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Optimal coordination of over-current relays using modified differential evolution algorithms

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ABSTRACT

Optimization of directional over-current relay (DOCR) settings is an important problem in electrical engineering. The optimization model of the problem turns out to be non-linear and highly constrained in which two settings namely time dial setting (*TDS*) and plug setting (*PS*) of each relay are considered as decision variables; the sum of the operating times of all the primary relays, which are expected to operate in order to clear the faults of their corresponding zones, is considered as an objective function. In the present study, three models are considered namely IEEE 3-bus model, IEEE 4-bus model and IEEE 6-bus model. To solve the problem, we have applied five newly developed versions of differential evolution (DE) called modified DE versions (MDE1, MDE2, MDE3, MDE4, and MDE5). The results are compared with the classical DE algorithm and with five more algorithms available in the literature; the numerical results show that the modified DE algorithms outperforms or perform at par with the other algorithms.

1. Introduction

Electrical power system operates at various voltage levels from 415 V to 400 kV or even more. This system can be divided into three parts: generation, transmission and utilization (load). Among these three parts, transmission of power, which is carried out by the electrical conductors is called transmission lines placed in open. Such lines undergo abnormalities more frequently than other parts in their life time due to various reasons like faults (which create over-current) over-load, over-voltage, under-frequency etc. One well-known source for occurrence of over-voltage in such lines is lightning. These abnormalities cause interruption of the supply and may damage the equipments connected to the system, arising the need for protection. Over-current relay is the most commonly used protection scheme in the power system to protect the system from various faults.

Directional over-current relays (DOCRs) are good technical and economic alternative for the protection of interconnected sub-transmission systems and secondary protection of transmission systems (Urdaneta et al., 1997). These relays are provided in electrical power systems to isolate only the fault lines in the event of the faults in the system. Relay is a logical element and issues a trip signal to the circuit breaker if a fault occurs within the relay jurisdiction and is placed at both ends of each line. Their coordination is an important aspect of the protection system design. Relay coordination problem is to determine the sequence of relay operations for each possible fault location so that faulted section is isolated, with sufficient coordination margins and without excessive time delays. This sequence selection is a function of power network topology, relay characteristics, and protection philosophy (Birla et al., 2006).

The DOCR protection scheme consists of two types of settings namely current, referred to as 'Plug Setting' or *PS*, and 'Time Dial Setting' or *TDS*, which must be calculated. With the optimization of these settings (main objective of this paper), an efficient coordination of relays can be achieved and the faulty transmission line may be isolated, thereby maintaining a continuity of supply to healthy sections of the power systems.

In the present study, the above stated problem of coordinating each DOCR with one another in electrical power system, modelled as a non-linear constrained optimization problem, is solved using the basic differential evolution (DE) and its improved and modified versions (MDE) for IEEE 3-bus, 4-bus and 6-bus systems. The two settings (*PS* and *TDS*) of each relay are taken as decision variables. Sum of the operating times of all the primary relays, which are expected to operate in order to clear the faults of their corresponding zones, is considered as an objective function and the constraints are bound on all decision variables, complexly interrelated times of the various relays (called selectivity

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constraints) and restrictions on each term of the objective function.

The remaining of the paper is organized as follows: in Section 2, we give a brief literature review of the techniques used for coordinating directional over-current relays. In Section 3, we discuss the problem formulation. The basic or the classical DE is given in Section 4 and the modified MDE versions are discussed in Section 5. Experimental settings and numerical results are discussed in Section 6 and finally the conclusions based on the present study are drawn in Section 7.

2. Literature review

Before the application of optimization theory in these problems, trial and error approach was used but it has a well-known drawback of slow convergence rate as a result of large number of iterations needed to reach a suitable relay setting. To overcome the disadvantage of trial and error method, many authors assumed the value of DOCR settings based on expert's experience and solved them in a linear environment (Irving and Elrafie, 1993; Chattopadhyay et al., 1996; Urdaneta et al., 1996; Urdaneta et al., 2001). However, it was observed that linear approach cannot ensure correct settings of the relays (Laway and Gupta, 1993) as it did not consider all possible operating conditions of the power system. Urdaneta et al. (1988) was the first to report the application of optimization theory in the coordination of DOCR. A detailed literature survey on this problem has been performed by (Birla et al., 2005). They have classified the previous works on DOCR coordination into three categories: curve fitting technique, graph theoretical technique and optimization technique.

Sparse dual revised simplex method of linear programming has been used in (Irving and Elrafie, 1993) to optimize the *TDS* settings for assumed non-linear *PS* settings. Some linear programming techniques applied in DOCR coordination problem include Chattopadhyay et al. (1996); Urdaneta et al. (1996); Braga and Saraiva (1996); Abyaneh and Keyhani (1995); and Abdelaziz et al. (2002).

Laway and Gupta (1993) applied simplex and Rosenbrock–Hillclimb methods to optimize the *TDS* and the *PS* settings, respectively, in a similar way, as used by Urdaneta et al. (1988). The optimization of DOCR settings using artificial intelligence (AI) and nature inspired algorithms (NIA) has received considerable attention recently. Some of the NIA algorithms like evolutionary programming (So and Li, 2000a), genetic algorithm (GA) (So et al., 1997; Razavi et al., 2008; Thakur, 2007), modified evolutionary programming (So and Li, 2000b, 2004), and particle swarm optimization (Mansour and Mekhamer, 2007; Zeineldin et al., 2006; Bansal and Deep, 2008) have been applied successfully for solving this problem. Self organizing migrating algorithm (SOMA) and its hybridization with GA have been applied by (Dipti, 2007). Some of the AI methods like fuzzy logic (Abyane et al., 1997) and expert systems (Brown and Tyle, 1986; Lee et al., 1989; Hong et al., 1991; Jianping and Trecat, 1996) have also been applied to this problem. Birla et al (2006) and Deep et al (2006) used random search technique (RST2) to solve the relay coordination problem for IEEE 6-bus model and IEEE 3-bus, 4-bus models, respectively.

Although DE is a robust and a popular optimization tool for solving complex optimization problems, as far as authors know no research paper is available on the implementation of DE for optimization of DOCR settings. In this paper an effort has been made to apply DE and its modified versions on the above mentioned problem of DOCR settings and the results are compared with other contemporary algorithms.

3. Problem formulation

An important characteristic of some types of protection in an electrical circuit is their capacity to determine the direction of the flow of power. Because of this feature they inhibit opening of the associated switch when the fault current flows in the direction opposite to the setting of the relays. Directional relays can tackle this situation when relays face fault currents in both directions because they operate only when fault current flows in specified tripping direction. Hence, directional over-current relays are used extensively for the protection of feeders having infeed from both the ends (e.g. loop systems and parallel feeders).

A DOCR consists of two units: (i) an instantaneous unit and (ii) a time-delay unit.

The instantaneous unit operates with no intentional time-delay when current is above a predefined threshold value, known as the instantaneous current setting. Time-delay unit is used for current, which is below the instantaneous current setting but exceeds the normal flow due to a fault. This unit operates at the occurrence of a fault with an intentional time-delay. Two settings are associated with the time-delay unit, which are as under

- time dial setting (*TDS*)
- plug setting (*PS*) (e.g. tap setting)

The *TDS* adjusts time-delay before a relay operates whenever the fault current reaches a value equal to or greater than the pick-up current. Tap setting is a value that defines the pick-up current of the relay, and currents are expressed as multiple of this. These settings essentially specify the particular time–current characteristics from the family of available curves and the multiple of tap setting to be used to find the relay operating time for a given current flowing through the relay. "Threshold" or "Pick-up current" is the minimum current for which the relay operates and is determined by selecting one of the plug setting taps available on the relay.

3.1. General model of the problem

The mathematical model of the problem followed in this paper is same as Thakur (2007)but DE and its modified versions are used to solve the given problem instead of GA.

The operating time (T) of a DOCR is a non-linear function of the relay settings (time dial settings (*TDS*) and plug settings (*PS*) and the fault current (I) seen by the relay. Thus, relay operating time equation for a DOCR is given by

$$T = \frac{\alpha * TDS}{\left(\frac{1}{PS * CT_{pri\_rating}}\right)^{\beta} - \gamma} \quad (1)$$

Only *TDS* and *PS* are unknown variables in above equation. These are the "decision variables" of the problem. Throughout this paper, the symbol "$*$" represents scalar multiplication. α, β and γ are the constants representing the behaviour of characteristic in a mathematical way, in which operating time of the DOCR varies and are given as 0.14, 0.02 and 1.0, respectively as per [IEEE std. (1997)]. Value of CTpri_rating depends upon the number of turns in the equipment current transformer (CT). CT is used to reduce the level of the current so that relay can withstand it. With each relay one "current transformer" is used and thus, CTpri_rating is known in the problem. Value of I (Fault current passing through the relay) is also known, as it is a system dependent parameter and continuously measured by measuring instruments. Number of constraints for systems of bigger sizes depends upon the number of lines in the system. Details of the number of lines in few larger systems are given in Table 1. In practice, in electrical