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Comprehensive coordination of radial distribution network protection in the presence of synchronous distributed generation using fault current limiter

Reza Mohammadi Chabanloo[a,*], Mahdi Ghotbi Maleki[a], S. Mohammad Mousavi Agah[b], Ehsan Mokhtarpour Habashi[c]

[a] *Electrical Engineering Department, Shahid Beheshti University, A.C., Iran*
[b] *Electricity Research Center at University College Dublin, Ireland*
[c] *Technical Department, Azarbaijan Shahid Madani University, Iran*

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ABSTRACT

Synchronous Machine-based Distributed Generations (SMDGs) are integrated into distribution networks due to their benefits. However, they may cause problems for protection systems, especially in radial distribution networks. In this paper, a coordination algorithm is proposed to modify Time Multiplier Setting (TMS) and pickup current settings of the protective devices, e.g. overcurrent relays, reclosers and fuses, in order to overcome conventional problems of installing SMDGs, e.g. nuisance tripping and fuses blowing, caused by the reverse fault currents of the SMDGs. The proposed algorithm employs the Fault Current Limiter (FCL), as well as re-coordination algorithm, to restore coordination of protection systems in radial distribution networks with high penetration of SMDGs. For this purpose, a multi-objective optimization algorithm is used to determine the minimum size of FCL and optimal setting of protection system. The algorithm is formulated based on hybrid genetic algorithm (GA) and linear programing (LP) method to reduce computation time. Simulations are carried out on a realistic distribution network, and the results demonstrate that the proposed method provides feasible and effective solutions for optimal coordination restoration, while minimizing the FCL size.

1. Introduction

With the widespread use of Distributed Generations (DGs), protection systems of electrical networks have been faced with new challenges. This is due to the additional fault current injected by DGs to network faults. Generators used in DG applications may be of synchronous, induction, or inverter-based types. The level of the fault current injected by DGs to network faults, and the associated impacts on the protection systems, depends on the generator type. For example, the inverter-based DGs have low fault current levels with negligible impacts on the coordination of protection systems. However, SMDGs produce considerable fault currents, which change the fault levels within networks. This alters discrimination of protective devices and reduces reach of overcurrent (OC) relays, leading to nuisance tripping, unintentional islanding, and mal-operation of reclosers. Further, depending on the location of the fault with respect to the DGs and the location of the protective devices, problems like bi-directionality may arise, which disturb the protection coordination of radial networks [1].

Much effort has been devoted in the literature to overcome the adverse impacts of SMDGs on the network protection. An expert system was applied in [2] to coordinate the distribution protective devices in the presence of SMDGs. In [3], a novel time-current-voltage characteristic was proposed for programmable OC relays applied in a distribution network with SMDGs in both grid connected and isolated modes of operation [3]. The authors of [1,4] surveyed protection issues that may occur when DGs are integrated into distribution networks and suggested some solutions, which were mainly based on replacing the protective devices or modifying their setting parameters. Such solutions were effective, but only applicable in limited cases with small sizes of DGs. A control strategy was proposed in [5] to achieve protection coordination when a limited fault current is contributed by some inverter-based DGs. In [6], solid state switches were proposed to disconnect DGs from the network when a fault occurs. However, this solution decreases the reliability of network. In order to avoiding DG disconnection, an adaptive protection scheme was proposed in [7] to divide the distribution network into breaker-separated zones and to identify the faulted section by using phasor measurements. In [8], a method is proposed to prevent the false tripping and improve the system reliability. This method is based on connecting DGs to feeders via four-way switches and dividing the feeder into few protection zones. A neural

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[*] Corresponding author.
E-mail address: re_mohammadi@sbu.ac.ir (R. Mohammadi Chabanloo).

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network-based adaptive protection method was used in [9] for distribution network with DGs. A similar method was presented in [10], which was based on communication between some relay and DG agents. These solutions seem practical and effective, but they require high initial investments due to their need to the communication links and some required changes in the network structure.

Fault Current Limiter (FCL) was first used in [11] to mitigate the adverse impacts of DGs on the distribution network protection. An FCL is a low impedance device installed in series with power lines and has no impact on the normal network operation. However, it exhibits a high series impedance during a fault and limits the fault current. In [12,13], an FCL device was implemented in series with a DG, where the FCL impedance was increased iteratively to obtain the minimum current limiting impedance required to restore protection coordination in interconnected networks. The main drawback of the FCL-based methods is the high cost of FCLs, which increases as a function of the FCL's impedance. Methods were presented in [14,15] to obtain the minimum required impedance of a FCL to limit the fault current of a DG to a desired level. GA was applied in [16] to optimize the number, size and location of FCLs. In [17], the optimal sizes of FCLs were determined using a multi-objective function in order to restore recloser-fuse coordination and to minimize voltage sags in distribution networks with DGs. Further, Superconducting Fault Current Limiters (SFCLs) were proposed in [18] to achieve protection coordination in radial distribution networks by considering the time-current curves of OC relays. In [19,20], the SFCL technology was adopted to improve coordination of protective devices in distribution network with DGs. However, these researches failed to propose a general formulation to achieve coordination of protective devices in the presence of DGs.

In this paper, a method is proposed to minimize the cost of an FCL by lowering its impedance aiming at only partial limitation of the DG fault current, instead of the full fault current limitation. A re-coordination method is proposed in order to restore protection coordination in both forward and reverse directions when a DG is integrated into the distribution network. The proposed method applies a GA-LP optimization algorithm with a new Objective Function (OF) for the coordination of protective devices. The optimization algorithm considers the constraints of the reverse fault currents to optimally use FCLs in series with DGs, and to overcome the issues of installing DGs in radial distribution networks.

2. Proposed method

In this section, a new algorithm is proposed to coordinate protective devices, e.g. fuses, reclosers and OC relays, in radial distribution networks (Section 2.1). The algorithm considers the constraints of reverse fault current, as explained in Section 2.2, to determine the optimal size of FCLs (Section 2.3) when restoring coordination of protection systems in the presence of DGs. Implementation of the anti-islanding protection is described in Section 2.4.

2.1. Coordination of the radial distribution network protection

Coordination of OC relays has been studied in previous researches, such as [21,22]. Here, an optimal coordination algorithm is formulated for protective devices of radial distribution networks, including OC relays, fuses and reclosers, a subject which has not been studied in the previous works. The operating time of relays, reclosers and fuses can be expressed as inverse functions of the short circuit current flowing through them. To obtain the operating time of the OC relays and reclosers, following popular time-current characteristic is considered.

$$t = TSM\left(\frac{\alpha}{(M)^{\beta}-1}\right),\left(M=\frac{I_{sc}}{I_P}\right) \tag{1}$$

where TMS and I_p are the time setting multiplier and the pickup current, respectively, and I_{sc} is the short circuit current passing through the protective device. The parameters α and β are the constants that vary with the type of the characteristic. In this paper, the IEC extremely inverse characteristic is used for the OC relays. the IEC very inverse and the IEC extremely inverse characteristics are considered as the fast and the delayed curves of the reclosers, respectively. The fuses are considered to be of the European type. The operating time of the fuses is a nonlinear function of the fuse rated current (FRC) and the short circuit current passing through the fuse, as given in Eq. (2).

$$t_{Fuse} = f\,(FRC, I_{sc}) \tag{2}$$

The TMSs of the relays and reclosers and the FRCs of the fuses are considered as decision variables in the coordination algorithm. Further, if the fast TMS (TMS_F) and the delayed TMS (TMS_D) of the reclosers are not equal, they are considered as two separate decision variables.

The current settings of the relays (I_{PRel}) and the reclosers (I_{PRec}) are also considered as decision variables to help achieving better results for the coordination problem. Eqs. (2) and (3) show that the operating times of the relays and reclosers are nonlinear functions of their pickup currents (I_{PRel} and I_{PRec}), and the operating times of the fuses are nonlinear function of the FRC. Further, the FRC as a decision variable takes discrete values. Thus, the coordination algorithm can be expressed as a mixed integer nonlinear programing problem.

Several methods were proposed for coordination of OC relays in previous studies. Mathematical methods such as linear programing (LP) [23], non-linear programing (NLP) [24], interior point algorithm [25] and heuristic methods such as; spherical search [26], firefly [27], TLBO [28] and GA [29], as well as hybrid methods were presented previously.

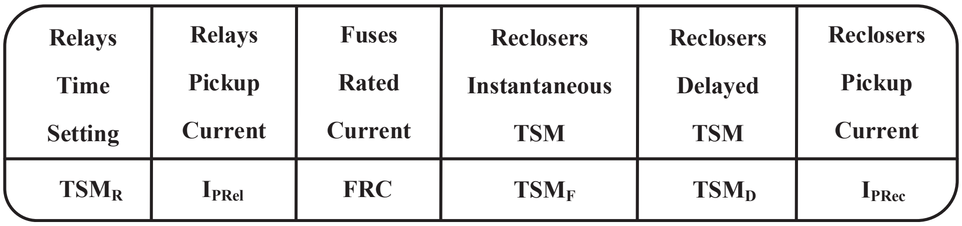
In this section, GA, as a powerful heuristic optimization technique, is applied to solve the optimal coordination problem. In order to reduce the computation time, the problem is formulated based on a hybrid GA-LP method in part E. The decision variables in the GA are usually encoded as a set of genes corresponding to chromosomes in biological systems. Fig. 1 shows the structure of the chromosome, including the decision variables.

The objective of the coordination algorithm is to minimize the operating times of the protective devices considering the constraints. Thus, the OF can be expressed as the sum of the operating times of the relays, fuses and reclosers, as shown by Eq. (3).

$$OF = \sum_i t_{rel_i} + \sum_i t_{fus_i} + \sum_i t_{rec_i} \tag{3}$$

The coordination constraints for the OC relays, fuses and reclosers are presented in [30]. These constraints have been formulated as coordination indices in Eqs. (4)–(11). Related parameters are defined in Table 1.

The required constraint for the Fuse-Fuse coordination is given as



Relays Time Setting	Relays Pickup Current	Fuses Rated Current	Reclosers Instantaneous TSM	Reclosers Delayed TSM	Reclosers Pickup Current
TSM_R	I_{PRel}	FRC	TSM_F	TSM_D	I_{PRec}

Fig. 1. Structure of chromosome in the optimal coordination algorithm using GA.