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Restoring recloser-fuse coordination by optimal fault current limiters planning in DG-integrated distribution systems

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ABSTRACT

In this paper, the Fault Current Limiter (FCL) is used to restore the coordination between the protection devices in distribution systems with high-level of DG penetration. The FCL allocation may be described as an optimization problem involving multiple objective functions which are contradictory and of different dimensions. So, it is formulated as a multi-objective constrained nonlinear programming problem. The interaction among different objectives gives rise to a set of compromised solutions, largely known as the Pareto-optimal solutions. The objectives are to simultaneously minimize: the increase in fault current levels due to the penetration of DG, voltage sag, and the total cost (size) of required limiters. The optimization problem is solved using Particle Swarm Optimization (PSO). The method is applied to two distribution test systems. Effects of different operating factors are assessed. Comparative analysis of results is provided.

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Introduction

Distributed generation (DG) is small generation units, integrated to low or medium voltage distribution systems. DG can provide emergency energy source, mitigate voltage violations, improve service continuity, reduce power losses, and lessen undesired gas emissions [1–4]. Distribution protection system incorporates relays, reclosers and fuses. Reclosers are usually installed on main feeders with fuses on laterals. Reclosers lower service interruptions because about 80% of faults that occur in distribution systems are temporary. A recloser can clear a temporary fault before allowing a fuse to blow. Operation coordination of fuses, reclosers and relays is a crucial issue [5].

DG integration to a distribution network causes changes in fault current. So, the coordination between the protection devices is not assured. Many factors, such as size of DG, location of DG, and type of DG (static or rotating machine), would influence the share of DG in total fault current [2]. The impact of DG on overcurrent protection devices in radial distribution systems is investigated in [6–15]. Many problems occur because of DG integration. They include fuse fatigue, nuisance fuse blowing, and recloser-fuse mis-operation.

Several methods have been proposed to keep coordination of protection devices in presence of DG [6–9]. Ref. [6] determines the maximum capacity of DG that would assure coordination between the recloser and fuses on a feeder. But this method limits the size of DG connected to a system blocking other operational benefits of DG. In [7], Brahma and Girgis discussed a microprocessor-based reclosing scheme to keep recloser-fuse coordination on a feeder with a high penetration level of DG. A method to modify recloser characteristics to achieve coordination is also described. The method assumes that DG will be disconnected before the recloser operates at the first time, which means that the DG status must be continuously monitored. Also, disconnecting the DG at every fault occurrence may degrade service reliability and quality because the faults on distribution feeders may be frequent and temporary.

Fault Current Limiter (FCL) has emerged as an active and effective way to limit fault currents [16,17]. It provides a sudden extra impedance in the way of the fault current. Examples of FCL devices are explosive limiters, solid state FCL, and superconducting FCL [16]. In general, a FCL provides a small impedance under normal system operating conditions and a large impedance during fault conditions. FCLs may lower system reliability, increase cost, and increase operational complexity [18]. Application of FCLs for keeping protection coordination is analyzed in [17–19]. The merits of FCLs greatly depend on their sizes and locations [20]. In [15], a genetic algorithm is used to find the optimal FCLs to minimize fault current under DG integration. The same is done in [21] using Particle Swarm Optimization (PSO). The method is applied to a small-scale simple test system.

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Usually, locations of FCL are assumed. Then, a simplified single-objective optimization problem is solved to get the size of FCL. The cost of FCLs is generally high as it typically involves power electronics or superconducting devices [16]. The FCL cost depends on the resistive and inductive elements sizes (values). The total size of determined FCLs might be prohibitively large that limit the economic feasibility of applying FCL. So, special care should be given to FCLs size when FCL installing is studied to reduce stress on power network equipment or to maintain protection coordination. Hence, if the planner main objective is to achieve protection devices coordination by FCLs, another crucial objective must be minimizing the size of the required FCLs. Besides, voltage sag accompanies the occurrence of faults. It can cause tripping of critical loads leading to serious consequences. Voltage sag is mitigated by proper setting and coordination of overcurrent protection devices [8]. So, if overcurrent protection devices coordination is concerned on one side, the voltage sag level must be considered on the other side. Allocation of FCLs can be done in such a way that it optimizes average voltage sag in the network. Nonetheless, optimizing FCL cost and voltage sag level are not tackled in the reported studies.

In this paper, FCL is used to restore the recloser-fuse coordination without disconnecting DG. The FCL allocation problem involves multiple objectives which are contradictory and of different dimensions.

The novel aspects in the paper are:

- The FCL allocation problem is formulated as a multi-objective constrained nonlinear programming problem. The objectives are to simultaneously minimize: the increase in fault current levels due to the penetrating of DG, average voltage sag level, and the total cost (size) of the required FCLs.
- Both the FCLs locations and sizes are searched. The FCLs locations are not assumed in advance like other studies. This results in much reduced total size of FCLs.
- Effects of DG size, location, type, network configuration and FCL type are investigated.
- The proposed method is applied to both small-scale and large-scale test distribution networks. Comparative analysis of results is presented.

The interaction among different objectives gives rise to a set of compromised solutions, known as Pareto-optimal solutions [22]. The optimization problem is solved using Particle Swarm Optimization (PSO).

Protection coordination

Fig. 1 depicts the protection scheme in a typical distribution network. Fuse must isolate permanent faults of the lateral feeder. Recloser has two modes, fast mode that trips the circuit for temporary fault before the fuse operates, and slow mode that serves as backup protection when a fuse fails to blow up. The breaker is used as the entire backup protection when both the recloser and lateral fuses fail to isolate a fault on the feeder. A fuse has two characteristics: "Minimum Melting (MM) and Total Clearing (TC)". Breakers and reclosers are normally equipped with reverse-time overcurrent relays having the characteristics given in (1) [13].

$$t(I) = \mathrm{TD}\left(\frac{A}{M^{p}-1}+B\right) \quad (1)$$

where A, B and p are constants for particular curve characteristics; t is operating time of device; M is ratio of $\frac{I}{I_{pickup}}$ (I_{pickup} is the relay current set point) and TD is time dial setting. The characteristic of fuses is similar to reverse-time overcurrent relay characteristic. General equation of fuses follows (2) [13].

$$\log(t) = a\log(I) + b \quad (2)$$

where t and I are the associated operating time and current, and the coefficients a and b are calculated from curve fitting.

Breaker–breaker mis-coordination

Fig. 2 shows a distribution system with two radial feeders. When a fault occurs at the upper feeder, the circuit breaker at this feeder must operate. But the circuit breaker at the lower feeder may operate because the DG feeds a fault current and it may lead to unnecessary electricity interruption on this healthy feeder. The solution for the false tripping on healthy feeders is using a directional overcurrent relay for the circuit breaker. Another solution for this problem is using same or similar circuit breakers for both feeders [13].

recloser-fuse mis-coordination

Fig. 3 presents the time-current characteristics of the recloser and the fuse, as well as the short-circuit current across the fuse before and after connecting DG. The penetration of DG will cause mis-coordination between fuse and recloser. When a fault occurs at the lateral feeder (see Fig. 1), the recloser at fast mode operates (opens) first to isolate the presumed temporary fault. If the fault still remains when the recloser closes again after a specific time, the fuse at the lateral feeder should blow up to isolate the fault that is actually a permanent fault. If the fuse fails to operate, the recloser at slow-mode will operate as a backup protection. To obtain this sequential operation, the fault current must rest between the minimum and maximum currents shown in Fig. 3.

To illustrate the problem, a connected DG is assumed at the downstream end of a main feeder. If a fault occurs at a lateral feeder downstream the recloser, the fault current seen by the recloser

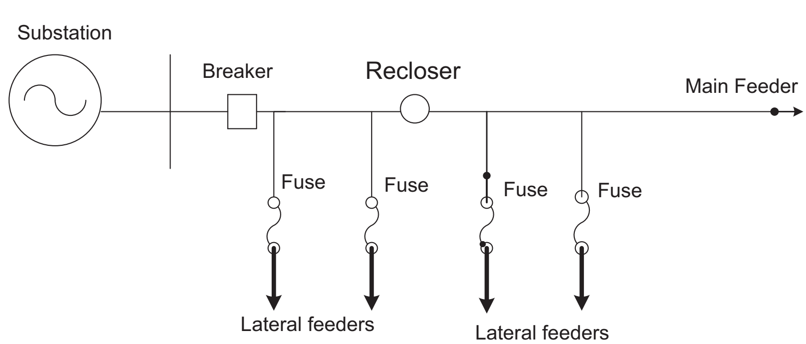

Fig. 1. Typical radial distribution feeder.

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