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Impact of distributed generator controllers on the coordination of overcurrent relays in microgrid

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Abstract: In the presence of distributed generators (DGs) the fault current sensed by relay in the forward direction is larger than that in the reverse direction. Thus, it is required to have different relay settings for both forward and reverse directions. This paper investigates the impact of DG controller operating modes on the coordination of conventional and dual setting overcurrent relays (OCRs). The different DG control modes are voltage control mode (VCM) and current control mode (CCM). A comparative study of protection coordination is presented in both the operating modes of the DG. This scheme is tested on a 3-bus meshed system and the IEEE 34-node distribution system in which an electronically interfaced DG is connected. The protection coordination problem is formulated as a nonlinear programming problem and the optimal settings of OCRs are determined by using a genetic algorithm.

Key words: Distributed generator, protection coordination, overcurrent relay, dual setting, controller, meshed system, voltage control mode, current control mode

1. Introduction

Along with the various advantages of distributed generators (DGs), they have negative impacts on the performance of the distribution system in terms of the level of fault current, which increases depending upon the location and penetration level [1]. The increase in short-circuit current may cause protection coordination problems. The consequences associated with the integration of DGs are blinding of protection, false/sympathetic tripping, recloser-fuse miscoordination, fuse-fuse miscoordination and failed auto reclosing [2–4]. The type of DG also has a significant impact on the protection coordination problem. For example, the fault current contribution of an electronically interfaced DG (ECDG) is low and therefore it has negligible impact on protection coordination [5–8]. However, ECDGs may also cause coordination problems if the penetration level of the DG is high [9].

Relays, reclosers, and fuses are mainly used in power systems for protection at subtransmission and distribution levels. These protective devices should be sensitive as well as selective enough such that they sense and isolate the fault as soon as possible. Coordination among protective devices in a distribution system is a very complicated power system protection problem. All these protective devices should be properly coordinated to ensure reliable and uninterrupted operation of the system. In this process the time of operation of the backup relay should delay the time of operation of the primary relay by some margin, which is known as the

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coordination time interval (CTI). If the backup relay operates prior to the primary relay or if the time margin between the operation of relays differs from the CTI, coordination among the operating relay pair fails [10,11].

This section presents an extensive literature survey of various heuristic optimization algorithms used to ensure coordination of directional overcurrent relays (OCRs). The conventional optimization methods proposed have some drawbacks as there is a limitation in terms of the number of constraints they can handle [12]. Evolutionary algorithms work on the theory of a population of individuals. These algorithms are based on the concept of Darwinian evolution of "the survival of the fittest", which depends on natural processes of reproduction, mutation, competition, and selection [13,14]. A genetic algorithm is a methodology of optimization that follows the evolution of a population. The convergence rate of a GA is fast towards the fittest value and also it consumes less memory [15]. Hybrid GAs have also been used to solve the directional OCR coordination for different network topologies [16]. In particle swarm optimization (PSO) the social behavior of flocking birds and schooling fish is used. PSO has an inherent property in terms of its robustness and high computational efficiency [17,18]. Various linear programming problem techniques have been used for OCR coordination [19]. A sequential quadratic programming method has been used for optimizing all the settings of OCRs [20].

In a distributed system where fault current has a tendency to flow in the forward or reverse direction, it is necessary to incorporate relays that respond differently for each direction. Due to this requirement dual setting OCRs have been proposed. In [21,22], the directional relays were associated with different settings for forward and reverse directions of fault current for radial and meshed distribution systems, respectively. However, the impact of DG control modes on the coordination of conventional and dual setting OCRs has not been addressed. Therefore, a comprehensive analysis of the fault current contribution of DGs operating in VCM and CCM and its impact on protection coordination of conventional and dual setting OCRs is presented in this paper.

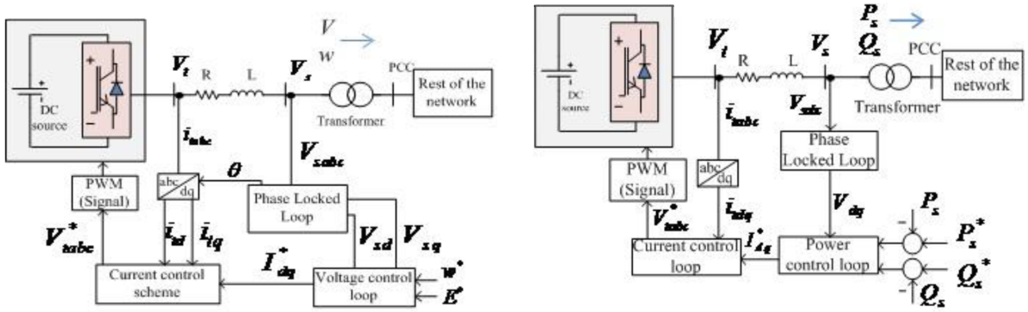
2. Distributed generator controllers and their control schemes

There should be proper coordination among the DG controllers such that the protection coordination of OCRs can be retained in both modes of operation of the microgrid. The DERs operate in constant real/reactive power control mode to reduce the power import from the utility grid in the grid-connected mode. However, during islanded mode the main objective of controllers should be to control the network frequency and voltage and also to fulfill the instantaneous power demand to loads. The islanding condition is to be detected by DG units and therefore the control mode is to be switched from CCM to VCM. In this entire study the impact of unbalanced load current and fault current on the earth fault relays has not been considered as the value of the earth fault current may become even lower than the load current due to large impedance between neutral and ground levels. In the presence of earth fault relays, it should be ensured that the setting of such relays be higher as compared to normal overcurrent relays. Hence, it is required to take the pick-up current above the maximum unbalanced current under normal conditions. A rule of thumb is to assume the maximum unbalance factor to be between 5% and 10%.

Figure 1a demonstrates the dynamic model of a 3-phase voltage source converter (VSC) working in the d-q reference frame. There are two control loops: an external control loop, which is working in the voltage control scheme, and an internal control loop, which is working in the current control scheme. Figure 1b shows the basic control structure of a 3-phase current source converter (CSC) working in the d-q reference frame.

3. Formulation of the protection coordination problem

In the conventional protection scheme inverse definite minimum time (IDMT) relays with normal inverse (NI) characteristics are used. The operating time of IDMT relays depends on the magnitude of the fault current,



(a) 3-Phase voltage source controller (b) 3-Phase current source controller

Figure 1. Control schemes used for DGs in different operating modes: a) 3-phase voltage source controller, b) 3-phase current source controller.

plug setting multiplier (PSM), and time multiplier setting (TMS). The magnitude of the fault current sensed by the relay depends on the type and location of the fault, whereas the other parameters like pick-up current ($\mathbf{I_p}$) and TMS are to be optimally determined. The coordination problem is formulated as a nonlinear programming problem where the objective functions (**OFs**) are the summation of the operating times of all the combinations of primary and backup relays. The time of operation of IDMT relays and its variation on other parameters is represented by Eq. (1). According to IEC 60255-151, IDMT relays are characterized as normal inverse, very inverse, and extremely inverse types. Depending on the value of A and B, the type of relay varies. In this paper normal inverse characteristics of IDMT relays are considered and hence the value of A and B is 0.14 and 0.02, respectively [23]. Numerical relays are of different types; however, each type has a similar configuration. Numerical relays have different setting groups, which vary from tens to hundreds of settings. The different functions accessible on a given relay are indicated by standard ANSI device numbers. The ANSI device number for the IDMT relay is 51. The **OF**, which is the summation of overall operating times of primary and backup relays, is represented by Eq. (3).

$$t = \frac{A}{\left(\frac{I_f}{I_p}\right)^B - 1} TMS \tag{1}$$

$$t = \frac{A}{(PSM)^B - 1} TMS \tag{2}$$

$$OF = \sum_{k=1}^{m} \left(\sum_{i=1}^{n} t_{pik} + \sum_{j=1}^{n} t_{bjk} \right) \tag{3}$$

In Eq. (3), **i** and **j** indicate the primary and backup relays having total number of relays where n and k represent the fault locations. The total location of fault is taken as m. Therefore $\mathbf{t_{pik}}$ represents the time of operation of the primary ith relay with fault at the kth location and $\mathbf{t_{bjk}}$ represents the time of operation of the jth backup relay. If the backup relay operates prior to the primary relay or if the time margin between the operations of relays differ from the CTI, the coordination among the relay pair fails. The value of the CTI generally varies from 0.2 s to 0.5 s, which is taken as 0.4 s here and is represented by Eq. (4). Another set of constraints are related to $\mathbf{I_p}$ and TMS. The minimum value for $\mathbf{I_p}$ is chosen such that it is slightly larger than the normal load current and it is represented by Eq. (5). In usual practice, pick-up current is 1.25% of the maximum load current and the load current should be the feeder current, not the bus load current. The upper and lower bounds for TMS have also been considered and are shown by Eq. (6). With the incorporation of the DG at the respective bus, the original setting with which the relay was supposed to operate gets changed due to the bidirectional power flow. Thus, the TMS value gets changed in a discrete manner so that adaptive setting is accomplished with respect to the change in system configuration.

To calculate the settings of OCRs, two different methodologies are utilized: a conventional approaches, for example trial and error [24], and optimization techniques. Because of the expanding size and complexity of power systems, the optimization techniques are broadly utilized as they have higher accuracy than the conventional approaches [25]. In this context, the GA is a strong candidate as a metaheuristic optimization technique in which the OF, as a function of TMS, is minimized. The total operating time of the relay decreases and hence the reliability of the system is enhanced. Another advantage of the GA is that its convergence rate is high, i.e. it gives better results in a faster time. Due to these advantages the GA has been used to minimize the overall operating time of relays. Therefore, the optimal settings of relays are evaluated, which satisfies the various coordination constraints as mentioned below.

$$t_{bjk} - t_{pik} \geq 0.4 \tag{4}$$

$$I_{p_{i\,\min}} \leq I_{p_i} \leq I_{p_{i\,\max}} \tag{5}$$

$$TMS_{i_{\min}} \leq TMS_i \leq TMS_{i_{\max}} \tag{6}$$

Dual setting directional OCRs operate for faults in both forward and reverse directions. Therefore, these relays have two different pairs of settings. In the forward direction for primary protection operation the relay setting is $\mathbf{TMS_f}$ and $\mathbf{I_{pf}}$, whereas in the reverse direction the backup protection setting of the relay is $\mathbf{TMS_r}$ and $\mathbf{I_{pr}}$. In this scheme the same relay acts as primary protection for fault current in the forward direction and behaves as secondary protection for fault current in the reversed direction. The characteristics of dual setting directional OCRs are expressed by Eqs. (7) and (8).

$$t_{f_{ik}} = \frac{0.14}{\left(\frac{I_{ffik}}{I_{pfi}}\right)^{0.02} - 1} TMS_{f_i} \tag{7}$$

$$t_{r_{jk}} = \frac{0.14}{\left(\frac{I_{frjk}}{I_{prj}}\right)^{0.02} - 1} TMS_{r_j} \tag{8}$$

The flow chart of the protection coordination problem for both conventional and dual setting relays is shown in Figure 2. The algorithm is the same for both conventional and dual setting OCRs, except for the formulation of the primary-backup combination of relays and objective functions.

4. System description and simulation setup

Figure 3a shows a three-bus meshed system. The parameters of the system are shown in Table 1. The directional OCRs of single setting R_1–R_6 are connected at both ends on the line connecting different buses. The DG is rated such that it can fulfill the load demand in islanded condition [26]. The power rating of generators G_1, G_2, and G_3 is 25 MVA, 50 MVA, and 100 MVA, respectively, whereas the operating voltage of each DG is 69

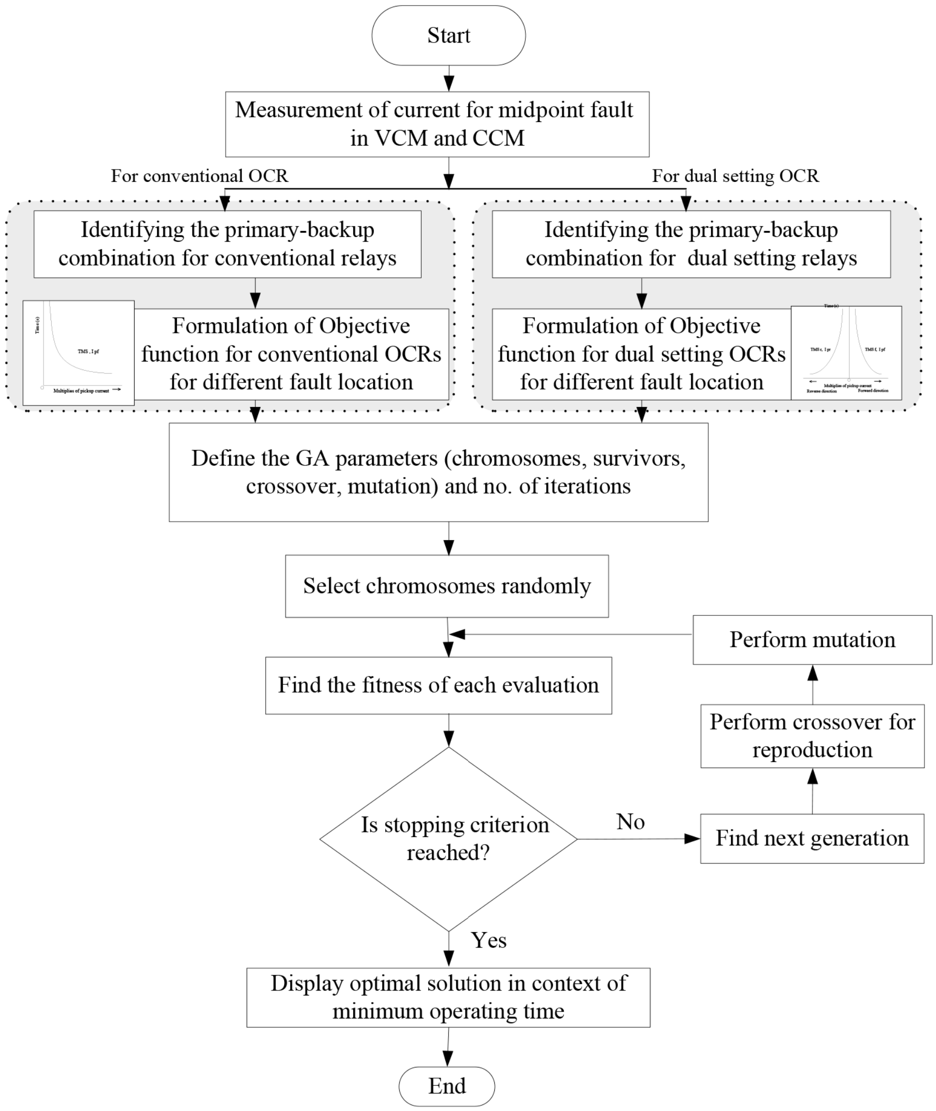
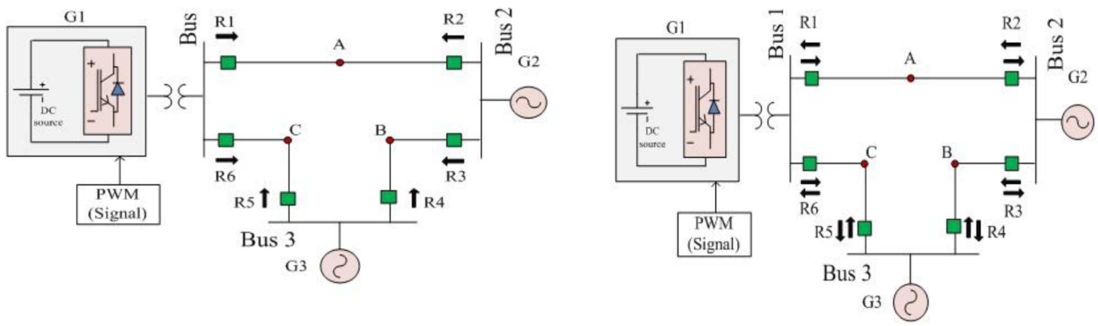


Figure 2. Flow chart of relay coordination problem using GA.

kV. For the transformer and generator, a differential protection scheme with dual slope characteristics is to be utilized. In this case, the major concern is the operation of differential relays. However, in this paper OCRs in the distributed system are addressed. To address the protection scheme of the generator and transformer a coordination of overcurrent, differential, and distance relay has to be accomplished. In the case that any line contains the series capacitor, then the equivalent impedance of that particular line will be reduced, which will in turn increase the level of current. Apart from the benefits of the series capacitor, their presence in the fault loop affects the voltage and current signals at the relay location [25]. In this condition the relays connected to the line may maloperate for the initial settings. Therefore, the setting of the OCRs should be fixed in such a manner that for normal line current the relay does not operate.

The fault current characteristics of inverter-based DERs (IBDERs) are completely different from the rotating machine-based DERs due to the lack of inertia and inductive property. The fault current of an IBDER is about 1.5–2 times the inverter rated current; however, there is a wide range for the magnitude of the fault



(a) 3-bus system with conventional OCRs

b) 3-bus system with dual setting OCRs

Figure 3. Three-bus distributed system with electronically coupled DG: a) 3-bus system with conventional OCRs, b) 3-bus system with dual setting OCRs.

Table 1. System parameters.

Grid voltage	1440 V	Switching frequency	3780 Hz
Grid frequency	50 Hz	Grid inductance	100 μH
Grid resistance	25 mΩ	DC bus voltage	1200 V
Transformer inductance	100 μH	Filter inductance	50 μH
Filter resistance	11.5 mΩ	Transformer ratio	3:1

current and clearance time in the case of higher DG penetration. Some IBDERs have fault current up to 7 times the rated current. In VCM, the voltage output of the DG is maintained nearly constant, whereas the current changes according to the type and location of fault. Therefore, in order to make the voltage of the PCC bus constant, the DG is operated in VCM mode. However, in CCM, the current contribution of the DG is nearly constant but the voltage changes according to the system conditions.

Therefore, to maintain the constant current, the DG is operated in CCM. In this way the current sensed by the relay is different in both of the operating modes. As the relays connected in the system are adaptive in nature, settings of the relays (I_P and TMS) will be automatically adjusted such that it can discriminate between the fault current and the normal load current.

4.1. Simulation result of 3-bus system consisting of conventional OCRs with single setting

The system is simulated for a fault at locations A, B, and C and the primary/backup combination of the relay using the conventional scheme is estimated. The primary and backup relay combination is formed, which is shown in Table 2. After estimating the fault current in VCM, the value of PSM is calculated for each relay, and using Eq. (2), the characteristics constant for each relay are evaluated, as shown in Table 3.

Table 2. Primary and backup combination of relays with DG operating in VCM.

Fault location	Operating relay (primary)	Fault current (A)	Operating relay (backup)	Fault current (A)
A	R1	224	R5	164.6
	R2	486.5	R4	263
B	R3	371	R1	199.8
	R4	584.9	R6	227.1
C	R5	588.8	R3	255.8
	R6	223	R2	163.3

Table 3. Characteristics constant for different pairs of relays in VCM.

Fault location	Relay characteristic constant					
	R1	R2	R3	R4	R5	R6
A	4.5982	3.0072		3.6743	6.3279	
B	3.4232		5.2696	3.3385		3.8936
C		4.6122	3.8787		3.3276	8.6583

$$OF = 8.0214\,TMS_1 + 7.6194\,TMS_2 + 9.1483\,TMS_3 + 7.0128\,TMS_4 + 9.6555\,TMS_5 + 12.5519\,TMS_6 \quad (9)$$

$$\mathbf{6.3279\,TMS_5 - 4.5982\,TMS_1} \geq 0.4 \quad (10)$$

$$3.6743\,TMS_4 - 3.0072\,TMS_2 \geq 0.4 \quad (11)$$

$$3.4232\,TMS_1 - 5.2696\,TMS_3 \geq 0.4 \quad (12)$$

$$\mathbf{3.8936\,TMS_6 - 3.33385\,TMS_4} \geq 0.4 \quad (13)$$

$$\mathbf{3.8787\,TMS_3 - 3.3276\,TMS_5} \geq 0.4 \quad (14)$$

$$4.6122\,TMS_2 - 8.6583\,TMS_6 \geq 0.4 \quad (15)$$

Table 3 is used to formulate the OF in VCM. The variation of OF with TMS of relays is represented by Eq. (9). Therefore, OF is to be minimized by satisfying the constraints of the coordination scheme. The constraints related to the CTI are represented by Eqs. (10)–(15). There is another set of constraints related to the minimum operating time of the relay. In this paper, it has been assumed that the minimum operating time of each relay should be greater than 0.2 s, whereas the range of TMS is taken from 0.02 s to 1.2 s. The optimal solution of the protection coordination problem using the GA is shown in Table 4, from which it has been found that the total relay operating time in VCM is 23.014 s.

Table 4. Optimum value of TMS in VCM when solved using GA.

TMS1	TMS2	TMS3	TMS4	TMS5	TMS6	Total relay operating time (T)
0. 8655	0.0280	1.2000	0.0200	0.0200	0.1174	23.014 s

The fault current sensed by the relay in CCM is different from the value of current in VCM, as shown in Table 2. As the time of operation of OCRs depends on the level of fault current, the time of operation of relays and also the settings will be different in CCM as compared to VCM. A similar study of protection coordination has been performed when the DGs are operating in CCM. The objective function has been derived in CCM, which is represented by Eq. (16).

$$OF = 7.8992\,TMS_1 + 7.9877\,TMS_2 + 9.6867\,TMS_3 + 7.4131\,TMS_4 + 9.4923\,TMS_5 + 13.2660\,TMS_6 \quad (16)$$

In this case there are six constraints related to the CTI, whereas six sets of constraints are related to the minimum operating time of each relay, which is taken as 0.2 s in this case while the TMS is taken in the range of 0.02 to 1.2 s. The optimal value of TMS of an individual relay along with the total operating time of the relay is shown in Table 5. It can be observed that total operating time in this case is 28.7658 s, which is larger than the total operating time when the DG is operating in VCM.

Table 5. Optimum value of TMS in CCM when solved using GA.

TMS1	TMS2	TMS3	TMS4	TMS5	TMS6	Total relay operating time (T)
0.3449	0.0200	0.9154	0.1221	0.0200	1.2000	28.7658 s

4.2. Simulation results of 3-bus system consisting of dual setting OCRs

In Figure 3b, six directional OCRs (R_1–R_6) with dual setting characteristics are shown. The primary and backup combination of relays for a fault at A, B, and C using a dual setting scheme is formulated, which is shown in Table 6. In the case of a fault at point A, R_1 acts as the primary, and if it fails to operate R_6 operates as the backup relay. However, for the same fault location, if relay R_2 acts as the primary, its backup combination is R_3. After calculating the fault current sensed by each relay, the PSM is calculated for both forward and reverse directions, and by using Eqs. (7) and (8), the characteristics constant for each relay are evaluated, from which the OF is formulated, which is represented by Eq. (17).

Table 6. Primary/backup combination of dual setting relays with DG operated in VCM.

Fault location	Primary relay	Fault current (A)	Backup relay	Fault current (A)
A	R1	224	R6	227.1
	R2	486.5	R3	255.8
B	R3	371	R2	163.3
	R4	584.9	R5	164.6
C	R5	588.8	R4	263
	R6	223	R1	199.8

$$OF = 9.5816\,TMS_1 + 8.8518\,TMS_2 + 12.6528\,TMS_3 + 8.8480\,TMS_4 + 12.1633\,TMS_5 + 17.1228\,TMS_6 \quad (17)$$

The OF represented by Eq. (17) is to be solved to get the minimum value of the overall operating time of OCRs by maintaining the various constraints related to the CTI and minimum operating time of relays. Table 7 shows the optimal solution of the protection coordination problem. From the different optimal values of TMS, the total operating time of relays has been computed as 15.2155 s.

Table 7. Optimum value of TMS in VCM for dual setting relays.

TMS1 = 0.0200	TMS2 = 0.0200	TMS3 = 0.2858
TMS4 = 0.0200	TMS5 = 0.6103	TMS6 = 0.2120
Total relay operating time (T) = 15.2155 s		

The same study has been performed when the DG controller is operating in CCM. The fault current sensed by the relays is shown in Table 8, which is used to calculate the PSM and constant relay characteristics. The OF is derived and represented by Eq. (18). The optimal solution of the problem is shown in Table 9, where it can be observed that the total relay operating time in CCM is 15.9684 s, which is higher than the total operating time of relays obtained in VCM.

$$OF = 9.5064\,TMS_1 + 8.3365\,TMS_2 + 12.6524\,TMS_3 + 8.8879\,TMS_4 + 10.4664\,TMS_5 + 18.3264\,TMS_6 \quad (18)$$

Table 8. Fault current sensed by dual setting relays with DG operated in CCM.

Fault location	Primary relay	Fault current (A)	Backup relay	Fault current (A)
A	R1	240.8	R6	214.9
	R2	422.2	R3	263.2
B	R3	352.3	R2	192.4
	R4	553.8	R5	204.6
C	R5	515.7	R4	266.2
	R6	212	R1	192.5

Table 9. Optimum value of TMS in CCM for dual setting relays.

TMS1 = 0.7480	TMS2 = 0.0200	TMS3 = 0.1744
TMS4 = 0.0200	TMS5 = 0.5449	TMS6 = 0.0329
Total relay operating time (T) = 15.9684 s		

4.3. Simulation results of IEEE 34-node system consisting of dual setting OCRs

The methodology adopted for the 3-bus system is extended in a similar manner for the IEEE 34-node system. There are four voltage levels in this 34-node system (66 kV, 33 kV, 11 kV, and 400 V). In this system the relay coordination scheme with the impact of DG control modes has been performed on the 11-kV part, which is shown in Figure 4. The IBDER is connected at node 864. In this system, a midpoint fault has been created at 13 locations (F_1–F_{13}) and the primary-backup combination has been formulated in the same manner, which is shown in Table 10. In this system, 16 dual setting overcurrent relays are connected at suitable locations.

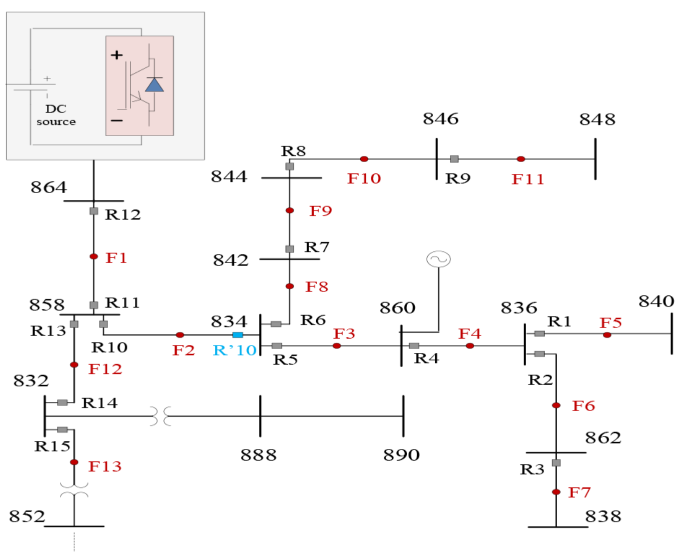


Figure 4. The 11-kV part of the IEEE 34-node distribution system.

$$OF = 2.108\,TMS_1 + 4.796\,TMS_2 + 2.232\,TMS_3 + 7.373\,TMS_4 + 5.053\,TMS_5 + 5.281\,TMS_6 + 4.777\,TMS_7 + 4.518\,TMS_8 + 2.102\,TMS_9 + 7.673\,TMS_{10} + 9.295\,TMS_{11} + 2.877\,TMS_{12} + 11.606\,TMS_{13} + 6.128\,TMS_{14} + 10.392\,TMS_{15} + 6.163\,TMS_{10'} \tag{19}$$

Eq. (19) represents the fitness function, which is a function of TMS, when the DG operates in VCM. On the same system, when the DG operates in CCM, the expression for fitness function is represented by Eq. (20).

Table 10. Primary and backup combination of relays in IEEE 34-node system.

Fault location	Primary relay (RP)	Backup relay (RB)
F1	R11	R14, R10'
F2	R10	R14, R12
F3	R5	R10
F4	R4	R5
F5	R1	R4
F6	R2	R4
F7	R3	R2
F8	R6	R10
F9	R7	R6
F10	R8	R7
F11	R9	R8
F12	R13	R12, R10'
F13	R15	R13

$$\begin{aligned} OF = \; & 1.841\,TMS_1 + 3.898\,TMS_2 + 1.840\,TMS_3 + 6.401\,TMS_4 + 6.731\,TMS_5 + 4.615\,TMS_6 \\ & +4.037\,TMS_7 + 3.919\,TMS_8 + 1.869\,TMS_9 + 12.886\,TMS_{10} + 17.105\,TMS_{11} \\ & +2.360\,TMS_{12} + 16.475\,TMS_{13} + 9.726\,TMS_{14} + 9.726\,TMS_{15} + 8.006\,TMS_{10'} \end{aligned} \tag{20}$$

The impact of control modes is also reflected through a series of simulation results with different case studies being carried out. Now Eqs. (19) and (20) are solved using the GA to get the optimum value of OF along with the optimal value of TMS of individual relays by considering the constraints related to minimum operating time and CTI. In this case the CTI and minimum operating time are also considered as 0.4 s and 0.2 s, respectively. The optimized value of TMS of an individual relay is shown in Table 11. Therefore, in this case, the total operating time in VCM is less than the total operating time in CCM.

Table 11. Optimal value of TMS using GA for dual setting OCRs.

TMS	VCM	CCM	TMS	VCM	CCM
TMS1	0.3127	0.2968	TMS9	0.9996	0.9803
TMS2	0.7107	0.7018	TMS10	0.0690	0.0671
TMS3	0.3719	0.3623	TMS11	0.0698	0.0668
TMS4	0.0920	0.0816	TMS12	0.0703	0.0690
TMS5	0.8784	0.8718	TMS13	0.0690	0.0690
TMS6	0.0690	0.0668	TMS14	0.0795	0.0598
TMS7	0.5644	0.5133	TMS15	0.2945	0.0811
TMS8	0.0690	0.0690	TMS10'	0.5613	0.2693
Total operating time in VCM				19.5034 s	
Total operating time in CCM				21.2050 s	

5. Conclusion

The contribution of a DG to a fault depends on the mode of operation of the controller, i.e. whether it is operating in VCM or in CCM. From various case studies it has been observed that the mode of operation of DG controllers has a significant impact on the setting and overall operating time of relays. It can also be concluded that total operating time of dual setting relays is reduced to a considerable extent in both operating modes as compared to conventional OCRs having a single setting. A comparative analysis of all the studies of protection coordination performed in this paper is demonstrated in Table 12. It has been noted that in VCM the operating time of relays reduces by 33.88% when dual setting relays are used in the system. In CCM, the operating time of relays reduces by 44.48% in the presence of dual setting relays.

Table 12. Comparative analysis of total relay operating time in 3-bus system.

Mode of operation	Operating time (conventional scheme)	Operating time (dual setting scheme)	Percentage reduction
Integrated VCM	23.0140 s	15.2155 s	33.88%
Integrated CCM	28.7658 s	15.9684 s	44.48%

If the DG penetration level increases, then it may be difficult to maintain the relay setting optimally in both operating modes. Therefore, the key issue that requires attention is to perform protection coordination studies by incorporating fault current limiters such that proper coordination can be retained among the various OCRs present in the system.

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