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An interior point method based protection coordination scheme for directional overcurrent relays in meshed networks

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ABSTRACT

In this work, interior point method based protection coordination schemes are presented for coordinating directional overcurrent relays. Also, for minimizing the operating times of primary and backup relays simultaneously, a new objective function (NOF) is developed. The effectiveness of the proposed solution methods and the developed objective function has been investigated on two test systems (one small and one large). The suitability of the proposed method for coordination of directional overcurrent relays in meshed networks has been established by comparing its performance with that obtained by genetic algorithm, differential evolution and two hybrid algorithms for the developed objective function. Also, the superiority of the develop objective function has also been established by comparing the protection coordination results obtained by using NOF with those obtained by the other objective functions reported in the literature.

Introduction

For designing an economic protection system, directional overcurrent relays (DOCRs) are used for primary protection of meshed or multi-sourced sub-transmission and distribution systems as well as for secondary protection of transmission systems. For ensuring that only the faulted portion of the network is disconnected thereby reducing the possibility of unwanted power outage, proper co-ordination among the DOCRs is necessary. Essentially, through coordination, the proper time multiplier setting (TMS) and plug setting (PS) of the relays are determined such that any fault is cleared by the corresponding primary relay as soon as possible. Further, both these settings of any relay should also be properly coordinated with the relays protecting the adjacent equipments which, in turn, makes the co-ordination problem quite complex. In addition, the complexity of the problem is dependent on the type of the DOCRs (electromechanical, static or numerical/digital). In numerical relays, both TMS and PS can take continuous values whereas in other relays (electromechanical and static) TMS can take continuous values and PS can take only discrete values. This further increases the complexity of the problem. Moreover, these relays may follow different characteristic curves such as inverse definite minimum time (IDMT), very inverse (VIN) or extremely inverse (EIN) making the selection of TMS and PS very difficult. It is to be noted that the directions of the DOCRs are always fixed and are considered to be towards the line being protected.

To solve this complex problem, several methods have been developed in the literature. These methods can broadly be classified into two categories, namely, network topology based approach and optimization based approach. The network topology based methods include application of a graphical selection procedure for selecting the settings of the relays [1] and identification of minimum break point set (MBPS) using expert system [2] and linear graph theory [3].

Optimization based approaches solve the protection coordination problem by minimizing an appropriate objective function subject to the constraints of maintaining certain minimum coordination time (MCT). In the literature, these optimization problems have been posed as either linear programming (LP), nonlinear programming (NLP) or mixed-integer nonlinear programming (MINLP) problems and application of various optimization techniques have been proposed to solve these problems. In LP formulation, the PS of the relays are assumed to be known and the sum of operating times of the relays are expressed as a linear function of the TMS of the relays. To determine the TMS of the relays, the Simplex method and its variants have been proposed in [4,5]. When both PS and TMS are to be determined simultaneously, the coordination problem becomes a NLP problem. In [6], this NLP problem has been solved using a Gauss–Seidel iterative procedure. Subsequently, application of various heuristic optimization techniques [7–12] have also been proposed in the literature consider-

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ing the problem as either NLP or MINLP. The application of these algorithms has been demonstrated on several small to medium sized systems in all these works. However, it is well known that, these evolutionary algorithms too suffer from getting trapped into local minima and as a result, these algorithms need to be run repeatedly by varying the parameters before selecting the statistically most important result. Consequently, some significant amount of time is required before the final settings of the relays are obtained by the heuristic optimization based approaches. Moreover, in medium and large interconnected networks it is very difficult to satisfy all the DOCR coordination constraints as observed in [13–15]. Consequently, the protection coordination problems have been reformulated as unconstrained programming problems by using penalty function approach for handling constraint violations. Such problems have been solved using genetic algorithm [13,14] and MBPS [15]. However, several violations of coordination constraints have been observed in these works.

Now, to achieve the most effective protection scheme with DOCRs in medium and large interconnected system, the protection coordination problem should be formulated such that the operating times of primary as well as the backup relays are minimized. Further, an appropriate solution procedure should also be developed such that the formulated protection coordination problem is solved in a reasonably short time without any constraint violation.

To realize these twin objectives, a new formulation for DOCR coordination problem is proposed with an objective to minimize both the primary relay operating times (of all the relays for the maximum fault current) and the corresponding backup relay operating times for all possible primary-backup combinations. In the proposed formulation, different types of relays (electromechanical, static and numerical) with different characteristic curves (IDMT, VIN or EIN) are considered. As a result, both continuous and discrete variables are involved in the proposed formulation which makes it an MINLP problem. Further, to solve the protection coordination problem, two interior point based algorithms are developed. Both these algorithms are two-phase optimization techniques and are named as IPM–IPM and IPM–BBM respectively. In the first phase of both the methodologies, interior point method (IPM) is used to obtain continuous values of TMSs and PSs of DOCRs. In the second phase of IPM–BBM technique, branch and bound method (BBM) and in the second phase of IPM–IPM technique, IPM is used to obtain final settings (continuous TMS values and discrete PS values) of DOCRs.

The suitability of the newly proposed formulation and the solution procedures are demonstrated on a small 6-bus system and the IEEE-118 bus system. Further, the results obtained by the proposed methods have also been compared with those obtained by two metaheuristic and two hybrid optimization approaches. The metaheuristic approaches used in the paper are: (i) genetic algorithm (GA) and (ii) differential evolution (DE). The two hybrid approaches are: (a) IPM-GA and (b) IPM-DE. Both these approaches are two phase optimization methods in which IPM is used in the first phase of both these methods. Subsequently, GA and DE are used in the second phase of IPM-GA and IPM-DE method respectively.

The rest of the paper is organized as follows. In Section 'Problem formulation of protective overcurrent relay coordination', the details of the coordination problem of DOCRs are described. In Section 'Procedures adopted to solve the MINLP protection coordination problem', relevant details about the optimization procedures are given. Simulation results on the test power system networks are presented in Section 'Result and discussion'. Finally, the conclusions are given in Section 'Conclusion'.

Problem formulation of protective overcurrent relay coordination

The coordination problem of DOCRs is usually formulated as a constrained optimization problem. For this purpose, several alternative objective functions have been proposed in the literature. The most common objective used in the literature is the minimization of the sum of the operating times of all the DOCRs for the maximum fault current (i.e. due to three-phase-to-ground fault) [4,8,16]. This objective function (denoted as OF1) is expressed as,

$$OF1 = \min \sum_{i=1}^{m} t_{op,i} \quad (1)$$

In Eq. (1), m is the number of relays in the system and $t_{op,i}$ is the operating time of primary relay R_i. The operating times of the relays are obtained from their characteristic curves which are defined by IEC/IEEE [17] as,

$$t_{op} = \frac{\lambda \times TMS}{(I_F/PS)^{\eta} - 1} + L \quad (2)$$

In Eq. (2) λ, η and L are the characteristic constants of the relays, whereas I_F is the fault current through the operating coil of the relay. For standard inverse definite minimum time (IDMT) relays, $\lambda = 0.14$, $\eta = 0.02$, and $L = 0$ [17]. For very inverse (VIN) relays, $\lambda = 13.5$, $\eta = 1$, and $L = 0$ and for extremely inverse (EIN) relays, $\lambda = 80$, $\eta = 2$, and $L = 0$ [17].

The objective function defined above is subjected to the following sets of constraints [1,7,8]:

(a) *Requirement of Protection Coordination Criteria*: If a primary relay R_i has a backup relay R_j for a fault at any line k, then the corresponding coordination constraint can be expressed as,

$$t_{ob,j} - t_{op,i} \geqslant MCT \quad \forall k \quad (3)$$

In Eq. (3), $t_{op,i}, t_{ob,j}$ are the operating time of primary relay R_i and its backup relay R_j respectively for the same fault and MCT is the minimum coordination time (MCT) required for proper operation of primary/backup relays.

(b) *Limitations on Relay Operating Time*: The operation of the relay should neither be too slow nor too fast. Mathematically, a constraint is imposed to restrict the speed of the relays as,

$$t_{i,min} \leqslant t_{op,i} \leqslant t_{i,max} \quad (4)$$

In Eq. (4), $t_{i,min}$ and $t_{i,max}$ are the minimum and maximum operating times of relay R_i for a fault at any point in the zone of operation.

(c) *Limitations on TMS and PS of the Relays*: The limits on TMS and PS are expressed as,

$$TMS_{i,min} \leqslant TMS_i \leqslant TMS_{i,max} \quad (5)$$

$$PS_{i,min} \leqslant PS_i \leqslant PS_{i,max} \quad (6)$$

In Eqs. (5) and (6), TMS_i and PS_i are the TMS and PS values of relay R_i respectively. Further, $TMS_{i,min}$ and $TMS_{i,max}$ are the minimum and the maximum limits of TMS_i respectively, whereas $PS_{i,min}$ and $PS_{i,max}$ are the corresponding quantities for PS_i respectively. The minimum and maximum values of TMS of the relays are specified by the relay manufacturer. The minimum value of PS is taken as the maximum of 1.25 times of the maximum load current and 1/3rd of the minimum fault current whereas the maximum value is taken as 2/3rd of the minimum fault current