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Optimal coordination of directional over current relays using a modified real coded genetic algorithm: A comparative study

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ABSTRACT

In a large distribution network, the coordination of relays is a highly constrained optimization problem with the objective to minimize the overall operating time of each primary relay. For proper functioning of the power system with distributed power generating stations, appropriate coordination of protection devices is crucial. The present work incorporates bounded exponential crossover and power mutation (BEX–PM) into Real Coded Genetic Algorithm (RCGA) in order to find optimal settings for the Directional Overcurrent Relays (DOCRs). Optimal settings are obtained to minimize the overall action time of all the primary relays as well as to get rid of miscoordination among the backup/primary relay pairs. Another objective of the work is to maintain the difference of response time of backup relay and corresponding primary relay to possible minimum. Results obtained are compared with various approaches available in the literature. The results of this work evidences the compatibility of the proposed strategy in solving complex real-world optimization problems and applicability of the obtained results.

1. Introduction

Several generating stations in modern power systems run parallely to feed a high voltage network. These networks connect millions of equipments. The consequences of development of fault in the power system may be devastating. In order to secure the network from such kind of abrupt circumstances, protective relays are infused into the system. These relays disconnect the malfunctioning part from the system by tripping the circuit.

Directional Overcurrent Relays (DOCRs) are widely used protection devices [1,2] that senses the current flowing in one direction only while current flowing in opposite direction is not noticed by them. For proper functioning of the system, a DOCR should operate for a fault appears in its zone only. The primary relay is supposed to operate on appearance of a fault. Primary relays are backed up by secondary relays, that operate on failure of primary relays. Proper coordination of DOCRs is important to improve performance of electric power devices and to prevent equipment damages. Coordination of the DOCRs can be mathematically modeled as a constrained optimization problem [3] with parameters *Time Dial Setting (TDS)* and *Plug Setting (PS)*. For each DOCR, tuning of *TDS* decides the operating time of the relay while, tuning of *PS* decides the pick up current.

Numerous approaches have been proposed to solve optimal relay coordination problem. These approaches can be classified as:

- Topological analysis approach.
- Classical optimization based approach.
- Artificial Intelligence (AI) based approach.

Before the involvement of computers the coordination problem were solved manually with the help of huge mathematical computation. These computations are time consuming, error prone and calculated settings are inappropriate practically. Topological analysis approach finds relays that open the maximum number of circuits using some heuristic strategy, considering *PS* as constant. The *TDS* values are computed from these relays for all the relays in the network sequentially. The process applied iteratively untill *TDS* values for all the relays are found. In classical optimization techniques the coordination problem is formulated as a linear optimization problem by considering *PS* constant. On the other hand, AI based approach employs metaheuristic algorithms which begins with a population of randomly generated solutions and every iteration improves the quality of the solution and finally whole population converges at an optimal solution.

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Finding optimal and practically applicable settings for relays becomes viable and fast for protection engineers with the help of computers. Initial significant attempts of using digital computers were made in [3–5]. Iterative algorithms based on Linear graph theory were proposed in [6,7] to systematically determines the relative sequence settings of the relays. Urdaneta [8], Urdaneta et al. [9] proposed various models as parameter optimization problem. These models defines objective function as sum of operating times of the primary relays for near-end faults. Jenkins et al. [10] used functional dependency concept to express constraints. Ramaswami et al. [11] proposed database management system based algorithm. The LP based approaches and variants of LP were applied in [12–19].

It is conspicuous that most of the classical optimization methods require an initial guess (solution) and suffer from a tendency of getting trapped in local optima near initial guess. AI based methods provide a smarter alternate option to deal with such difficulties and can be used by power system protection engineers as a powerful design and planning tool (see [20] for details).

Deep et al. [21] and Birla et al. [22,23] applied Random Search Technique (RST) and Sequential Quadratic Programming (SQP). Mixed integer nonlinear programming formulation is used in [24–28] and problem is solved using various variants of PSO. A combination of evolutionary strategy and linear programming was reported in [29]. DE algorithm and various modified variants of DE applied successfully to solve the coordination problem are reported in [30–33].

Amraee [34] applied seeker algorithm with adaptive search direction and step length. Singh et al. applied two approaches, the Teaching Learning Based Optimization (TLBO) [35] and Informative differential evolution strategies [36], Alipour et al. [37] applied an improved Group Search Optimization method and Gokhale et al. [38] applied a modified firefly method, the chaotic firefly algorithm, to find the optimal settings. Zeineldin et al. [39,40] and Ates et al. [41] briefly discussed the impact of integration of DG in radial distribution system. Zeineldin [39] used dual setting DOCRs which are coordinated for the proper functioning of the distribution system.

The most important characteristic of *stochastic population based searching optimization algorithm* like GA is their capability to escape from local optima and hence they demonstrate better chances to find global optimal point in comparison to the classical optimization techniques. So et al. [42–44] discussed an over-current grading method for the user preference based ring fed circuit and applied GA, evolutionary programming technique and modified version of evolutionary algorithm to find the optimal relay settings. Razavi et al. [45] and Bedekar and Bhide [46] applied GA and Continuous Genetic Algorithm (CGA) respectively to solve the optimization problem. Some new variants of RCGA have been proposed by Thakur [47] to solve the coordination problem.

Adelnia et al. [48] proposed a new formulation considering negative effect of adding discrimination times in the OF and GA is used to solve the proposed OF. In Moravej et al. [49] the problem is formulated as a multiobjective optimization problem by considering operating times of primary and backup relays as distinct objectives and problem is solved using NSGA-II.

A brief summary of important developments in various techniques and methodologies to achieve optimum time overcurrent relay coordination are discussed in [50–52].

In the present work an attempt is made to find the optimal settings for the relay parameters for the planning of reliable and efficient large and practical networks. In order to obtain optimal parameter settings a new variant of RCGA, proposed by Thakur et al. [53] is applied. To check the applicability of the found settings the Time Margin is analysed. In this work four standard IEEE models are solved and obtained results are compared with the published results of the most of the algorithms.

The remainder of the paper is organised as follows. Section 2 presents a mathematical model of the relay coordination problem. Thereafter, the BEX–PM GA [53] used to solve the coordination problem for four models, viz. IEEE 3-bus, 4-bus, 6-bus and 14-bus, is discussed in Section 3. Results are presented and discussed in Section 5. And finally the conclusions of this study and future directions are provided in Section 6.

2. Problem formulation

Optimal relay setting is obtained by finding values of two decision variables *TDS* and *PS*. Operation time (T) of a relay is a nonlinear function of TDS, PS and the power flow I_f seen by the relay [47] and is given by:

$$T = \frac{a \times TDS}{\left(\frac{I_f}{PS \times CT_{pr\_rating}}\right)^b - c} \tag{1}$$

In the above formula, only *PS* and *TDS* are the decision variables of the problem. *PS* is determined according to pickup current I_p and is tuned so that relay operate for minimum short circuit current but do not respond for the maximum load current. Minimum value of *TDS* is tuned in such a way that the difference between the response time of primary and the backup relay is sufficient. a, b, and c represents the relay characteristics mathematically and are known constants. This formulation considers the use of Inverse-Definite Minimum Time (IDMT) over current relays for which the constants are defined as 0.14, 0.02, and 1.0 respectively as per IEEE standards [54]. I_f is the fault current at CT primary terminals in case of fault. CT_{pr_rating} is current transformer's primary rating. If CT's secondary rating is 1 then the current seen by the relay I_r is ratio of I_f and CT_{pr_rating}.

$$I_r = \frac{I_f}{CT_{pr\_rating}} \tag{2}$$

Nonlinearity in the equation is implied by the ratio of I_r and *PS*.

2.1. Objective Function (OF)

A *close-in* fault, also known as *near-end* fault, occurs at near end of a relay, on the other hand a fault that occurs at the opposite end of the line is known as a *far-bus* or *far-end* fault for that relay. If N_c is number of close-in relays and N_f is number of far-bus relays, then the objective function is defined as aggregation of operating times of all primary relays.

$$OF = \sum_{i=1}^{N_c} T_{i,pri\_cl\_in} + \sum_{j=1}^{N_f} T_{j,pri\_far\_bus} \tag{3}$$

where T_{i,pri_cl_in} is response time of relay i to clear close-in fault and given as:

$$T_{i,pri\_cl\_in} = \frac{0.14 \times TDS_i}{\left(\frac{I_{f_i}}{PS_i \times CT_{i,pr\_rating}}\right)^{0.02} - 1}$$

T_{j,pri_far_bus} is response time of relay j to clear far-bus fault and given as

$$T_{j,pri\_far\_bus} = \frac{0.14 \times TDS_j}{\left(\frac{I_{f_j}}{PS_j \times CT_{j,pr\_rating}}\right)^{0.02} - 1}$$

The values of I_f and *current transformer rating* (*CTR*) for model-I, model-II, and model-III are provided in Tables 1–6 respectively. For IEEE 14-bus system the data is taken from [47].