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Online coordination of directional overcurrent relays using binary integer programming

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ABSTRACT

This work presents a binary programming model for online coordination of directional overcurrent relay problems in interconnected power distribution and subtransmission systems. The proposed model considers discrete time dial and pickup current settings as in microprocessor-based relays. The coordination problem is solved for every topological change in the network and whose optimized settings are remotely adjusted on each relay through a SCADA system, enhancing the speed and sensitivity of the protection system. A pre-processing step is performed to ensure that the operation time of each relay be below the melting curve of the protected cable. Computational results for the binary programming model solved by CPLEX optimization package are compared to heuristic-based techniques. The simulation results indicates that our approach is suitable for online applications, since an optimal solution can be found in reduced times.

1. Introduction

Overcurrent relays are used as primary protection for distribution and subtransmission lines as well as backup protection for transmission lines, power transformers and generators.

In fault situations, when the primary relay does not operate, a remote backup relay must operate and the associated circuit breaker eliminates the fault. In order to guarantee that the backup relay does not operate before the circuit breaker associated to the primary relay, an intentional time delay is considered to adjust the backup. This process is called coordination. This protection philosophy is used in power distribution and subtransmission networks. In interconnected power systems and considering distributed generation (DG), a known adversity in coordinating the non-directional overcurrent protection requires the application of directional overcurrent relays (DOCR).

In some cases, selecting the appropriate settings for DOCR to ensure coordination, speed and sensitivity for the protection system may be a challenge. For instance, it is common that minimum fault currents at the end of the backup zone be lower than the maximum load current. In this situation, when a pickup current above the maximum load current is chosen, the relay will not provide backup protection for such fault currents.

In an offline coordination process, considering the different $n-1$ contingency topologies, the obtained settings may lead to high operation times for some topologies. To overcome this issue [1,2] propose to re-coordinate all DOCR for every topological change in the network. This concept is also used in this study, considering the possibilities and the growth of smart grids.

The coordination of DOCR has been formulated as an optimization problem and solved with several techniques. To determine continuous time dial settings (TDS), linear programming solvers have been used in [3–6] considering fixed pickup current settings (PCS). In [7,8], mixed integer non-linear programming and mixed integer programming solvers, respectively, have been used to determine discrete PCS and continuous TDS. Continuous TDS and PCS have been determined using a non-linear programming solver in [9,10].

Evolutionary techniques have been used, such as the genetic algorithm (GA) [11–15], nondominated sorting genetic algorithm-II (NSGA-II) [16], particle swarm optimization (PSO) [17,18], seeker optimization algorithm (SOA) [19], ant colony algorithm [1], differential evolution (DE) algorithm [1], opposition based chaotic differential evolution (OCDE) algorithm [20], adaptive differential evolution (ADE) algorithm [21] and teaching learning-based optimization algorithm [22]. Hybrid techniques have also been used in [23,24], combining metaheuristics with deterministic solvers. The main drawback from these heuristic-based techniques is the

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presence of parameters that must be correctly chosen in order to provide the convergence of the algorithm. The optimal parameters may not be the same for different instances, thus this choice is performed in a trial-and-error procedure. Also, given the non deterministic nature of such algorithms, more than one simulation may be necessary to achieve the optimal.

Nonconventional, or non-standardized, characteristics for inverse DOCR have been considered in [25,26]. The GA and a nonlinear programming problem solver, respectively, have been used to optimize TDS, PCS and the shape – characteristic – of the curve of each DOCR, taking advantage of numerical relays.

In general, when the coordination of DOCR is addressed using the techniques previously listed, the TDS are determined as a continuous variable. However, if the step of the TDS of a microprocessor-based relay is not small enough, such as 0.01, miscoordinations may occur whether we round the continuous solution to the nearest available settings [12].

To overcome the described issues, this paper presents a binary integer programming (BIP) model considering discrete TDS and PCS, within the available range. The online coordination of DOCR for three test systems in presence of DG is performed using the CPLEX optimization package. In order to show the effectiveness of the proposed approach, the results are compared with recently used heuristic-based techniques. The novelties of this paper are described below:

- The coordination of DOCR problem is modeled using a BIP model and solved by a mixed integer programming solver running on its default configuration, i.e., the user does not need to set parameters. Also, a single simulation is necessary to achieve the optimal;
- The TDS and PCS are determined in the discrete form, as available in electromechanical and microprocessor-based units with noncontinuous settings;
- A pre-processing step is performed to ensure that the operating times of the DOCR be below the melting curve of the protected cables. This step reduces the simulation times, making the proposed approach suitable for online applications.

The other sections of this paper are organized as follows: in Section 2, the conventional formulation of the DOCR problem is described. The proposed online coordination procedure is detailed in Section 3. In Section 4, the proposed approach is applied over three test systems and the simulation results are discussed. Finally, the conclusions are provided in Section 5.

2. Conventional problem formulation

The objective of the DOCR coordination problem is to minimize the operating times of the relays operating as primary protection. The objective function (OF) is then expressed by

$$\min_{\mathrm{PCS}_i,\mathrm{TDS}_i} \mathrm{OF} = \sum_{i=1}^{m}\sum_{k} T_{ik} \tag{1}$$

where m is the number of relays in the network; PCS_i and TDS_i are the pickup current and time dial settings of the ith relay, respectively; and T_{ik} is the operation time of the ith relay for a fault at k, defined as follows.

$$T_{ik} = \mathrm{TDS}_i \times \left[\frac{A}{\left(I_{ik}/\mathrm{PCS}_i\right)^{P} - 1} + B\right] \tag{2}$$

where I_{ik} is the fault current seen by the ith relay for a fault at k; A, B and P are standardized coefficients. In this work, the Type A curve from the IEC 255-3 has been used, where $A = 0.14$, $B = 0$ and $P = 0.02$.

The constraints of the problem are defined as follows.

2.1. Limits of the settings

The bounds of the settings can be expressed by

$$\mathrm{TDS}_i^{\min} \le \mathrm{TDS}_i \le \mathrm{TDS}_i^{\max}, \quad i = 1, \ldots, m \tag{3}$$

$$\mathrm{PCS}_i^{\min} \le \mathrm{PCS}_i \le \mathrm{PCS}_i^{\max}, \quad i = 1, \ldots, m \tag{4}$$

where ${\mathrm{TDS}_i}^{\min}$ and ${\mathrm{TDS}_i}^{\max}$ are the lower and upper limits of TDS of the ith relay, respectively; ${\mathrm{PCS}_i}^{\min}$ and ${\mathrm{PCS}_i}^{\max}$ are the lower and upper limits of PCS of the ith relay, respectively.

Moreover, for phase protection, the PCS must be greater than maximum load current and lower than minimum fault current seen by each relay, including a safety margin, which depends on the relay technology and current transformer (CT) errors.

2.2. Limits of relay operation time

Minimum and maximum operating times can be established for each relay by

$$T_{ik}^{\min} \le T_{ik} \le T_{ik}^{\max}, \quad i = 1, \ldots, m \tag{5}$$

where ${T_{ik}}^{\min}$ and ${T_{ik}}^{\max}$ are the minimum and maximum operation times of the ith relay for a fault at k, respectively.

2.3. Coordination of primary and backup relays

The backup relays must operate with an intentional time delay, called coordination time interval (CTI), in relation to the primary relay. Thereby, the backup operates only when the primary protection fails. This time interval includes factors such as the circuit breaker operation time, CT errors, relay overtravel time and a safety margin. Its value is usually selected between 0.2 s and 0.5 s.

$$T_{jk} - T_{ik} - \mathrm{CTI} \ge 0, \quad i = 1, \ldots, m \tag{6}$$

where T_{jk} is the operation time of the jth backup relay for a fault at k inside the zone protected by the ith primary relay.

This constraint must be satisfied for all primary/backup pairs. Usually, near-end and far-end fault currents are used, providing coordination for most of the fault situations.

2.4. Topological changes of the network

The coordination constraint (6) is considered not only to the main topology of the network, but also to other possible configurations.

3. Proposed approach

This section presents the proposed online coordination procedure. The main steps are the supervisory control and data acquisition (SCADA) system, the pre-processing step and the process to create and solve the BIP model.

3.1. SCADA system

The main tasks of the SCADA system are to run load flow and short-circuit analysis for each topological change of the power network, to optimize the TDSs and PCSs, and to re-set each relay remotely. Although the communication between a remote device and a supervisory system is already a reality in the state-of-the-art of digital relays, a fully implemented system to execute such re-setting in interconnected power distribution and subtransmission networks is not available. Thus, this re-setting system is supposed to have been implemented.