Optimal Protection Coordination and Sizing of Fault Current Limiter in Radial Distribution System with Distributed Generation

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Abstract

With the integration of Distributed Generation (DG) into the distribution network, the magnitude and direction of both normal and fault current is affected. The effect of DG on fault current can lead to false or failure in operation of protection devices in the existing protection system. It is also technically challenging and costly to redesign and to reconfigure the overall protection system whenever a new DG is integrated into the distributed network. One way to deal with this problem is to use Fault Current Limiter (FCL) with the addition of necessary new relays and reconfiguration of few existing relays. In this paper, three cases with different FCL and relay configuration is considered. The value of FCL and the setup value of relays are optimized using Genetic Algorithm (GA). It is found that existing protection coordination can be achieved, using FCL in addition of new relays only in series with each new DG's. To increase the availability of power in the network after a permanent fault, few existing relay must be reconfigured with directional capability in addition with the use of FCL and with the use of necessary new relays.

Keywords: Protection coordination; Distributed Generation (DG); Fault Current Limiter (FCL); Over-current Relay (OCR); Genetic Algorithm (GA).

1. Introduction

'A fault in a circuit is any failure which interferes with the normal flow of current' [1]. During a fault condition, a large current flow in the faulted path of the network. A fault must be detected and cleared quickly, to prevent the damage of the fault current to the devices in the network. A protection system is implemented, to quickly isolate a faulty section while reducing the section of the network being isolated during a fault condition [2].

Electrification of various sectors, use of sustainable energy sources, energy mix, energy security and efficient use of energy has been a growing concern in recent years. Such concerns along with technological improvement and commercial availability, has increased the adaption of Distributed Generation (DG), based on renewable energy sources. DG has both positive and negative impact on the network it is connected. One of the negative impacts of DG is its contribution to fault current, which can lead to miscoordination of the existing protection system.

The objective of the work presented here is to optimize protection coordination and fault current limiter size in a radial distribution network with distributed generation, while also minimizing the modification to the existing protection system.

2. Methodology

Figure 1, shows the flowchart of the overall process. IEEE33 bus radial system [3] is used to test the proposed methodology. Constant generation and load profile is considered for all calculation. Protection system based on Over-current Relay (OCR) as the protection devices is developed for the IEEE33 bus system before DG integration.

Equation (1), represents the objective function [4] used for optimizing the operating time of the relays.

$$OF_{Protection\ Coordination} = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(t_{ij} + \sum_{k=1}^{P} t_{ik} \right) \qquad (1)$$

Here, i is the fault location identifier, j is the primary relay identifier for a given fault i and k is the backup

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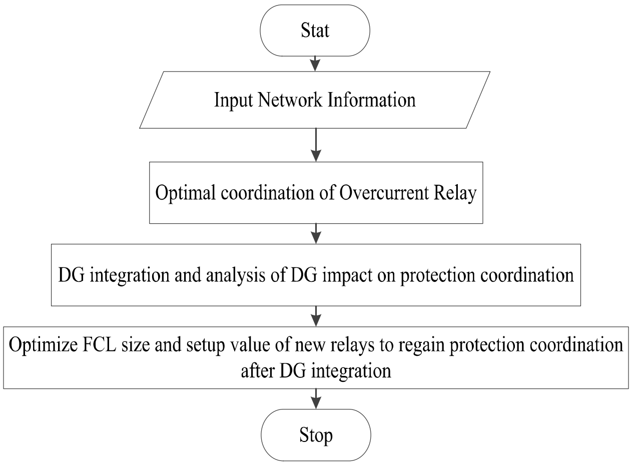

Figure 1: Flow chart of the overall process.

relay identifier for a given primary relay j. N is the total number of fault location considered, M is the total number of primary relay for a given fault condition and P is the total number of backup relay for a given primary relay. t_{ij} is the operating time of the primary relay j for a given fault location at the bus i. t_{ik} is the operating time of the backup relay k for a given fault location at the bus i.

The operating time of relay [5], is an inverse function of short circuit current. The operating time of each relay is calculated based on equation (2).

$$t_{relay} = TMS\left(\frac{\alpha}{\left(\frac{I_{SC}}{I_{pickup}}\right)^{\beta}-1}\right) \tag{2}$$

Here, TMS and I_{pickup} are the time multiplier setting and pickup current, respectively. I_{SC} is the short circuit current passing through the protective device. α and β are constants and its value vary with the characteristic of the relay being used. IEC extremely inverse characteristic is used for relays.

Inequality (3) to (5) [5] represents the constraints used for optimization.

$$TMS_{minimum} \le TMS \le TMS_{maximum} \tag{3}$$

$$I_{load(Max.)} \times K_m < I_{pickup} < I_{fault}(Min.) \tag{4}$$

$$OT^{Backup}_{realy} > OT^{Primary}_{relay} + CTI_{relay-relay} \tag{5}$$

The TMS of the relay should be between the minimum and the maximum TMS range of the protective device. The range of TMS is considered to be between 0.05 and 2 [5].

The pickup current of relay must be between the maximum load current and the minimum fault current. The value of K_m address future overloading scenario in the network and its value ranges from 1.2 to 2 [5]. The value of K_m is set to 1.6 for the calculation [4].

For a given fault current I_{SC} , the operating time of the relay (t_{relay}) can be varied using the setup value TMS and I_{pickup}. The setup value, TMS and I_{pickup} for each relay is optimized, to minimize the operating time (i.e. the objective function) of the overall protection system while satisfying the inequality constraint. To attain coordination between relays, the operating time of backup relay ($OT^{Backup\ Relay}$) must be greater than the operating time of primary relay ($OT^{Primary\ Realy}$) by a Coordination Time Interval (CTI) for any given fault condition. $CTI_{relay\text{-}relay}$ is the coordination time interval between the primary relay and the backup relay while a maximum fault current is flowing through both the relays. The value of $CTI_{relay\text{-}relay}$ is considered to be 0.4 seconds.

Sizing and location of DG for IEEE33 bus system is considered from [6]. Here, the objective of DG integration is to reduce the line loss and improve the voltage profile of the network. Fault model of DG is used to analyze the effect of DG on the fault current level. Maximum current supplied by the DG during a fault condition, is used to model the DG [7].

Three types of DGs are considered. Ratio of short-circuit current to rated current (or I_{SC}/I_r) is used to distinguish different types of DG. Synchronous based DG, asynchronous based DG and power inverter based DG is represented by I_{SC}/I_r ratio of 8, 5 and 2 respectively [7]. To study the effect of DG on existing protection system inequality (5) and (6) are used.

$$I_{reverse\ fault\ current} < I_{pickup} \tag{6}$$

Inequality (6), deals with the pickup current of the relay. If the reverse fault current exceeds the pickup current of the relay than the relay false operates for a given fault condition.

To regain protection coordination after DG integration, three cases are considered. In case I, FCL is located in series with DG along with a new OCR for each DG. In case II, FCL is located in the branches of the network, rather than its placement in series with the DG. Similar to that in case I, OCRs location is unchanged

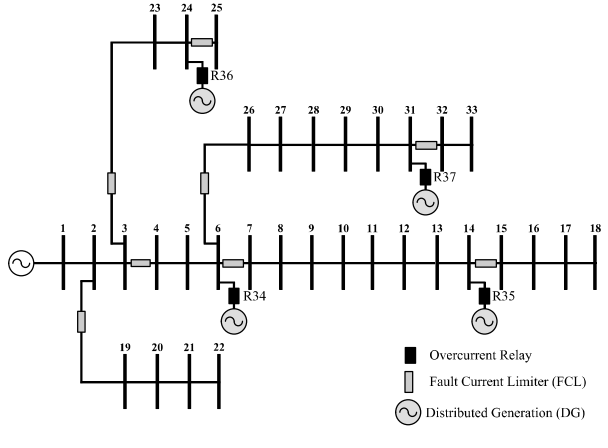

Figure 2: Case II, FCL in branches of the network.

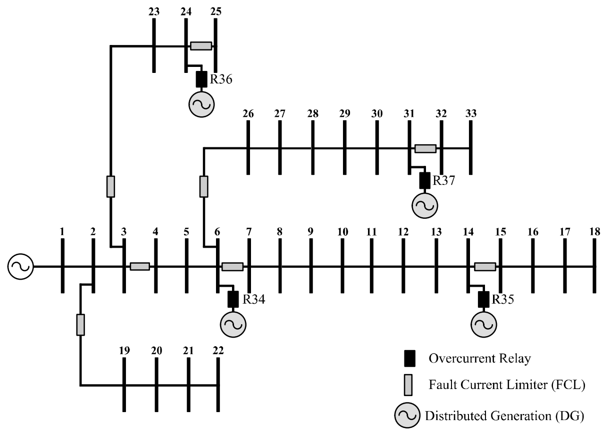

Figure 3: Case III, addition of dual setting DOCR

in case II. Case III, is similar to case II, with an addition of islanding capability of DG.

The islanding capability of DG is made possible with the use of dual setting Directional Over-current Relay (DOCR). The dual setting DOCRs replaces few existing OCRs and are strategically located in the branches, so that in an event of a three phase symmetrical fault, the isolated DG is capable of supplying adequate active power to the load. Case II is represented in Figure 2 and Case III is represented in Figure 3.

Genetic Algorithm (GA) function of MATLAB is used for solving the optimization problem. Two optimization problem is solved using GA. One for the optimal protection coordination of relay and another for the optimal sizing of FCL.

For optimal protection coordination of relay, TMS and pickup current setup value of each relay is assigned as the variable to be optimized by GA, equation [1] is used as the fitness function, and inequality [5] is assigned as the nonlinear constraints for the GA. Inequalities [3] and [4] are used as the lower and upper bound for the variables of GA.

For optimal sizing of FCL, the impedance value of FCL is assigned as the variable for the GA, equation (7) is used as the fitness function and inequality [5] is assigned as the nonlinear constraints for GA.

$$OF_{FCL\,sizing} = \sum_{x=1}^{n} Z_x \tag{7}$$

Some of the parameters used for GA are mentioned in the following paragraphs. For, variables less than 5, population size is set to 50, while for variables greater than 5, population size is set to 200. Fitness scaling is done based on the rank of the fitness function of each individual. GA uses a selection function called, stochastic uniform, which lays out all the parents in a line, whose length is proportional to the value obtained from the fitness scaling. Starting with a randomly generated step size and then after a constant step size, parents are selected based on where the step lands on the line. The selected parents are used for the reproduction process.

Reproduction process uses three steps for generating the next generation of individuals. First step is the elite population, the count of elite population is determined based on the ceiling value obtained from 0.05 times the population size. Excluding the elite population, 80% of the new population is generated through crossover and the remaining 20% is generated based on mutation. GA uses a function called, scattered, for crossover operation, which generates a random binary vector to select the genes for the children from the two parent individual.

GA uses a function called, adaptive feasible, for mutation operation, which randomly generate an individual that are adaptive with respect to the last successful and unsuccessful generation. GA runs the selection and reproduction process until it encounters a stopping criteria. Maximum generation count is 100 times the number of variables being solved by the GA. Function and constraint tolerance of 1e-6 and maximum stall generation of 50 is used as the stopping criteria.

3. Results and Discussion

OCR based protection system was implemented successfully in IEEE33 bus radial distribution system before DG were integrated into the system. GA takes an average of 381 seconds for solving the optimization problem. The minimum value of the fitness function was found to be 24.17 seconds. The convergence graph of GA is shown in figure 4. Time Current Curve (TCC) of a coordinated relay pair is presented in Figure 5.

DG were integrated into the network after the implementation of protection system. Integration of DG, reduced the active power loss from 182 kW to 34 kW and improved the minimum bus voltage of 0.984 *pu* to 0.992 *pu* After DG integration, it effected the existing coordination system.

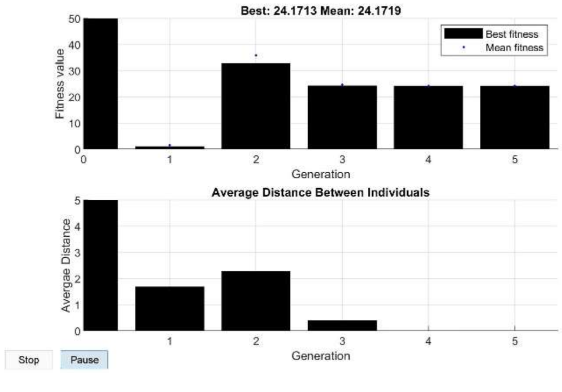

Figure 4: Convergence graph of GA for protection coordination.

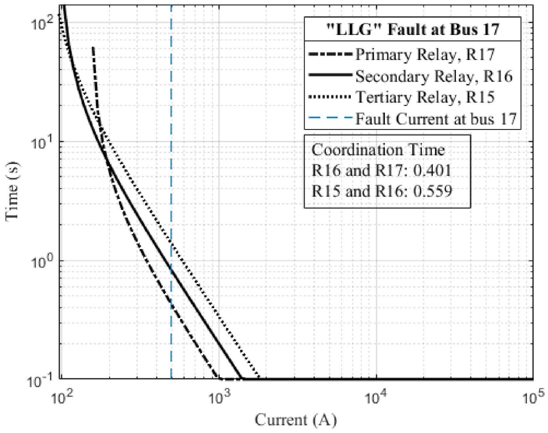

Figure 5: Relay coordiantion in IEEE 33 bus ystem before DG integration

Out of 252 constraints based on inequality (5), 92 constraints were violated by synchronous based DG and out of 3204 constraints base on inequality (6), 692 constraints were violated by synchronous based DG. Miscoordination between a relay pair is show in Figure 6. To regain protection coordination after DG integration, case I was implemented.

Successful protection coordination could not be obtained from case I. For case I, use of large value of FCL, resulted in lower short-circuit current supplied by DG. Which reduced the sensitivity of DG OCR to fault current, thus the DG OCR was unable to detect and clear a fault.

For case I, use of small value of FCL, could not limit the short-circuit current supplied by DG. Which resulted in miscoordination between existing relays. Case II and case III, was successfully implemented. Protection coordination after DG integration was successfully achieved after the implementation of Case II and Case III. The minimum value of the fitness function (or FCL size) was found to be 7.824 ohms for a synchronous based DG.

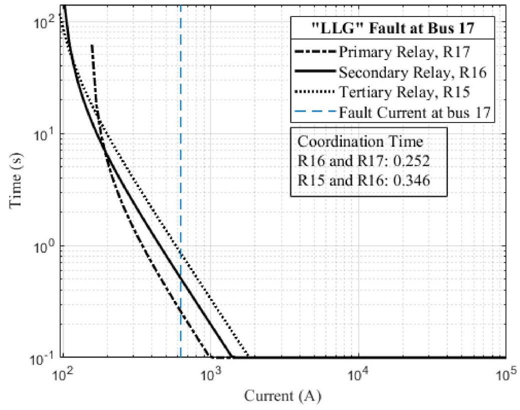

Figure 6: Relay miscoordiantion in IEEE 33 bus ystem after DG integration

Table 1: Coordination of new relay with existing relay

Primary Relay (Existing Relay)	Backup Relay (New Relay)	CTI (s) for different type of DG (I_{SC}/I_r)		
		8	5	2
R7	R34	0.865	0.87	2.62
R15	R35	0.501	0.51	1.82
R25	R36	1.029	1.12	5.03
R32	R37	0.521	0.58	2.04

Table 1, represent the coordination of new OCR with existing relay, for a three phase symmetrical fault at the buses corresponding to the relay number of the primary relay (e.g. for primary relay R7, the fault is at bus 7). Figure 7 represents a comparison between the loss of load for case II (without the implementation of Dual Setting DOCR) and for case III (with the implementation of Dual Setting DOCR) for a permanent three phase symmetrical fault in different buses of the network. From the figure, it can be seen that the loss of load for case III is lower than that for Case II.

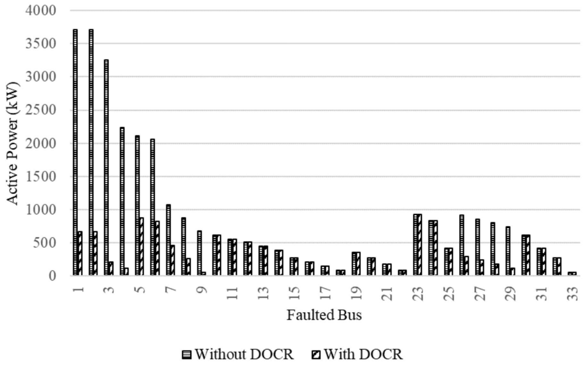

Figure 7: Loss of load for cases, with and without DOCR.

4. Conclusions

Optimal protection coordination and optimal sizing of FCL was obtained for IEEE33 bus radial distribution system after the integration of DG. FCL were located in the nearest branch downstream of DG connected bus and in the nearest branch adjacent to the DG connected branch. New OCRs were used for each DG being integrated into the system. The value of FCL and the setup value of OCR were optimized using GA. To enable DG in islanding mode, few existing OCRs were strategically replaced with dual setting DOCRs. The setup value of DOCRs were also optimized using GA.

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