Study of Impact of Dual Setting Overcurrent Relay Characteristics on Protection Coordination in Synchronous DG based Microgrids

N RAJASEKHAR
Transmission Corporation of
TELANGANA, Hyderabad, 500004
INDIA
nrjshkr.239@gmail.com

STP SRINIVAS
BITS Pilani - Hyderabad
Dept of Electrical & Electronics Engineering
INDIA
stps@hyderabad.bits-pilani.ac.in

Abstract: Communication-based protection plays a vital role in microgrid operation in smart power grids. Operation of microgrids with Distributed Generation (DG) has features like bidirectional flows and variable short circuit currents, which challenge the performance of conventional directional overcurrent relays (CDOCRs). In the microgrid scenario, dual setting overcurrent relays (DS-DOCRs) have shown better operation in line protection compared to CDOCRs. This paper investigates the performance of CDOCRs and DS-DOCRs and proposes a methodology for microgrid protection with the assistance of communication channels, which can be used to overcome the limitations of directional relay miscoordination. The relay coordination problem is formulated as nonlinear constrained optimization and solved by using the GA-NLP programming approach. The communication-based microgrid protection logic was tested for 9 bus microgrid test systems and IEEE 30 bus system, and the performance is found to be satisfactory.

Key–Words: Overcurrent relay, Protection coordination, dual relay settings, nonlinear optimization, communication logic

1 Introduction

Increasing concerns of global warming and preventive actions to reduce carbon footprint led electrical power generation to look towards more eco-friendly ways of power generation from freely available renewable natural resources. This type of power generation is fuel-free and can be made so compact that it can be fit in the neighborhood of power consumers. Such a type of power generation can be termed as Distributed Generation (DG). An electrical distribution system with DG can be made independent if the DGs are capable of supplying the available load with or without the help coupling to the main power grid. Such self-reliable distribution systems can be termed as microgrids. Microgrid operation, though advantageous in terms of utilizing renewable energy and autonomous operation, is complex in terms of control and protection. Because of the existence of DGs in the distribution side, the fault currents become bidirectional. DG connected distribution system mimics the behavior of an interconnected transmission system [1] for which directional overcurrent relays can be an economical and effective means of protection. Changes in network configuration, which is quite prevalent in microgrids, change both current magnitude and direction, and it is tough to recalibrate the relay settings every time the topological network change is detected. In traditional power systems, optimal relay settings may be achieved by considering all possible network topologies [2,3] by properly defining the objective function and constraints. In low DG penetrated microgrids, DGs are ceased from contributing to the fault current [4]. But, with significant DG penetration protection, coordination becomes increasingly complex, and it is not suggestive of ceasing the DGs as it interrupts a large amount of power flow in the system [4],[5]. When it comes to fault current contribution, synchronous DGs have a profound effect on protection coordination as compared with inverter-based DGs [5]. In order to overcome these issues, the protection system components have to be designed with sophisticated relay algorithms, including the adaptive feature. Adaptive relays can change their settings online, and whenever a topological change is detected, the relay settings are updated automatically to make the protection system resilient and adaptive to system changes [6].

After the advent of numerical protection, microprocessor-based DOCRs have been designed to be feasible in including user-defined relay characteristics, which helped researchers to design new non-standard overcurrent relay characteristics [8,9] those are suitable for operation in distribution networks integrated with DGs. It is to be noted that the traditional protection schemes employed for conventional distribution networks with high inertia are not valid in the microgrid network as its behavior is likely to change more often. For this reason, MPDOCRs require effective communication assistance and fast data acquisition systems to work in par with changing network conditions.

A centralized protection monitoring system may be called Microgrid Protection Monitoring System (MPMS) must exist to monitor the microgrid and detect any changes in the network, recalibrate the relay settings, and monitor the status of protection devices connected in the network. The MPMS must also be able to transmit trip signals to the relays via communication channels in case of relay failures. Many adaptive protection schemes have been suggested to overcome the protection issues in the microgrid perspective. But the existing adaptive protection schemes are condition-specific and developed according to the changes in grid configuration from time to time [7]. The overcurrent scheme, reported in [10], which considers the coordination of both relay and fuses for microgrid protection. The adaptive protection strategy proposed in [11] includes a central protection unit for microgrid, which monitors for configuration change and adjust the protection parameters adaptively. [12] reported a low voltage microgrid control scheme, which does not require communication and adaptive features. [13],[14] proposed effective digital protection schemes for microgrids using wavelet packet transform, and the protection scheme is designed without requiring any adaptive features.

In [15], two approaches for relay coordination applied to power networks connected with DGs have been proposed where the approaches work for both adaptive relay and non-adaptive relays depending on system capability. In [16], authors have suggested an automatic, instantaneous CPU based digital protection algorithm which calculates the system and the microgrid impedance using the voltage and current fault components in a real-time manner. IEC 61850 communication based adaptive scheme for microgrid protection is proposed in [17], where the relay settings are updated online based on the mode of operation.

The objective of this paper is to investigate the performance of traditional protection catered by CDOCRs and DS-DOCRs for active non-radial and meshed distribution networks in the presence of DGs under a microgrid perspective. The incapabilities of CDOCRs in coordination for highly meshed distribution networks are evaluated and compared with the performance of DS-DOCRs. This paper also proposes an intelligent digital communication-based protection strategy to automate the relay set according to microgrid operating mode as well as any change in the network topology.

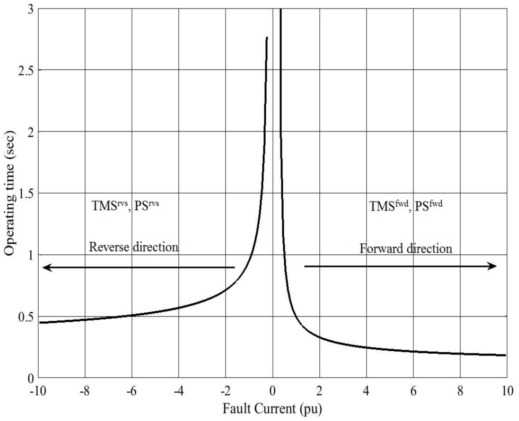


Figure 1. Time Current Characteristics of DS-DOCRs

2. Dual Setting Overcurrent Relays (DS-DOCRS)

Dual setting overcurrent relays (DS-DOCRs) [18-20] are directional overcurrent relays which are designed to operate in forward and reverse directions to handle the purpose of primary and backup protection. DS-DOCRs sense the fault event in both directions and operate according to the time and pickup settings. Thus, DS-DOCRs have time, and pickup settings in both directions, which means a total of four settings are required to be set for the DS-DOCRs, which are twice as compared to CDOCRs. The time-current characteristics of DS-DOCRs are shown in Figure 1. DS-DOCRs are efficient enough to have bidirectional fault sensing and fast in responding to the fault. But the operation of DS-DOCRs is prone to miscoordination during the backup operation. This is depicted in Figure 2.

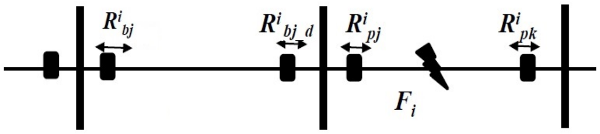


Figure 2. Miscoordination in case of DS-DOCR backup operation

When a fault F_i is seen by the primary DS-

DOCRs R^i_{pj} and R^i_{pk}, on account of primary relay failure $R^i_{bj\_d}$ is to be set to trip the faulted line. However, since R^i_{bj} also sees the fault in the same direction. Hence, R^i_{bj} also trips as per its settings. Now, a miscoordination is prone between R^i_{bj} and $R^i_{bj\_d}$. To address this problem and additional constraint is to be added to the problem.

3 Relay Coordination Problem Formulation

The DOCR coordination problem is formulated with relay operating times given by,

$$t_{ij} = \frac{\alpha(TS_{ij})}{\left(\frac{I_{Fij}}{PS_i}\right)^{\beta} - 1} \tag{1}$$

In case of DS-DOCRs, the operating times are different in forward and reverse directions with four different relay settings and is given as follows:

$$t^p_{ij} = \frac{\alpha(TS^{fwd}_{ij})}{\left(\frac{I_{Fij}}{PS^{fwd}_i}\right)^{\beta} - 1} \tag{2}$$

$$t^b_{ij} = \frac{\alpha(TS^{rvs}_{ij})}{\left(\frac{I_{Fij}}{PS^{rvs}_i}\right)^{\beta} - 1} \tag{3}$$

where, i is the relay number, j is the fault identifier, α and β are constants and are taken to be 0.14 and 0.02 respectively. In (1) TS_{ij} and PS_i are the Time Setting (TS) and Plug Setting (PS) settings of i^{th} relay for a fault at j^{th} location. In (2) and (3) (TS^{fwd}_{ij}, PS^{fwd}_i) and (TS^{rvs}_{ij}, PS^{rvs}_i) are the TS and PS settings of DS-DOCRs in forward and reverse directions respectively. t^p_{ij} and t^b_{ij} are the relay operating times in forward and reverse directions respectively. The objective function is defined as follows:

$$min\ T = \sum_{i=1}^{N}(t^p_{ij} + \sum_{k=1}^{K} t^b_{kj}) \quad \forall\ (i,k)\ \in\ \Omega \tag{4}$$

Where Ω represents the set containing primary and backup relays, N is the relay number, K is the number of backup relays for a i^{th} primary relay, k is the backup relay number. The values for t^p_{ij} and t^b_{kj} can be obtained from (2) and (3). From (1) - (3), it can be found that each CDOCR is operated with two settings, and each DS-DOCR operates with four settings. Thus, the objective function is solved for 2N variables for the N number of relays in the CDOCR case and 4N variables in the case of DS-DOCR. This objective function is subjected to limit and coordination constraints as given below,

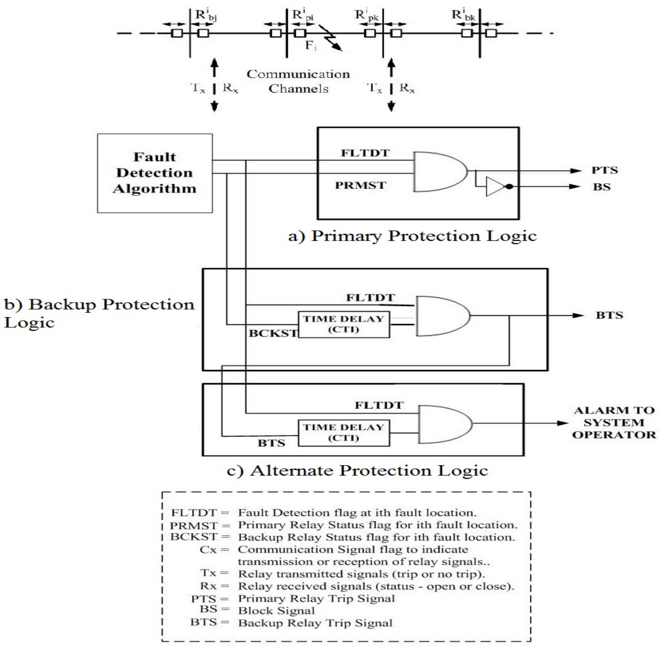


Figure 3. Symbolic diagram of proposed logic for relay tripping

3.1 Constraints

The associated constraints are given below,

$$t^b_{kj} - t^p_{ij} \ \geq\ CTI \quad \forall\ i,k,j \tag{5}$$

To counteract the possibility of miscoordination between the backup relays in case of DS-DOCRs a new constraint is being added as formulated below,

$$t^b_{lj} - t^b_{kj} \ \geq\ CTI \quad \forall\ k,j,l \tag{6}$$

where, l is the backup relay identifier in forward direction. The Operation speed of the relay is constrain to get reliable settings,

$$t^{min}_i \ \leq\ t_{ij} \leq\ t^{max}_i \tag{7}$$

$$TS^{min}_{ij} \ \leq\ TS_{ij} \ \leq\ TS^{max}_{ij} \tag{8}$$

$$PS^{min}_i \ \leq\ PS_i \ \leq\ PS^{max}_i \tag{9}$$

With the above-stated constraints, the relay coordination problem converts into a constrained nonlinear optimization problem, which is solved by using a hybrid GA-NLP method [27]. The MPMS takes care of running the relay coordination algorithm and finds the optimum values of TS and PS settings for each relay and update the settings online.

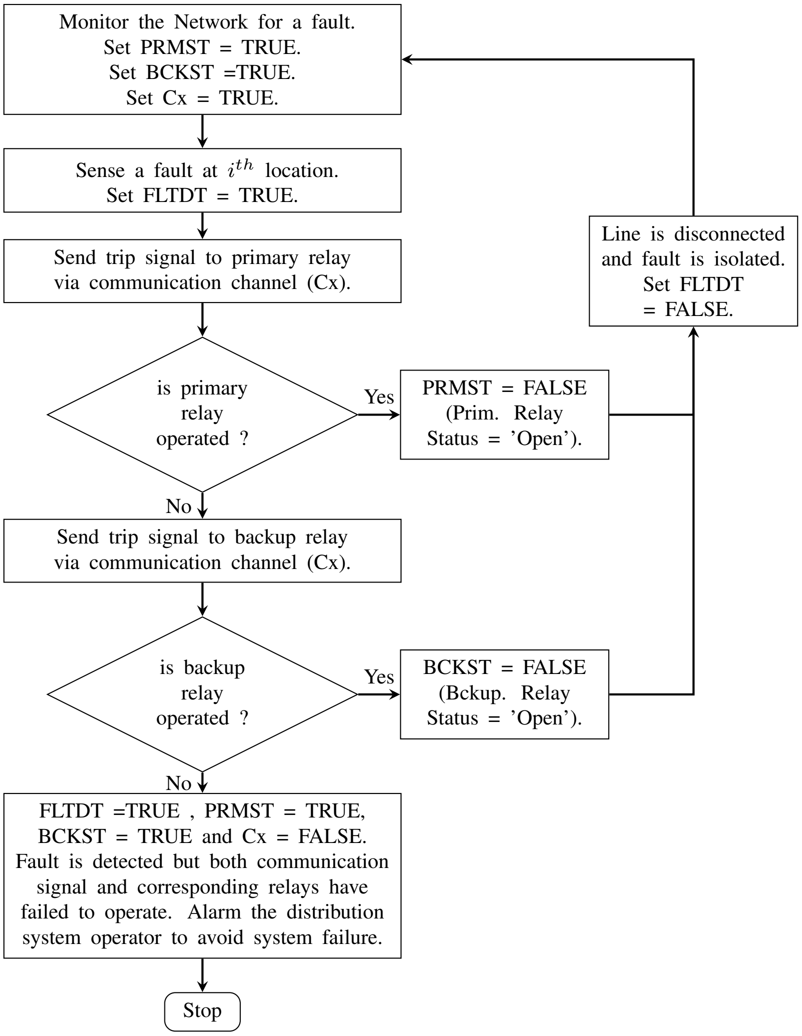


Figure 4. Flowchart for proposed IDCP logic.

4. Intelligent Digital Communication Based Protection (IDCP) Strategy

As discussed earlier, an effective microgrid protection algorithm with communication assistance is effective when each relay is adaptive in updating the relay settings according to network dynamics. The communication channels are provided to each relay in one to one connection with the MPMS. The communication logic works in three stages. The logic diagram is shown in Figure 3, and the flowchart is given in Figure 4. Further discussion is given below,

4.1 Primary protection logic

On the event of a fault, the MPMS sets the *FLTDT* flag to digital logic '1' and collects the *PRMST* flag (primary relay status flag) status from the primary relays of the faulted line via a communication channel. The *PRMST* flag indicates logic '1' or 'True' when the CB to which primary relay is connected (for simplicity, let us call relay) is closed and logic '0' or 'False' to open the relay. By operating *FLTDT* and *PRMST* with AND operation, the trip signal is generated given by primary trip signal (PTS). In case the primary relays don't operate according to its optimally coordinated settings, the communicated trip signal from MPMS is used as a backup signal to invoke the CB tripping. If the primary relays are operated, and the fault is cleared, a blocking signal is communicated to the backup relays (R^b_{ij} and R^b_{ik} in this case) to avoid any miscoordinations or sympathy trips.

4.2 Backup protection logic

Backup protection strategy is invoked when primary protection fails due to either communication signal loss or relay failure. If a fault is detected on the line

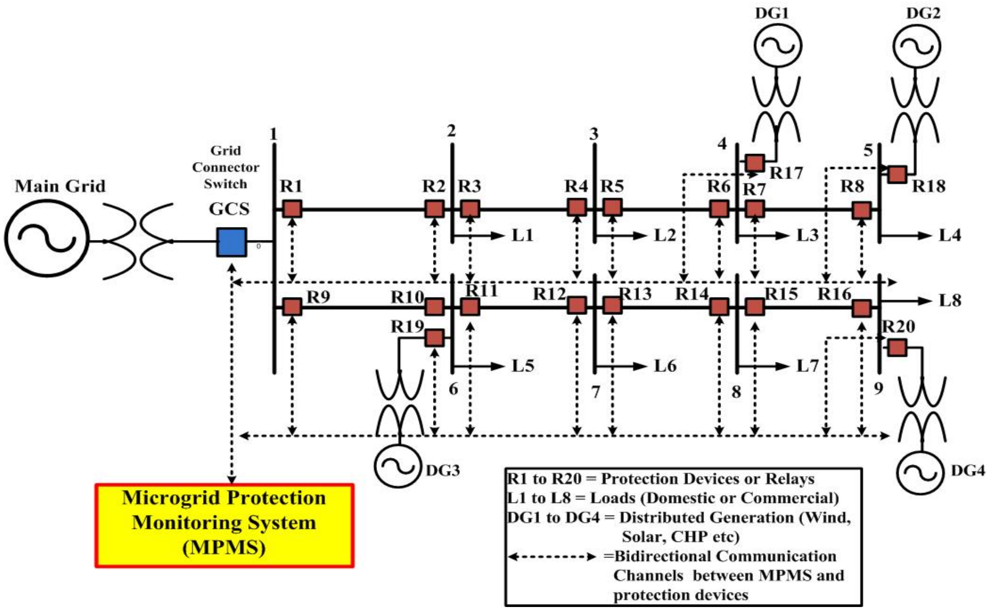


Figure 5. Urban canadian benchmark 9 bus test distribution system.

and after setting PTS, if the primary relay still fails to operate, then backup relays should bear the responsibility in clearing the fault. The trip signal to backup relay is delayed by a time interval of CTI to give the primary relay sufficient time gap to operate. As long as fault is detected (*FLTDT* flag is 'True' or logic '1') and primary relay is inactive the *PRMST* flag is 'False' or logic '0'. The two flags are AND operated, and the output of this logic setup is given as trip signal (BTS) to the backup relays. In the case of DS-DOCRs, a block signal (*BS*) may also be generated to restrain the remote backup relay from tripping while the local backup relay is set to trip. This strategy is useful to avoid the miscoordination between the remote and local backup relays when DS-DOCR characteristic is used for protection.

4.3 Alternate protection logic

This is the worst-case scenario when both primary and backup protection strategies fail. The reasons may be due to communication signal loss or backup relay failure. As long as the backup trip signal is not issued and the fault still exists, then it is to be understood that both primary and backup relay strategies have failed to clear the fault. The respective flags (*FLTDT* and *BTS*) are AND operated to output an alarming signal which alerts the Microgrid Protection System Operator (MPSO) to perform alternate protection procedures to take immediate action in order to prevent system failure.

5. Systems Under Study and Solution Technique

This section provides a detailed description of the test systems considered to perform the relay coordination algorithm in the microgrid scenario and then analyze the proposed communication assisted digital protection scheme. Two systems viz. 9-bus Canadian urban distribution system [1] and 33kv distribution portion of the IEEE 30 bus system are considered for the study. The IEEE 30 bus system is considered in particular to account for the coordination behavior of big meshed systems under both modes of microgrid operation simultaneously [1]. The relay coordination algorithm used for MPMS is solved using a hybrid GA - NLP Technique [21].

Table 1. Canadian Urban Benchark System

Utility Grid X/R ratio	6
Utility Grid Capacity	500 MVA
Line Impedence	0.1529 + j 0.1406 Ω / km
Line Section length	500 m each
DG Rating	4 X 5 MVA
Load Rating	8 X (2 MVA, 0.9pf lag)
DG Transformer Rating	5 MVA, 12470/ 480 V

5.1 Study system I: 9 bus test system

The first system considered for the study is the Canadian urban distribution system [1], as shown in Figure 5, which is a two 4-feeder distribution system with each feeder rated at 12.47 kV, 8.7 MVA. The specifications of the test system are given in Table 1.

The system is equipped with 20 microprocessor-based DOCRs (MPDOCR) and one Grid Connector Switch (GCS). The relays are optimally set online by relay coordination algorithms. Each line in the test system, being non-radial in nature, is protected with two DOCRs relays connected on both ends. The backup relays considered for the relays with CDOCR characteristics would be different to those when DS-DOCR characteristics are considered. For example, when CDOCRs are considered, for a fault on line 1-2, the primary relays are R1 and R2, and backup relays are R10 and R4, respectively. Whereas for DS-DOCRs, R9 and R3 would backup the relays R1 and R2.

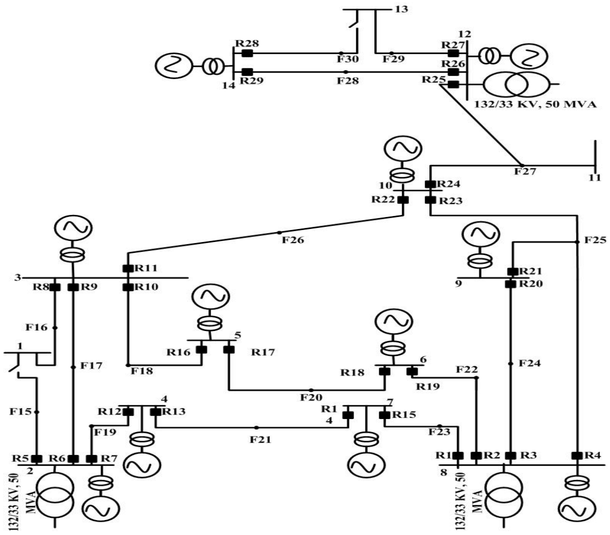


Figure 6. Modified distribution system portion of IEEE 30 bus system

5.2 Study system II: Distribution portion of IEEE - 30 bus test system

The second system considered for the study is the distribution portion of the IEEE 30 bus system [18] with 14 buses and 16 lines. The distribution portion is supplied with three transformers of 132/33 KV, 50 MVA capacity. This system is connected with 29 overcurrent relays. The relay coordination process is performed in two modes of microgrid operation, i.e., grid coupled and islanded modes and optimal values of TS and PS for both forward and reverse directions are found for each relay in each mode. For islanded operation the 33/132 KV transformers (connected at 2,8 and 12) are disconnected.

5.3 Solution technique and constraint handling

The relay coordination problem in this paper is solved by using the hybrid Genetic Algorithm-Nonlinear Programming (GA-NLP) Method [21]. The objective function which is given in (4) and constraints (5) to (9) is said to be a nonlinear optimization problem (NLP), which is solved by '*fmincon*' function available in the optimization toolbox of MATLAB. The initial solution to the NLP is obtained by running a fixed number of iterations of GA, and for GA, the constraints (5) & (6) are handled by adding constraints violations to the objective function via penalty factors [21].

6. Results and Analysis

Before applying the IDCMP method, the relay coordination is performed for the test systems in which optimal TS and PS of DOCRs are constrained to be obtained using the discussed solution technique. The numerical optimization solution is computed in three cases as shown below,

- Case I: Coordination using CDOCRs characteristics.
- Case II: Coordination using DS-DOCRs characteristics.
- Case III: Coordination using DS-DOCRs characteristics by including remote and local backup relay coordination constraints in the relay coordination algorithm.

6.1 Coordination Analysis

6.1.1 Case I: Coordination using CDOCRs characteristics

The optimal relay coordination algorithm is tested on the study systems using CDOCR characteristics. The relay coordination problem is solved for both grids coupled and islanded modes of operation. For the system I, grid coupled-mode consists of 21 coordination constraints, and islanded mode consists of 42 coordination constraints. For system II, the relay coordination problem is solved for 50 coordination constraints in grid coupled mode and 100 coordination constraints for islanded mode. In the case of the system I, an optimal coordination solution is achieved with zero constraint violations. The optimal relay settings for the system I is shown in Table 2. Whereas for system II case, the optimal solution is not achieved, and many coordination constraints are found to be violating while using CDOCRs but achieved an optimal solution with DS-DOCRs. The optimal settings of sys-

Table 2. Optimal relay settings for 9 bus test system

Relay	Conventional DOCRs (CDOCRs) TS in sec; PS in pu		Dual Setting DOCRs (DS-DOCRs) TS in sec; PS in pu			
-	TS	PS	TS^{fwd}	PS^{fwd}	TS^{rvs}	PS^{rvs}
1	0.3231	1.1509	0.8463	0.169	0.6151	1.0832
2	0.2678	1.2598	0.238	1.0102	1.0796	0.4884
3	0.2011	0.94	0.1431	0.3718	0.4446	1.0027
4	0.346	1.2771	0.1086	0.5314	0.4946	0.8509
5	0.1002	1.2076	0.182	0.3675	0.5483	1.2374
6	0.4362	1.3245	0.182	0.7902	0.5276	0.5815
7	0.1355	0.2525	0.1906	1.0059	0.4148	0.1054
8	0.5724	0.545	0.1949	0.238	0.3811	0.2403
9	0.3041	0.661	0.1518	1.2	1.0292	0.3051
10	0.2688	2.4532	0.6824	0.7125	0.4274	1.8756
11	0.2969	0.7095	0.4882	0.5961	0.6079	0.7174
12	0.3303	0.7286	0.7341	0.6867	0.3158	0.6163
13	0.2382	0.2989	0.4624	0.9196	0.217	0.6197
14	0.4249	0.7471	0.1216	0.8549	0.5321	0.786
15	0.1176	0.1495	0.6953	1.131	0.39	0.5557
16	0.5347	0.7611	0.6996	0.7082	0.7923	0.816
17	0.3288	1.0602	0.6565	1.1439	0.3381	1.1926
18	0.5958	0.674	0.6306	0.6478	0.706	0.4231
19	0.7997	0.4037	0.6176	0.8506	0.462	0.4239
20	0.3514	1.9361	0.2984	0.8506	0.7772	1.5265
21	0.7636	0.5213	0.9584	0.3761	0.3962	0.6677

Table 3. Optimal relay settings for IEEE 30 bus system using DS-DOCRS

Relay	TS^{fwd}	PS^{fwd}	TS^{rvs}	PS^{rvs}	Relay	TS^{fwd}	PS^{fwd}	TS^{rvs}	PS^{rvs}
1	0.117	0.2469	0.2868	0.1836	16	0.1165	0.4055	0.2112	0.4055
2	0.1	0.2093	0.2319	0.2447	17	0.1540	0.1190	0.2957	0.119
3	0.1015	0.4704	0.2478	0.4704	18	0.154	0.119	0.2537	0.119
4	0.125	0.2190	0.1497	0.2899	19	0.101	0.2447	0.2767	0.2093
5	0.1301	0.1519	0.3965	0.1523	20	0.1	0.4717	0.2116	0.4704
6	0.1	0.4758	0.1673	0.4758	21	0.1	0.2134	0.2757	0.1346
7	0.1	0.4684	0.1738	0.4684	22	0.108	0.2174	0.1711	0.2174
8	0.1207	0.235	0.1427	0.2543	23	0.1157	0.1694	0.2293	0.1694
9	0.1	0.4758	0.1841	0.4758	24	0.1	0.2715	0.1061	0.4681
10	0.1	0.4055	0.1798	0.4055	25	0.1	0.3251	0.5	0.3251
11	0.112	0.2174	0.1987	0.2268	26	0.1298	0.0744	0.2192	0.0744
12	0.1	0.4684	0.2026	0.4684	27	0.1191	0.1051	0.4482	0.1087
13	0.1309	0.1909	0.2564	0.1909	28	0.1669	0.0293	0.4012	0.03
14	0.1309	0.1909	0.2577	0.1909	29	0.112	0.0747	0.2544	0.0744
15	0.1412	0.1836	0.3139	0.1836					

Table 4. Miscoordination scenarios in IEEE 30 bus system using CDOCR characteristics

Fault Location	Relay No.	Grid coupled mode Fault Current (A)	Grid coupled mode Oper. Time (sec)	Islanded mode Fault Current (A)	Islanded mode Oper. Time (sec)
F18	pri: R16	1906.93	1.3375	902.74	1.5537
	bck: R18	1987	0.4680	956.34	0.8958
F19	pri: R12	2481.24	0.6606	1979	1.3656
	bck: R14	2488.73	0.4613	2021	0.5712
F22	pri: R19	1397.28	0.4853	827.9	1.3064
	bck: R17	1418.91	0.2883	872.78	0.9764

pri: primary relay; bck: backup relay

tem II is shown in Table 3. Table 4 shows the miscoordinated cases for system II when using CDOCRs. Miscoordination events are recorded for faults F18, F19, and F22 in both grids coupled and islanded scenarios. Thus from Table 4, it can be understood that for a highly meshed system like system II robust co-

Table 5. Operating times (sec) in IEEE-30 bus system using DS-DOCRs

Fault	Grid coupled mode				Islanded mode			
Location	pri	bck1	bck2	bck3	pck	bck1	bck2	bck3
F15	R5 0.1969	R6 0.8351	R7 0.5459	-	R5 0.2063	R6 0.7443	R7 0.5797	-
F16	R8 0.2596	R9 0.5772	R10 0.5596	R11 0.5596	R8 0.2801	R9 0.782	R10 0.5801	R11 0.5801
F17	R6 0.1882	R7 0.4882	-	-	R6 0.2194	R7 0.5194	-	-
	R9 0.1720	R10 0.5027	R11 0.5118	-	R9 0.2194	R10 0.5256	R11 0.5276	-
F18	R10 0.1879	R9 0.4879	R11 0.5587	-	R10 0.2088	R9 0.5542	R11 0.5870	-
	R16 0.2311	R17 0.5311	-	-	R16 0.2432	R17 0.5487	-	-
F19	R7 0.2100	R6 0.5300	-	-	R7 0.2181	R6 0.5181	-	-
	R12 0.1787	R13 0.4787	-	-	R12 0.2181	R13 0.5181	-	-
F20	R17 0.2317	R16 0.5318	-	-	R17 0.2453	R16 0.5634	-	-
	R18 0.2269	R19 0.5269	-	-	R18 0.2416	R19 0.5634	-	-
F21	R13 0.2224	R12 0.5224	-	-	R13 0.2334	R12 0.5609	-	-
	R14 0.2224	R15 0.5224	-	-	R14 0.2334	R15 0.5624	-	-
F22	R2 0.1699	R1 0.5877	R3 1.0280	R4 0.5909	R2 0.1670	R1 0.6077	R3 0.9200	R4 0.5892
	R19 0.1699	R18 0.4699	-	-	R19 0.1758	R18 0.4758	-	-
F23	R1 0.1788	R2 0.5113	R3 0.8177	R4 0.4788	R1 0.1952	R2 0.5403	R3 0.7810	R4 0.4955
	R15 0.2101	R14 0.5300	-	R15 0.2187	R14 0.5187	-		
F24	R3 0.1824	R1 0.5106	R2 0.4993	-	R3 0.2036	R1 0.5455	R2 0.5402	-
	R20 0.1801	R21 0.4801	-	-	R20 0.2008	R21 0.5021	-	-
F25	R4 0.2384	R1 0.5384	R2 0.5814	R3 0.5384	R4 0.2664	R1 0.5664	R2 0.5664	R3 0.6162
	R21 0.1637	R20 0.4637	-	-	R21 0.1723	R20 0.5261	-	-
	R23 0.2137	R12 0.5137	R24 0.5137	-	R23 0.2174	R12 0.5360	R24 0.5174	-
F26	R11 0.2049	R9 0.5763	R10 0.6926	-	R11 0.2111	R9 0.6752	R10 0.7410	-
	R22 0.1999	R24 0.5454	R23 0.5	-	R22 0.2050	R24 0.6294	R23 0.5218	-
F27	R24 0.2000	R22 0.5586	R23 0.5317	-	R24 0.2190	R22 0.5694	R23 0.5422	-
	R25 0.2000	R26 0.5000	-	-	R25 0.2615	R26 0.5615	-	-
F28	R26 0.2000	R25 0.5095	-	-	R26 0.2154	R25 0.6626	-	-
	R29 0.1726	-	-	-	R29 0.1860	-	-	-
F29	R27 0.1874	R25 0.4874	R26 1.4910	-	R27 0.2036	R25 1.5934	R26 1.2373	-
F30	R28 0.2365	R29 0.5365	-	-	R28 0.2499	R29 0.6049	-	-

pri: primary relay; bck: backup relay; all operating times in sec.

ordination solution cannot be achieved using CDOCR characteristics in both modes of microgrid scenario without relaxing certain coordination constraints.

6.1.2 Case II: Coordination using DS-DOCRs characteristics

When DS-DOCR characteristic is used for the relay coordination problem, an improved coordination solut!]

Table 6. Miscoordination scenario when constraint (6) is included for IEEE 30 bus system case

Fault Location	Primary Relay	Remote Backup Relay	Local Backup Relay	constraint violation $(t^b - t^p)$
F22	R2: 0.1427	R15: 0.5356	R1:0.4604	**-0.0752**
		R20: 0.8032	R3: 0.7400	**-0.0632**
		R21: 0.8543	R4: 0.4931	**-0.3612**
		R23: 0.4724	-	-

t^b = backup relay operating time; t^p = primary relay operating time

Table 7. Performance evaluation of CDORs and DS-DOCRs

Test System	Operating Mode	Overall Operating Time with CDOCRs	Overall Operating Time with DS-DOCRs	% Reduction	Overall % Reduction
9 Bus	Grid coupled mode	40.154 sec	26.624 sec	33.69 %	30.62 %
	Islanded mode	44.516 sec	32.119 sec	27.84 %	
IEEE 30	Grid coupled mode	78.610 sec	31.561 sec	59.8 %	59.61 %
	Islanded mode	87.29 sec	35.346 sec	59.5 %	

tion is achieved with reduced overall operating times for both the test systems. The optimal DS-DOCR settings for the system I are shown in columns 4-7 of Table 2. In the case of system II, the miscoordination events recorded in case I have been nullified by using DS-DOCRs and, having a different time and plug settings in forward and reverse directions, DS-DOCRs have successfully coordinated in clearing the fault. Table 5 shows the relay operating times for system II with DS-DOCR characteristics.

6.1.3 Case III: Coordination using DS-DOCRs characteristics by including backup relay constraint

Though DS-DOCRs are found to be successful in coordination for highly meshed systems like system II, miscoordination may occur between the local and remote backup relays operating in forward and reverse directions that may result in unwanted disconnection of neighbor line, as depicted in Figure 2. This coordination problem is already explained in section 3. Based on the philosophy of power system protection, relays (primary or backup), which are nearest possible to the fault, should operate quickly to isolate the fault such that fault clearance time is minimum. So proper coordination between the backup relays of forward and reverse direction is necessary in case DS-DOCR characteristic is being used. For this reason, the coordination constraint limits the coordination time between local and remote backups, which is indicated by eq.(6) included in the relay coordination problem. However, an optimal coordination solution is not achieved for this case, and many miscoordination events are noticed. The number of coordination violations for the two test systems operating in both microgrid modes is shown in Figure 7. For the system I a total of 19 constraints, and in the case of system II, 43 constraints are found to be violated. For example, the constraint violations for a fault F22 in system II are shown in Table 6 where the remote backup relays (R15, R20, R21, R23) and local backup relays (R1, R3, R4) are unable coordinate each other when primary relay R2 fails to operate.

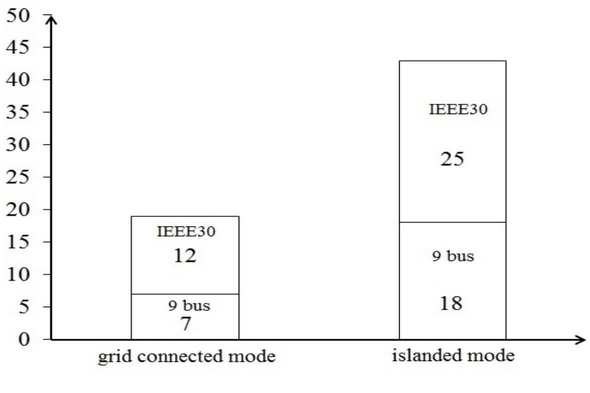
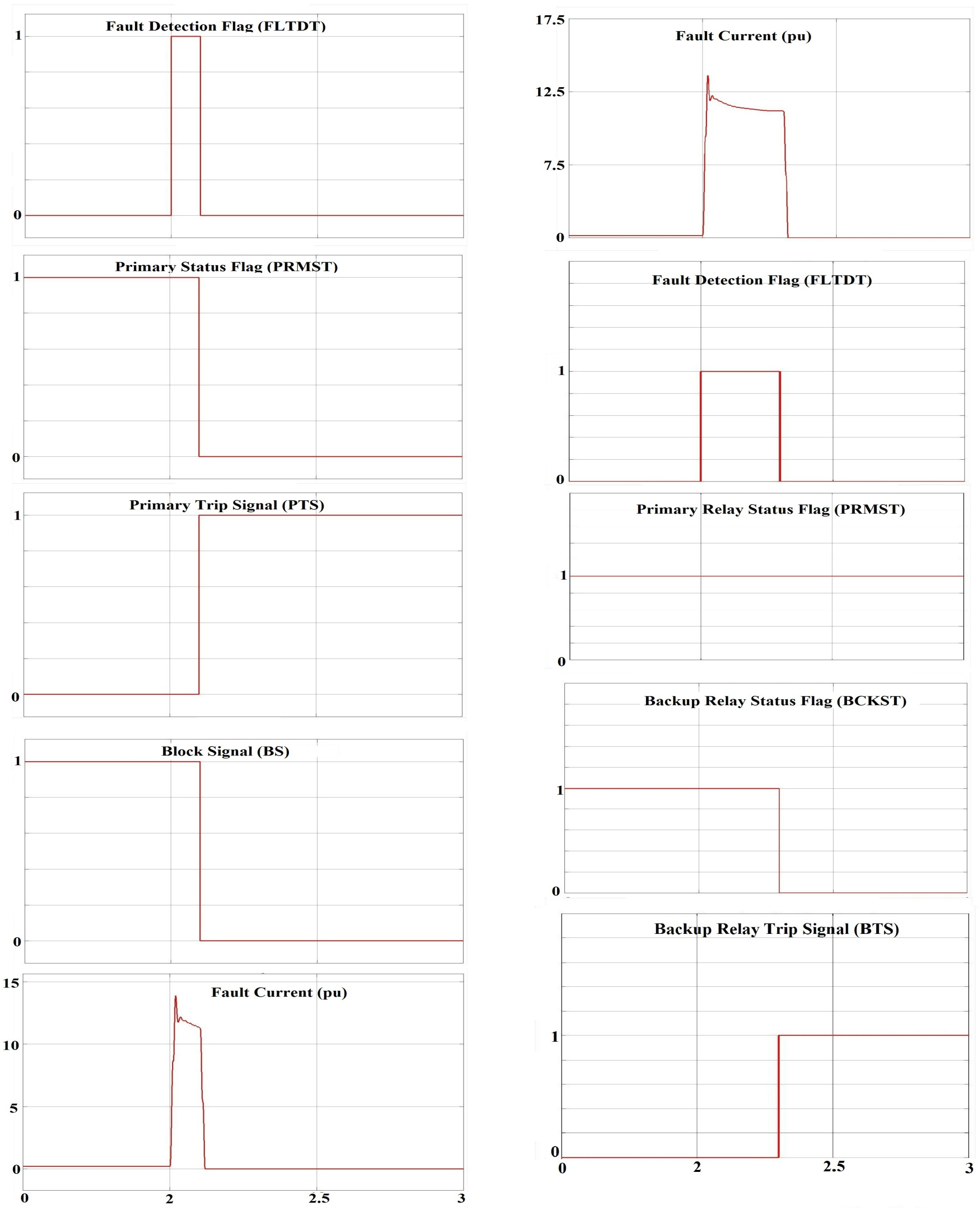


Figure 7. Constraint violations when using DS-DOCRs for case III

The performance of CDOCR and DS-DOCR are evaluated for the case I and Case II, as shown in Table 7. It can be seen that an overall reduction of 30.62% is achieved using DS-DOCRs for system I, and an overall reduction of 59.61% is achieved in the case of system II. These results show the robustness of DS-DOCRs over CDOCRs in optimally coordinating for microgrid case.

6.2 Communication based microgrid protection

From the three cases, it is found that DS-DOCRs can provide optimal coordination solution with a good



(a) (b)

Figure 8. Implementation of proposed digital protection logic for a fault on 1-5 line in 9 bus system in grid coupled mode. a) primary protection logic , b) backup protection logic

response as compared to CDOCRs. However, DS-DOCRs can provide complete fault clearance only when remote and local backup relays coordinate with each other properly. But, many such scenarios are found to be violating, as explained in case III. A more appropriate solution to this problem can be provided by using communication-based intelligent protection. Keeping in mind, the development of smart protection schemes in modern power networks, the communication system plays a pivotal role in system protection. This work proposes a simple communication based protection strategy to tackle miscoordination problems. The protection logic using communication systems is explained earlier in section 4 and a detailed functional logic diagram is given in Figures 3 and 4. A depiction of this logic, which is applied to the system I is depicted in figure 8. Figure 8a shows the operation of primary protection logic, for a fault on line 1-5 on system I. A three-phase fault is initiated at 2 sec. The fault is detected by the fault detection flag ($FLTDT$) and is set to logic '1' or 'TRUE.' The MPMS gathers the primary status flag ($PRMST$), and if the primary relays, R9, R10 in this case, are found to be closed, a trip signal (PTS) is issued to the primary relays. When (PTS) is high at 2.1 sec, the primary relay is said to have operated and ($FLTDT$) becomes low, indicating that the fault is isolated). When PTS is issued to primary relays, the other backup relays are said to be blocked by issuing a block signal (BS). Similarly, Figure 8b show the operation of backup protection logic. When the primary relay fails to operate, the backup relays are supposed to step-in and trip the line after a specified time interval (CTI). So, as soon as it is found that the primary relay is not responsive, the backup relay status ($BCKST$) is monitored, and if it is found to be closed, a trip signal (BTS) is issued to the backup relay. Once the backup relay operates and the fault is found to be isolated, ($FLTDT$) becomes false, indicating that the fault is isolated. Here the relay operating times are considered by neglecting the communication time delay and packet loss.

7. Conclusion

This paper investigated the performance of conventional directional overcurrent relays (CDOCRs) and dual setting directional overcurrent relays (DS-DOCRs) in optimal coordination for the microgrid. From the simulation results, it has been found that for largely meshed distribution networks, DS-DOCRs works better than CDOCRs. The drawback of backup mal-operation in the case of DS0-DOCRs has also been investigated. Finally, a communication-based protection strategy for the microgrid is proposed and tested on both test systems, and simulation results are presented. It is found that the performance of proposed communication-based protection logic is found satisfactory.

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