Design optimization of Earthing Transformers based on Differential Evolution Algorithms

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Abstract— **Differential Evolution (DE), a vector population based stochastic optimization method which is an improved version of Genetic Algorithm(GA) has been used for solving different problems with grounding of the isolated systems of distribution or interconnected networks. Earthing 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. In that regard, special interest is dedicated to the minimization of production and exploitation costs of the interconnected star earthing transformer. In this paper, an effective application of the combinatorial optimization algorithm based on Differential Evolution is proposed with the aim of minimizing the cost of the active part of wound core earthing 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. Our approach provides very good results, which are highly competitive with those generated by the compared EAs in constrained evolutionary optimization.**

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

I. INTRODUCTION

Optimization is a procedure of finding and comparing feasible solutions until no better solution can be found. Solutions are termed good or bad in terms of an objective, which is often the cost of fabrication, efficiency of a process, product reliability, or other. Classical optimization methods are in convenient to solve multi-objective optimization problems, as they could at best find one solution in one simulation run. However, Evolutionary algorithms (EAs) can find multiple optimal solutions in one single simulation run due to their population-based search approach.

The difficulty in resolving the optimum balance between the cost of earthing 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.

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 earthing 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. Due to this conversion, the solution falling outside the feasible region is penalized and the solving process is guided to fall into the feasible solution space after a few generations. The method is applied to the design of an earthing transformer and the results are compared with a heuristic transformer design optimization methodology, resulting in significant cost savings.

II. RELATED WORK

Price & Storn (1997) gave the working principle of DE with single strategy. Later on, they suggested ten different strategies of DE (Price & Storn, 2003). A strategy that works out to be the best for a given problem may not work well when applied for a different problem.

The key parameters of control in DE are: *NP*-the population size, *CR*-the crossover constant, and *F*-the weight applied to random differential (scaling factor). Babu et al. (2002) proposed a new concept called 'nested DE' to automate the choice of DE key parameters. As detailed above, the crucial idea behind DE is a scheme for generating trial parameter vectors. Basically, DE adds the weighted difference between two population vectors to a third vector. Price & Storn (2003) have given some simple rules for choosing key parameters of DE for any given application. Normally, *NP* should be about 5 to 10 times the dimension (number of parameters in a vector) of the problem. As for *F*, it lies in the range 0.4 to 1.0. Initially $F = 0.5$ can be tried then *F* and/or *NP* is increased if the population converges prematurely. A good first choice for CR is 0.1, but in general CR should be as large as possible. DE has been successfully applied in various fields. Some of the successful applications of DE include: digital filter design (Storn,1995) [17], optimal design of heat exchangers (Babu & Munawar, 2000; 2001) [8], B. V. Babu and M. Mathew Leenus Jehan in [7] have applied Differential Evolution with a Penalty Function Method and Weighting

Factor Method for finding a Pareto optimum set for the different problems. Mezura-Montes and Coello in [11] present a Differential-Evolution based approach to solve constrained optimization problems.

III. THE DIFFERENTIAL EVOLUTION (DE) ALGORITHM

The DE algorithm is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The main difference in constructing better solutions is that genetic algorithms rely on crossover while DE relies on mutation operation. This main operation is based on the differences of randomly sampled pairs of solutions in the population. The algorithm uses mutation operation as a search mechanism and selection operation to direct the search toward the prospective regions in the search space. The DE algorithm also uses a non-uniform crossover that can take child vector parameters from one parent more often than it does from others. By using the components of the existing population members to construct trial vectors, the recombination(crossover) operator efficiently shuffles information about successful combinations, enabling the search for a better solution space.

An optimization task consisting of *D* parameters can be represented by a *D*-dimensional vector. In DE, a population of *NP* solution vectors is randomly created at the start. This population is successfully improved by applying mutation, crossover and selection operators. The main steps of the DE algorithm are given below:

```
Initialization
Evaluation
Repeat
    Mutation
    Recombination
    Evaluation
    Selection
Until (termination criteria are met)
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For each target vector a mutant vector is produced. The parent vector is mixed with the mutated vector to produce a trial vector. All solutions in the population have the same chance of being selected as parents without dependence of their fitness value. The child produced after the mutation and crossover operations is evaluated. Then, the performance of the child vector and its parent is compared and the better one is selected. If the parent is still better, it is retained in the population.

Fig. 1 shows DE's process in detail: the difference between two population members (1,2) is added to a third population member (3). The result (4) is subject to the crossover with the candidate for replacement (5) to obtain a proposal (6). The proposal is evaluated and replaces the candidate if it is found to be better.

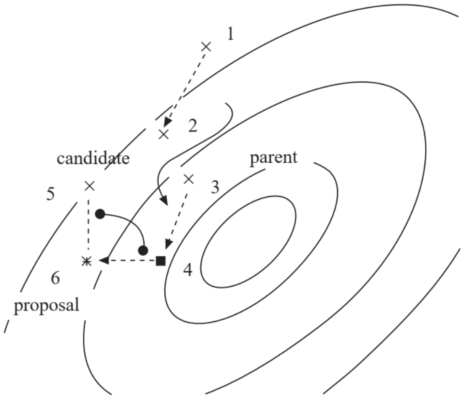

Fig.1 Obtaining a new proposal in DE

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. In all, three factors control evolution under *DE*, the population size *NP*, the weight applied to the random differential *F* and the crossover constant *CR.*

IV. EARTHING TRANSFORMER

An Earthing or (Grounding) of power system is very important since the reliability, short circuit fault current withstand capability, over voltage and basic insulation levels, etc. depend on the characteristics of neutral grounding. The desirable quantities of earthing transformer are low zero sequence impedance and low losses (no load losses). Zero sequence impedance plays a significant role in the effectiveness of grounding, and the accurate prediction of the zero sequence impedance of earthing transformer is very important for power system designers, from a cost point of view as well as a safety point of view. The earthing transformer is usually of the wye delta or zig-zag connections, but in this paper we shall concentrate on the zig-zag connection, with the neutrals connected to earth. Fig.1, Fig.2 shows the Zig-Zag transformer connection with connection group ZNyn(d)5.

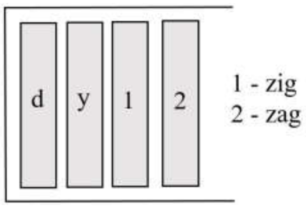

Fig.2 Earthing Transformer window – usual windings

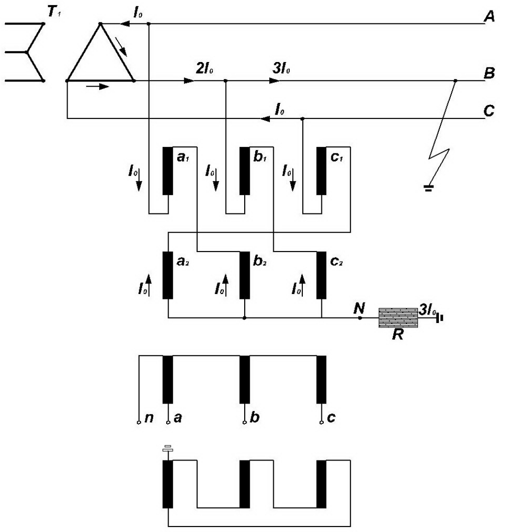

Fig.3 Earthing transformer with connection group ZNyn5, rated power on secondary winding 200 kVA(11000/400 Volts) and rated to carry 400 Amps continuous at Neutral

V. MATHEMATICAL MODELLING AND OPTIMIZATION OF EARTHING TRANSFORMERS

Constrained optimization problems, especially nonlinear optimization problems, where objective functions are minimized under given constraints, are very important and frequently appear in the real world. Let us consider nonlinear constrained optimization problems as follows:

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) && \\ &\text{subject to} && g_j(\boldsymbol{x}) \le 0, && j = 1,\dots,q \\ & && h_j(\boldsymbol{x}) = 0, && j = q+1,\dots,m \\ & && l_i \le x_i \le u_i, && i = 1,\dots,n, \end{aligned} \tag{1}$$

where $\boldsymbol{x} = (x_1, x_2, \bullet\bullet\bullet, x_n)$ is the n dimensional vector of unknown quantities, $f(\boldsymbol{x})$ is an objective function, $g_j(\boldsymbol{x}) \le 0$ and $h_j(\boldsymbol{x}) = 0$ are q inequality constraints and $m - q$ equality constraints, respectively. Functions f, g_j and h_j are linear or nonlinear real-valued functions. Values u_i and l_i are the upper bound and the lower bound of x_i, respectively. In order to find the global optimum design of an earthing 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 earthing transformer. Under these definitions, a DE algorithm in conjunction with the penalty function approach is focused on the minimization of the cost of the earthing transformer:

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

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 earthing transformer is subject to the constraints:

$$S - S_N \le 0;\ P_{CU} - P_{CUN} \le 0;\ P_{FE} - P_{FEN} \le 0;\ Z_0 - Z_{0N} \le 0 \tag{3}$$

where: S is designed earthing transformer rating (kVA), S_N is earthing transformer nominal rating (kVA), P_{FE} is designed no-load losses (W), P_{CU} is designed load losses (W), Z_0 is designed zero sequence impedance of an earthing transformer (ohms/phase), P_{FEN} is guaranteed no-load losses (W), P_{CUN} is guaranteed load losses (W) and Z_{0N} is guaranteed zero sequence impedance (ohms/phase). Accordingly, the objective function for the model is:

$$\begin{aligned} f(x_2,x_3,x_5) = (41.7\cdot x_5 + 248.5\cdot x_3 + 3.2)\cdot 10^3 \cdot x_2^2 + \\ 1.98\cdot x_2^3 + (69.8\cdot x_2 + 144.6\cdot x_3 + 1.38)\cdot 10^4 \cdot x_3 \cdot x_5 \end{aligned} \tag{4}$$

The constraints of the analyzed mathematical model are entered as follows: Constraint 5 match to an earthing transformer nominal rating, Constraint 6 match to guaranteed load losses, Constraint 7 match to guaranteed no-load losses and Constraint 8 guaranteed zero sequence impedance. Constants in front of decision variables have been taken from the reference [9].

$$402.4 \cdot x_1 \cdot x_2^2 \cdot x_3 \cdot x_4 \cdot x_5 \cdot 10^3 - 1682 \le 0 \tag{5}$$

$$(4.34\cdot x_2 + 7.71\cdot x_3 + 6.23\cdot 10^{-2})\cdot x_3 \cdot x_4^2 \cdot x_5 \cdot 10^{-7} - 24500 \le 0 \tag{6}$$

$$\begin{aligned} &(-0.42\cdot x_1^2 + 1.22\cdot x_1 - 0.049)\cdot \\ &((40.2\cdot x_5 + 225.3\cdot x_3 + 3.12\cdot 10^3)\cdot 10^3 \cdot x_2^2 + 2.13\cdot x_2^3)\cdot 0.57 - 1350 \le 0 \end{aligned} \tag{7}$$

$$\begin{aligned} &(72.3\cdot x_2 + 172\cdot x_2 \cdot x_3 + 294.3\cdot x_3 + 18235.0\cdot x_3^2 + 1.6)\cdot 10^{-4} \cdot 311.3\cdot \\ &0.016\cdot x_3 \cdot x_4 / x_1 \cdot x_2^2 - 4.7 \le 0 \end{aligned} \tag{8}$$

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	1.510010
X2	0.231260
X3	0.056270
X4	2.801650
X5	0.420400

TABLE II COMPARATIVE RESULTS OF TWO METHODOLOGIES

	B	*g*	*D*	*a*	*b*	*Cost of Active part*
DE Algorithm	1.51	2.80	231	56	420	9170
Lagrange with New.Rap.[10]	1.50	2.88	226	58	435	9980

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 paper, DE with penalty function approach is applied to designing of earthing transformers.

The rating of earthing transformer is entirely different from that of a power transformer. Power transformers are designed to carry total load continuously, whilst grounding transformer carries no load, and supplies current only if one of the lines becomes grounded. Since it is almost working on no-load, dictates to have low iron losses. The kVA rating of a three phase earthing transformer is the product of normal line to neutral voltage (kV) and the neutral or ground amperes that the transformer is designed to carry current under fault conditions for a specified time. Most earthing transformers are designed to carry their ground current for a limited time only, such as 10seconds to 1 minute.

Moreover, this approach is easy to implement and its computational cost is relatively low. The use of the DE computer program is applied to the analyzed mathematical model. In the first methodology, the single objective DE optimization showed that single optimum could be obtained quickly, even when constraints in the penalty function method are complex. 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 8.8 %.

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