the following phase shift angles: –12°, –6°, 0°, +6° and +12°. As mentioned, one of the characteristics of rectiformers for aluminum plants is a very large regulating voltage range, from 0 Volts up to potentially 2,000 Volts (DC), depending on how many pots are connected in series.

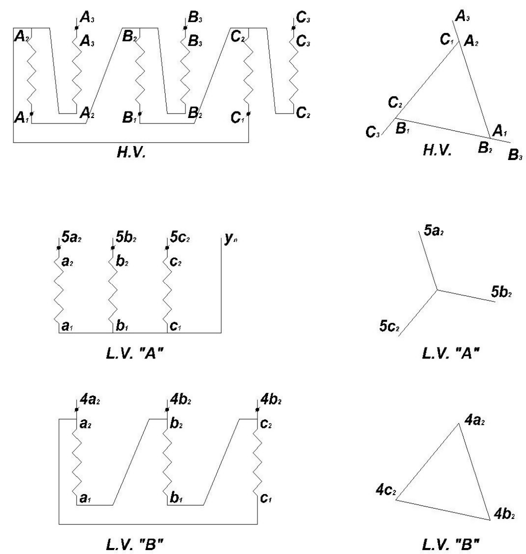

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Fig.3 Vector relationship Dd -15^0 Dy $+15^0$ of a rectifier transformer under consideration(1470 kVA, 11000/(690/690) Volts)

V. MATHEMATICAL MODELLING AND OPTIMIZATION OF RECTIFIER TRANSFORMERS

A mathematical description of a global constrained minimization problem requires us to apply an appropriate model which has limited number of parameters (design variables). In the mathematical notation consider the following optimization problem:

$$\text{Min } f(\boldsymbol{x}) \tag{1}$$

$$\text{s.t. } h(\boldsymbol{x}) = \begin{bmatrix} h_1(\boldsymbol{x}) \\ \cdot \\ \cdot \\ h_M(\boldsymbol{x}) \end{bmatrix} = \boldsymbol{0} \text{ and } g(\boldsymbol{x}) = \begin{bmatrix} g_1(\boldsymbol{x}) \\ \cdot \\ \cdot \\ g_L(\boldsymbol{x}) \end{bmatrix} \le \boldsymbol{0} \tag{2}$$

$$\boldsymbol{x}^{LB} \le \boldsymbol{x} \le \boldsymbol{x}^{UB}$$

where $\boldsymbol{x} = [x_1, x_2, \bullet\bullet\bullet, x_n]^T$ is the vector of unknown quantities, $h(\boldsymbol{x})$ and $g(\boldsymbol{x})$ are the restriction constraints, which can be represented mathematically as equations and/or inequations and $\boldsymbol{x}^{LB}$ and $\boldsymbol{x}^{UB}$ are the lower and upper bound of the decision parameters, respectively. In order to find the global optimum design of a rectifier transformer, DE in conjunction with the penalty function approach technique is used. The goal of the proposed optimization method is to find a set of integer variables linked to a set of continuous variables that minimize the objective function (active part cost) and meet the restrictions imposed on the rectifier transformer. Under these definitions, a DE algorithm in conjunction with the penalty function approach is focused on the minimization of the cost of the rectifier transformer:

$$\min_{x} \sum_{j=1}^{2} c_j \cdot f_j(\boldsymbol{x}) \tag{3}$$

where c_1 is the winding unit cost (€/kg), f_1 is the winding weight (kg), c_2 is the magnetic material unit cost (€/kg), f_2 is the magnetic material weight (kg), and $\boldsymbol{x}$ is the vector of the five design variables, namely the width winding (a), the diameter of core leg (D), the winding height (b), the current density of winding (g) and the magnetic flux density (B). The minimization of the cost of the rectifier transformer is subject to the constraints:

$$S - S_N \le 0;\ P_{CU} - P_{CUN} \le 0;\ P_{FE} - P_{FEN} \le 0;\ U_K - U_{KN} \le 0 \tag{4}$$

where: S is designed rectifier transformer rating (kVA), S_N is rectifier transformer nominal rating (kVA), P_{FE} is designed no-load losses (W), P_{CU} is designed load losses (W), U_K is designed short-circuit impedance of a rectifier transformer (%), P_{FEN} is guaranteed no-load losses (W), P_{CUN} is guaranteed load losses (W) and U_{KN} is guaranteed short-circuit impedance (%). Accordingly, the objective function for the model is:

$$\text{Min } f(\boldsymbol{x}) = (41.7 \cdot x_5 + 248.5 \cdot x_3 + 3.2) \cdot 10^3 \cdot x_2^2 + 1.98 \cdot x_2^3 + (69.8 \cdot x_2 + 144.6 \cdot x_3 + 1.38) \cdot 10^4 \cdot x_3 \cdot x_5 \tag{5}$$

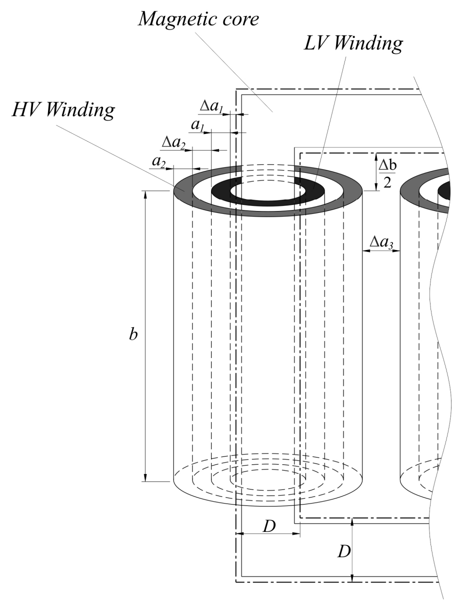

Fig.4 Active part of a rectifier transformer – main dimensions

The constraints of the analyzed mathematical model are entered as follows: Constraint 6 match to a rectifier transformer nominal rating, Constraint 7 match to guaranteed load losses, Constraint 8 match to guaranteed no-load losses and Constraint 9 guaranteed short-circuit impedance. Constants in front of decision variables have been taken from the Fig.4 and reference [9].

$$437.6 \cdot x_1 \cdot x_2^2 \cdot x_3 \cdot x_4 \cdot x_5 \cdot 10^3 - 1470 \le 0 \tag{6}$$

$$\left(3.88 \cdot x_2 + 8.92 \cdot x_3 + 7.68 \cdot 10^{-2}\right) \cdot x_3 \cdot x_4^2 \cdot x_5 \cdot 10^{-7} - 16000 \le 0 \tag{7}$$

$$\left(-0.48 \cdot x_1^2 + 1.60 \cdot x_1 - 0.06\right) \cdot \left(\left(41.7 \cdot x_5 + 246.5 \cdot x_3 + 3.20 \cdot 10^3\right) \cdot 10^3 \cdot x_2^2 + 1.93 \cdot x_2^3\right) \cdot 0.6 - 2400 \le 0 \tag{8}$$

$$\left(85.0 \cdot x_2 + 188 \cdot x_2 \cdot x_3 + 322.8 \cdot x_3 + 17880.0 \cdot x_3^2 + 1.8\right) \cdot 10^{-4} \cdot 319.6 \cdot 0.019 \cdot x_3 \cdot x_4 / x_1 \cdot x_2^2 - 7.5 \le 0 \tag{9}$$

These values are multiplied by a penalty co-efficient, which is then added to the objective function to continue the process of optimization. This process is often termed as a penalty function approach.

TABLE I THE OPTIMAL VALUE OF DECISION VARIABLES

Parameter	***Value***
X1	1.670110
X2	0.246260
X3	0.030270
X4	2.901650
X5	0.620400

TABLE II COMPARATIVE RESULTS OF TWO METHODOLOGIES

	B	*g*	*D*	*a*	*b*	*Cost of Active part*
DE Algorithm	1.67	2.90	246	30	620	6680
Lagrange with New.Rap.[10]	1.65	2.98	242	32	625	7410

The parameters X_1, X_2, X_3, X_4, X_5 match respectively to the magnetic flux density (B), the diameter of core leg (D), the width of secondary winding (a), the current density of secondary winding (g) and the core window height (b).

VI. CONCLUSION

In this study, DE with penalty function approach, an improved version of GA, is applied to designing of rectifier transformers. The rectifier technologies employed in industrial applications are commonly known as double star (DSS) or double bridge (DB). DSS systems use an interphase transformer and are predominately applied as 6- or 12-pulse units where high currents are required with very low nominal voltages. DB systems are applied as 6-, 12-, 24-, 48- or 60-pulse systems, as required to suit the harmonic mitigation and process stability requirements. A higher number of pulse groups can be applied but tend to be less commercially attractive

Our approach based DE with penalty function is integrates in a single unique algorithm and was tested on different devices which belong to power objects with non-rotating parts. The use of the DE computer program is applied to the analyzed mathematical model. Compared with the second methodology in the same table, the cost of materials for the active part of the reviewed object are lower by approximately 11 %.

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