Electric Power Systems Research 110 (2014) 122–132

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

On-line coordination of directional overcurrent relays: Performance evaluation among optimization algorithms

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A R T I C L E I N F O

Article history:
Received 1 November 2013
Received in revised form 7 January 2014
Accepted 16 January 2014
Available online 8 February 2014

Keywords:
Ant colony algorithm
Differential evolution algorithm
Dynamic network topologies
Genetic algorithm
On-line
Overcurrent relay coordination

A B S T R A C T

The coordination of directional overcurrent relays is most commonly studied based on a fixed network topology in a mesh electrical system. However, in real life, the network topology and the operation of elements of sub-transmission and distribution systems are constantly changing. In addition, modern electrical systems tend to operate near boundary conditions to satisfy the clients. As a result, the directional overcurrent relays (DOCRs) lose speed and sensitivity. Therefore, the principal objective of this paper is to perform on-line coordination of the directional overcurrent relays in order to enhance speed and sensitivity. The secondary objective is to formulate the differential evolution algorithm and compare it with the genetic algorithm and ant colony algorithm. The objectives were accomplished by developing an on-line algorithm that worked with the optimization algorithms.

1. Introduction

The fundamental objective of a protective relay is to detect and isolate the faulted element as soon as possible, so that the impact to the rest of the system is minimized, leaving intact as many non-faulted elements as possible. As different protections are used in different voltage levels of the power system, the directional overcurrent relays (DOCRs) are widely implemented in sub-transmission and distribution systems due to their competing costs. The propose of coordinating the DOCRs is to encounter settings that minimize the operation time for faults within the protective zone, while at the same time offering pre-specified timed backup for relays that are in the adjacent zones. Two settings (degrees of freedom) were considered: “dial” which is also known as time-dial setting and “k” which is the security factor that multiplies with the load current in order to obtain the pickup current setting.

As the number of clients increased, the size of sub-transmission and distribution systems grew. More elements (fault limiters, distributed generators, batteries, etc.) are introduced into the network which made the system become more reliable but at the same time more complicated. Loads of modern electrical system tends to grow exponentially with no accurate predictable data. Therefore, the system is forced to operate near boundary conditions to satisfy the new clients. The load currents increased significantly, but did not increase the fault currents at all. To avoid improper relay operations, the possible increase of load currents is accounted for the coordination purpose using the security factor k. When these ideas are applied, the accounted pickup currents are far bigger than they really need to be. In addition, the high value of pickup currents is held fixed throughout the coordination study. This made the obtained coordination settings become stiff and rigorous which also lead to greater relay operation time and lower relay sensitivity.

Over the past decades, manual coordination of DOCRs has been the most common practice performed by protection experts. However, because of its complexity and nonlinearity, manual coordination has been formulated as an optimization problem. Several optimization methods (deterministic, heuristic, hybrid) have been proposed to solve this problem. Such as the use of linear programming (LP) [1–3], particle swarm optimization (PSO) [4], genetic algorithm (GA) [5–8], hybrid GA and mixed PSO [9,10]. These algorithms have been used in the studies of coordinating the DOCRs off line for fixed network topologies and also for considering different network topologies [9,11,12].

The DOCRs have constantly improved throughout the years from electro-mechanic relays to digital relays. The digital relays emulate the operating principles of the electro-mechanic relays with new features such as data registration, settings groups, the use of no conventional curves and the ability to use continuous parameter settings. These new features allow re-setting of relays (possible

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http://dx.doi.org/10.1016/j.epsr.2014.01.013

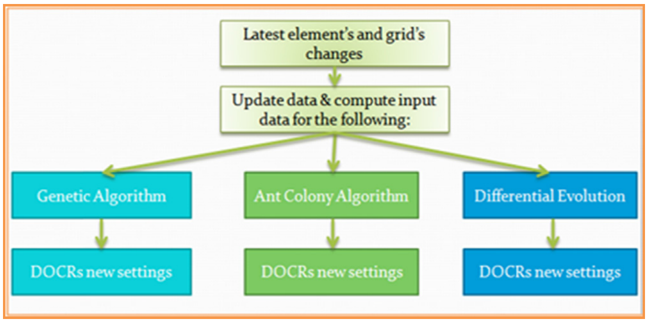

Fig. 1. On-line coordination flow diagram.

on-line coordination). This idea has been implemented in radial distribution lines to solve specific problem but has not yet been implemented in interconnected system due to its complexity. Manufacturers such as SEL and SIEMENS have dedicated their effort in manufacturing these relays.

When DOCRs are coordinated off line according to the reported literatures, there are disadvantages such as: high operation time of relays, low sensitivity of relays and limited or no ability to withstand contingencies.

On the other hand, the on-line coordination proposed in this paper is to re-coordinate all DOCRs for every change of network topology and element operation. The advantages by doing so are minimum relay operation time, increase of sensitivity, and the ability to withstand another unknown contingency. Moreover, the idea is to coordinate DOCRs on-line, which as a result enhances in meeting the fundamental requirements [13].

First, the developed on-line algorithm updates data from the latest changes of the system. Then it computes load flow and fault analysis in order to obtain input data for the optimization algorithms. In this paper, ant colony optimization (ACO), differential evolution (DE) and GA were selected to work with the on-line algorithm. ACO has lately been used to study reactive power flow planning [14], power flow economic dispatch [15] and power generation scheduling [16]. ACO is a powerful tool in solving complex problems in different areas [17]. The DE has not yet been used in any power analysis, but it is reported to be notably efficient in different areas [18]. The advantage of ACO compared with GA is the role of global memory played by pheromone matrix which improves solution convergence, whereas the advantage of DE compared with GA is the fast and simple execution logic of the algorithm. Hence, the idea to formulate the coordination problem using DE is original. GA, which is widely known in the coordination area, is used as the comparison reference. In addition, GA is improved and selected because of its simplicity, robustness and easy implementation.

2. Formulation of the on-line coordination

As presented in the previous section, the on-line coordination of DOCRs enhances meeting the fundamental requirements of sensitivity, selectivity, reliability and speed [13]. Therefore, the on-line coordination algorithm and the formulation of coordination problem are presented sequentially.

2.1. On-line coordination

The flow diagram of on-line coordination of DOCRs is presented in Fig. 1.

The on-line algorithm is a very important segment of this paper, as presented in Fig. 1. It consists of collecting data of the latest element and network changes, from which input data for posterior relay coordination are computed. The online update hardware system is assumed to have been manufactured; the hardware requires only the installation of an appropriate on-line algorithm. The GA, ACO and DE in Fig. 1 are for comparison purpose only.

The detailed description of the algorithm is as follows. First, the system's data are updated according to element and network changes. Then, the Ybus is constructed or modified from the obtained data using the Incident method and the inverse of Inspection method. Next, both lists of "Relay Names" and "Coordination Pairs" are generated automatically. After that, the load flow analysis is run using the Newton Raphson or another method. Then, the Zbus is constructed or modified by the Block construction method and Partial Inversion Motto. Finally, fault analysis is run using Thevenin's method or Symmetrical Components [19]. When all of the above are done, the algorithm will have defined the coordination pairs and computed the maximum load currents and fault currents (3-ph primary, 3-ph backup, 2-ph backup, 1-ph) I_{load}, coordination$_{\text{pairs}}$, $I_{\text{sc}3\phi\text{primary}}$, $I_{\text{sc}3\phi\text{backup}}$, $I_{\text{sc}2\phi\text{backup}}$ of each relay for the optimization algorithms of the original network topology. Therefore, the on-line algorithm is actually an implementation of existing methods.

However, to ensure that the relay settings obtained from the posterior coordination algorithm are suitable for at least one element output without coordination loss, the maximum load and fault currents must be computed according to the different $n-1$ contingency topologies. All elements are taken out one at a time and the simulation is repeatedly performed for the different $n-1$ contingency topologies. Only the maximum load and fault currents are stored as data for coordination use.

Finally, this algorithm performs a sensitivity filtration before passing the data to the optimization algorithms which coordinate the overcurrent relays. This step ensures that all coordination pairs can be coordinated. The coordination pairs that do not satisfy the requirement of sensitivity analysis will be omitted from the coordination process. Thus, the optimization algorithms will not spend extra time to find settings for these insensitive relay pairs, which have no settings that will suit them.

2.2. Formulation of coordination problem

2.2.1. Objective function

The purpose of formulating the coordination of DOCRs as an optimization problem is to minimize the principal and backup relay operation time while maintaining selectivity. It is of great importance to establish a good objective function that evaluates the fitness of the settings because this is the key to encounter optimum solutions using optimization algorithms. The fitness is given in the following equation:

$$\text{Fitness} = \left(\frac{\text{NV}}{\text{NCP}}\right) + \left(\frac{\sum_{a=1}^{\text{NCP}} t_{\text{primary}_a}}{\text{NCP}}\right) \times \alpha + \left(\frac{\sum_{b=1}^{\text{NCP}} t_{\text{primary}_b}}{\text{NCP}}\right) \times \beta + \left(\sum_{L=1}^{\text{NCP}} E_{\text{CTI}_L}\right) \times \delta \tag{1}$$

where α, β and δ are factors that increase or decrease the influence of each sub-objective function and will do for any other system, *NV* is the number of violation of coordination constraints, NCP is the number of coordination pairs, t_{primary_a} is the primary operation time of relay a, t_{primary_b} is the backup operation time of relay b, and E_{CTI_L} is the CTI error of Lth coordination pair.

2.2.2. Primary and backup relay constraints

To coordinate the relays, there must be a time difference between the primary and backup relays. This time difference is called coordination time interval (CTI). In this way, whenever the