A Comparative Study on Scenario Based Optimal Overcurrent Relay Coordination for Distribution System with Distributed Generator Using Linear Programing

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Abstract

This paper presents the optimal coordination of overcurrent relay (OCR) with the presence of distributed energy resources (DER) using linear programming techniques. In addition, a comparative scenario-based between non-adaptive relay settings and adaptive relay settings has been investigated. A four-bus radial distribution system is used to test the proposed method. The simulation prosperously has shown that the linear programing can successfully solve for optimal OCR coordination. Meanwhile, an adaptive relay setting can handle the overcoming distribution network problem more efficiently than a non-adaptive relay setting.

Keywords: adaptive protection, optimal coordination of overcurrent relay, linear programing (LP).

1. Introduction

Modern distribution systems consist of various distributed generators (DG) to make reliable power systems [1] and commonly used to supply the local loads [2]. The penetration of distributed generation leads to violating the overcurrent relay (OCR) coordination in the distribution network [2]. The effects of DG on the distribution system is the loss of coordination of distribution system protection. This is because the fault current can be higher when the short circuit location is near to the generator. The impact of DG on OCR coordination effects on both current setting and the operating time of OCR. The coordination time interval (CTI) associated with primary and backup relay pairs is getting violated due to changes in the fault current level [2]. Thus, conventional coordination between primary and backup relays usually fails in the presence of DG. Hence, the interconnection of DG in the distribution system causes an adverse impact on protection coordination. Meanwhile, relay coordination problem has many constraints due to coordination criteria [2]. Therefore, coordination of overcurrent relays with DG is a big challenge for protection engineers.[1]

Several methods to find the optimal value for the coordination of OCR are illustrated in the available literature. Linear programming technique is a powerful scheme for obtaining a basic feasible solution [3]. Big-M and dual simplex methods are used to find the optimum values of time multiplier settings (*TMS*) [4]. With the optimum values for both pick-up current (I_p) and *TMS* nonlinear programming problem (NLP) is a grateful method [5]. Particle swarm optimization (PSO) is a metaheuristic method that follows the social behavior of animals such as bird flocking and is very efficient [6]. A genetic algorithm (GA) is also proposed to find the optimum solution for relay settings in [2]. The latest optimization technique Gravitational Search Algorithm (GSA) is a new technique based on newton's laws of attraction to find the optimum solution for relay setting [1]. Meanwhile, a comparative study of optimization techniques for OCR coordination with DG is mentioned in [7].

However, most researches on optimal OCR coordination concern only non-adaptive OCR, without comparing to adaptive OCR coordination. The investigation on the advantage of emerging adaptive OCR is a benefit to the system. Consequently, the motivation of this paper is to find the optimum values of the OCR setting by used linear programming techniques and comparing the results between using conventional setting and adaptive setting of OCR.

This paper was arranged into four sections as follows. Section 2 represents the problem formulation limit constraint and determined all of the variables. Section 3 indicates the result and discussion form the four bus radial distribution test system. Finally, section 4 provides the conclusion.

2. Problem Formulation

In the general form, the objective function of OCR coordination is a non-linear optimization problem.to optimize both *TMS* and I_p. However, solving nonlinear optimization problem methods are complex as well as time-consuming [2]. To avert complexity, this problem commonly formulated as a linear programming problem (LP) by predetermined I_p based on minimum fault current for relay. In this case study, linear programming is adapted to find optimal *TMS* only. The objective function of the problem is the total operating time of all the relays present in the system [7]. The function is to be minimized so that each relay operates in minimum time and reliability of the system is maintained [7]. The formulated objective function is,

$$\text{minimize } Y = \sum_{i=1}^{NR} t_i, \tag{1}$$

where,

$$t_i = A_i TMS_i, i = 1, \ldots, NR, \tag{2}$$

The manuscript received September 20, 2020; revised November 2, 2020; accepted December 1, 2020; available online April 8, 2021.
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$$A_i = \frac{K_i}{\left(\frac{I_{Ri}}{I_{Pi}}\right)^{n_i} - 1}, i = 1,..., NR, \quad (3)$$

subjected to the coordination constraint,

$$t^k_{b,i} - t^k_{m,i} \geq \Delta t_i, i = 1,..., NC, \quad (4)$$

relay operating time constraint,

$$t_i \geq t_i^{\min}, i = 1,..., NR, \quad (5)$$

and the time multiplier limit constraint,

$$TMS_i^{\min} \leq TMS_i \leq TMS_i^{\max}, i = 1,..., NR. \quad (6)$$

Where,

Y is the total relay operating time (s),
t_i is the operating time of relay *i* for main fault (s) ,
$t_i^{\min}$ is the minimum operating time of relay *i*,
A_i is the constant predetermined for different zones of protection of relay *i*,
TMS_i is the time multiplier of relay *i*,
$TMS_i^{\max}$ is the maximum time multiplier of relay *i*,
$TMS_i^{\min}$ is the minimum time multiplier of relay *i*,
K_i is the constant characteristic of relay *i*,
n_i is the constant characteristic of relay *i*,
I_{Ri} is the current flowing through relay *i* (A),
I_{Pi} is the pick-up current setting of relay *i* (A),
$t^k_{b,i}$ is the operating time of backup relay *i* for fault in zone *k* (s),
$t^k_{m,i}$ is the operating time of primary relay *i* for fault in same zone (s),
Δt_i is the coordination time interval (CTI) (s),
NR is the total number of relay, and
NC is total number of relay for primary and backup coordination.

3. Results and Discussion

According to the problem formulation the main target is to find the *TMS* of all relay and comparative total operating time of relay between non-adaptive relay setting approach and adaptive relay setting approach, so *TMS* is variable here and the total operating time of all the relays for fault in main zone is taken as the objective function which is to be minimized. The objective function is found by integrating the relay characteristic constraint (equations 2 and 3). The other inequality constraints are included in the algorithm. In this paper, the OCR used is IEC Standard Inverse Curve (SI). Therefore, the constraint K = 0.14 and n =0.02, in equation (3). CTI = 0.3 s, in equation (4). The $t^{\min}$ normally used = 0.1 s, in equation (5), and the *TMS* limit in the range is 0.1-1, in equation (6).

3.1 Test Case

A single source four bus radial system with the presence of DG at bus 1. In order to prevent faults in all areas of the system, use five OCR (R_{Gr}, R_{DG}, R_1, R_2 and R_3) installed at the upstream of each transmission line. The multi-scenario of OCR setting is categorized into;
Case I: Grid connected without DG
Case II: Grid connected with DG
Case III: Islanding mode with DG.

As shown in Fig. 1. The fault is created at each bus and fault current is found by relay. Table 2, 3, and 4 gives the fault current seen by each relay for all case.

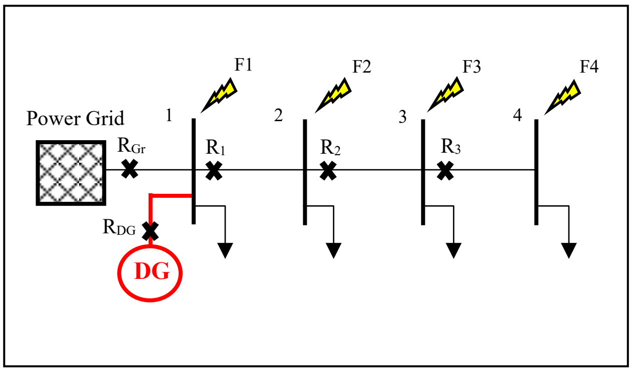

Fig. 1 Four buses radial test system

Table 1 Parameter of the system

No.	Particular	Ratings
1	Line	0+j1.0331 p.u
2	Generator	100 MVA ,22 kV , X'd = 1.00 p.u
3	DG	0.5+j0.5 MVA ,22 kV, X'd = 1.20 p.u

Table 2 Fault current of case I

Fault Point	Fault Current (A)	R_{Gr}	R_{DG}	R_1	R_2	R_3
Bus1	Max	2624.3	-	-	-	-
	Min	2272.7	-	-	-	-
Bus2	Max	1290.8	-	1290.8	-	-
	Min	1117.9	-	1117.9	-	-
Bus3	Max	855.9	-	855.9	855.9	-
	Min	741.2	-	741.2	741.2	-
Bus4	Max	640.2	-	640.2	640.2	640.2
	Min	554.4	-	554.4	554.4	554.4

Note: ‘-‘indicates that the fault is not seen by the relay

Table 3 Fault current of case II

Fault Point	Fault Current (A)	R_{Gr}	R_{DG}	R_1	R_2	R_3
Bus1	Max	2624.3	2186.9	-	-	-
	Min	2272.7	1893.9	-	-	-
Bus2	Max	906.8	755.7	1662.5	-	-
	Min	785.3	654.4	1439.8	-	-
Bus3	Max	548.1	456.8	1004.9	1004.9	-
	Min	474.6	395.6	870.2	870.2	-
Bus4	Max	392.7	327.3	720.0	720.0	720.0
	Min	340.1	283.4	623.5	623.5	623.5

Table 4 Fault current of case III

Fault Point	Fault Current (A)	R_{Gr}	R_{DG}	R_1	R_2	R_3
Bus1	Max	-	2186.9	-	-	-

	Min	-	1893.9	-	-	-
Bus2	Max	-	1175.2	1175.2	-	-
	Min	-	1017.8	1017.8	-	-
Bus3	Max	-	803.5	803.5	803.5	-
	Min	-	695.8	695.8	695.8	-
Bus4	Max	-	610.4	610.4	610.4	610.4
	Min	-	528.6	528.6	528.6	528.6

The procedure of this paper starts from reading the system data, find the short circuit current flowing through each relay, predetermined I_p, and calculate the *TMS* using LP as shown in Fig.2

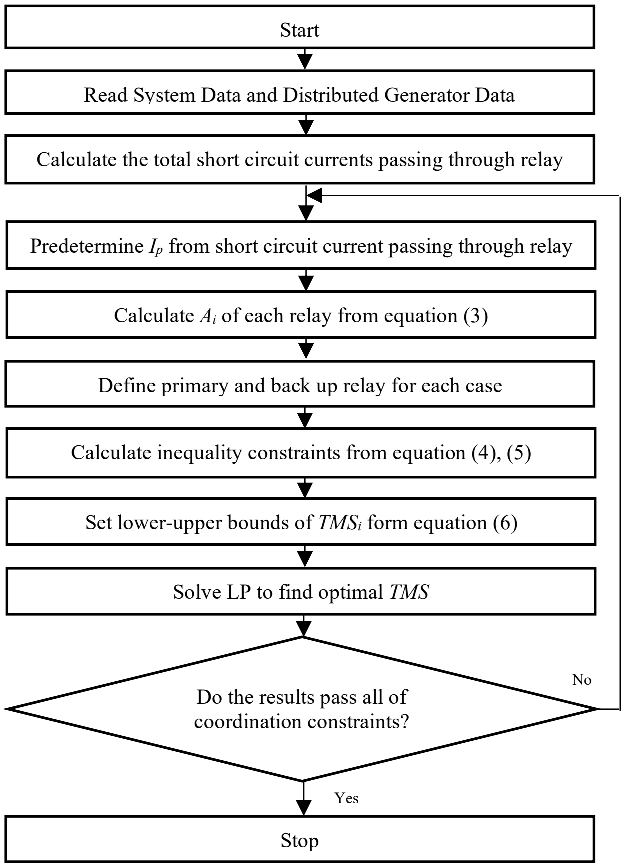

Fig. 2 Computational procedure

3.2 Non-adaptive relay setting

In this non-adaptive relay setting case, the relay will be set I_p and *TMS* only once for all situations, and must be set to cover all of the fault cases that can occur in the system (Cases I-III). I_p is predetermined by the smallest fault current flowing through the relays of the three cases divided by three. The predetermined of I_p as shown in Table 5 and the selection of the primary relays and backup relays for coordination as shown in Table 6.

Table 5 Pick-up current for each relay with non-adaptive relay

Relay	I_p (A)
R_{Gr}	261.76
R_{DG}	218.13
R_1	231.93
R_2	176.20
R_3	176.20

Table 6 Primary and backup relay with non-adaptive relay

Fault Point	Primary	Backup
Bus1	R_{Gr}, R_{DG}	-
Bus2	R_1	R_{Gr}, R_{DG}
Bus3	R_2	R_1
Bus4	R_3	R_2

In this non-adaptive relay setting case has three difference objective function for comparative three difference case .The value of A_i shown in Table 7 and the optimal *TMS* result shown in Table 8.

Table 7 Constant A_i with non-adaptive relay

	Case I	Case II	Case III
A_1	2.967	2.967	0
A_2	0	2.967	2.967
A_3	4.008	3.484	4.244
A_4	4.359	3.951	4.544
A_5	3.536	4.903	5.564

Table 8 The optimal *TMS* results with non-adaptive relay

	Non-adaptive relay setting		
	Case I	Case II	Case III
TMS_{Gr}	0.2544	0.2544	0.2544
TMS_{DG}	0.2802	0.2802	0.2802
TMS_1	0.1991	0.1991	0.1991
TMS_2	0.1612	0.1612	0.1612
TMS_3	0.1	0.1	0.1
Y (s)	2.791	3.4068	2.9652

3.3 Adaptive relay setting

In adaptive relay setting case, the relay can be set I_p and *TMS* multiple times depending on where the system is working at that time. So, I_p can be predetermined appropriately in each case. The predetermined of I_p for each system case as shown in Table 9, the selection of the primary relays and backup relays for coordination as shown in Table 10, the value of A_i shown in the Table 11, and the optimal *TMS* result shown in Table 12.

Table 9 Pick-up current for each relay with adaptive relay

Relay	I_p (A)		
	Case I	Case II	Case III
R_{Gr}	372.63	261.76	-
R_{DG}	-	218.13	339.26
R_1	247.06	290.06	231.93
R_2	184.8	207.83	176.2
R_3	184.8	207.83	176.2

Table 10 Primary and backup relay with adaptive relay

Fault Point	Case I		Case II		Case III	
	Primary	Backup	Primary	Backup	Primary	Backup
Bus1	R_{Gr}	-	R_{Gr} R_{DG}	-	R_{DG}	-
Bus2	R_1	R_{Gr}	R_1	R_{Gr} R_{DG}	R_1	R_{DG}
Bus3	R_2	R_1	R_2	R_1	R_2	R_1
Bus4	R_3	R_2	R_3	R_2	R_3	R_2

Table 11 Constant A_i for with adaptive relay

	Case I	Case II	Case III
A_1	3.517	2.967	0
A_2	0	2.967	3.687
A_3	4.164	3.939	4.244
A_4	4.497	4.372	4.544
A_5	5.564	5.564	5.564

Table 12 The optimal *TMS* results with adaptive relay

	Adaptive relay setting		
	Case I	Case II	Case III
TMS_{Gr}	0.1874	0.1777	-
TMS_{DG}	-	0.1777	0.1909
TMS_1	0.1783	0.1749	0.1796
TMS_2	0.1539	0.1539	0.1539
TMS_3	0.1	0.1	0.1
Y (s)	2.6501	2.9726	2.722

3.4 Discussion

Table 13 Comparative non-adaptive and adaptive relay

	Case I		Case II		Case III	
	Non-adaptive	Adaptive	Non-adaptive	Adaptive	Non-adaptive	Adaptive
TMS_{Gr}	0.2544	0.1874	0.2544	0.1777	0.2544	-
TMS_{DG}	0.2802	-	0.2802	0.1777	0.2802	0.1909
TMS_1	0.1991	0.1783	0.1991	0.1749	0.1991	0.1796
TMS_2	0.1612	0.1539	0.1612	0.1539	0.1612	0.1539
TMS_3	0.1	0.1	0.1	0.1	0.1	0.1
Y (s)	2.791	2.6501	3.4068	2.9726	2.9652	2.722

From the simulation results, the DG penetration at bus 1 when considering the system operation (Cases I-III). However, the short circuit current of the three cases will flow in the same direction. The primary and backup relay assignments for coordination are still similar in all three cases. In case II the level of short circuit current is significantly increased. but still, it is possible to use a non-adaptive relay setting method and find the optimal *TMS* to decrease the total relay operating time as in the table and can be seen that the non-adaptive relay setting method there will be only one optimal *TMS* scenario which is used to protect all of the system operations. However, comparing to the adaptive relay setting method, it can be seen that the optimal *TMS* is appropriate for each system operation. Resulting in the total relay operating time of the system is significantly reduced, as shown in the table.The reduction of fault clearing time is leading to system reliability enhancement.

4. Conclusion

The linear programing optimization technique is used in this paper to find the optimal *TMS* of five OCR relays so that their operating time can be minimized. The objective function is formulated for three cases. Further, it is minimized by maintaining the range of *TMS* of each relay as 0.1-1 and CTI as 0.3 s. The range of I_p determined for each relay is based on minimum fault current flowing through a relay. A comparative study between the adaptive relay setting and non-adaptive relay setting for every case of the system was mentioned in this paper. From the simulation results, it was found that the adaptive relay setting method results in the total operating time of all relay faster than the non-adaptive relay setting method. Therefore, it can be concluded that the adaptive relay setting method is more suitable for distribution systems with the presence of DG.

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