Optimal Protection Coordination for Meshed Distribution Systems With DG Using Dual Setting Directional Over-Current Relays

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***Abstract*—In the presence of distributed generation (DG), it is important to assure a fast and reliable protection system for the distribution network to avoid unintentional DG disconnection during fault conditions. In this paper, dual setting directional over-current relays are proposed for protecting meshed distribution systems with DG. Dual setting relays are equipped with two inverse time-current characteristics whose settings will depend on the fault direction. The protection coordination problem for the dual setting directional relay is formulated as a nonlinear programming problem where the objective is to minimize the overall time of operation of relays during primary and backup operation. The proposed protection coordination scheme using dual setting relays is compared against the conventional approach, which relies on the conventional one setting directional relay. The proposed scheme is applied to the power distribution network of the IEEE 30-bus system equipped with synchronous and inverter-based DG. The results show that the proposed protection coordination scheme with dual setting relay can significantly reduce the overall relay operating time, making it an attractive option for distribution systems with DG.**

***Index Terms*—Directional overcurrent relays, distributed generation (DG), optimization, protection coordination, tripping characteristics.**

I. Introduction

PROTECTION relaying plays a vital role within the operation of any power system. Relay coordination is an important aspect in the protection system design as coordination schemes must guarantee fast, selective, and reliable relay operation to isolate the power system faulted sections. Directional over-current relays (DOCRs) are an attractive economical and technical choice for the protection of interconnected sub-transmission systems. Distribution systems are transforming from the commonly radial nature toward a meshed and looped structure due to the increasing penetration of distributed generation (DG) and the increasing interest in smart grids.

Generally, integration of DG has different impacts on distribution systems and one major challenge is its effect on the protection system [1]. The impact of DG integration on the protection scheme depends on the type of DG as well as the nature of the distribution system (radial or meshed). In [2], it has been shown that synchronous-based DG (SBDG) generate higher fault current levels than inverter-based and thus resulting in a much more profound impact on the protection systems. The impact of inverter-based DG (IBDG) on the distribution system protection is minimal since IBDG fault currents typically range from 1 to 2 per unit.

Radial distribution systems are typically protected by reclosers, fuses, and over-current relays [3]. For such systems, IBDG have almost negligible impacts on protection coordination [4]. On the contrary, in the presence of SBDG, the fuse might operate before the recloser's first operation and thus affecting the fuse saving strategy. Similarly, SBDG can impact the coordination between fuse and over-current relay resulting in unnecessary tripping of a whole feeder [5]. Mitigating such problems would require either fuse replacement or retuning the setting of the recloser or over-current relay [6]–[10]. In [11], a new protection scheme, for radial distribution systems with DG, which relies on an automatic telecontrol system, is proposed that takes action after line protective devices have tripped. The need for changes and modifications to the present distribution protection philosophies was highlighted in [12], especially with increasing penetration of DG.

For meshed distribution systems, DG can continue, after fault isolation, to supply power through other feeders. Protective devices that can provide fast fault isolation are important so that the low voltage period remains short and thus enhancing DG fault ride through [13]. For meshed systems, DOCRs become an attractive option due to the bi-directionality of fault currents. Such relays are coordinated optimally to minimize the overall time of operation of all relays [14]. To overcome the impact of DG, new optimal relay settings need to be determined that take into account the presence of the DG. Different optimization methods, including conventional and heuristic techniques, have been applied to determine the optimum time dial and pickup current settings of DOCRs that guarantee coordination and minimum total relay operating times [15]–[23]. Other protection coordination

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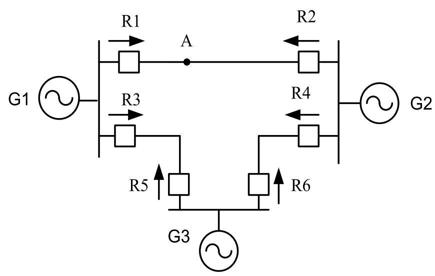

Fig. 1. Conventional directional overcurrent relays.

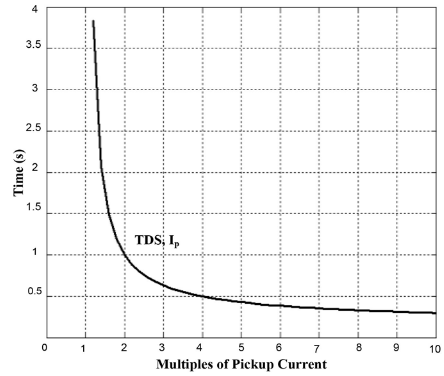

Fig. 2. Time-current characteristics—the conventional DOCR.

strategies take advantage of the capabilities of digital DOCRs, to improve the protection system performance especially in presence of DG, either by using different or modified groups of relay settings and characteristics [24]–[27], or by utilizing the communication potentials in digital relays [28], [29].

For power systems with fault currents flowing in forward and reverse directions, it is advantageous to have relays that can respond differently for each direction [30]. Dual setting directional relays have been proposed by relay manufacturers, such as in [31] and [32]. In [33], directional relays were equipped with two sets of settings for forward and reverse direction for a radial distribution system with DG. Yet, the capabilities and application of the dual setting relay for the protection coordination problem of meshed distribution systems with DG has not been addressed in the literature. For dual setting relays, each overcurrent relay element can be programmed with different settings for forward and reverse direction [32]. The advantage of this capability is that a single relay can perform the function of two directional relays [31].

In this paper, a new protection coordination scheme is proposed that relies on dual settings DOCRs. Each directional relay is equipped with two pairs of settings for the two possible directions; two time dial settings (TDSs), and two pickup current settings. The new scheme is implemented and applied to the meshed power distribution system of the IEEE 30-bus system equipped with synchronous DG. The problem is modeled as a nonlinear programming (NLP) problem where the dual relay settings are optimally determined. The results of the proposed scheme are compared against the conventional protection coordination scheme.

TABLE I
PRIMARY/BACKUP RELAY PAIRS BASED ON CONVENTIONAL AND PROPOSED PROTECTION COORDINATION SCHEMES FOR A 3-BUS SYSTEM

Primary Protection Relay	Backup Relay Based on Conventional DOCR	Backup Relay Based on Dual Setting DOCR Scheme
R1	R5	R3
R2	R6	R4
R3	R2	R1
R4	R1	R2
R5	R4	R6
R6	R3	R5

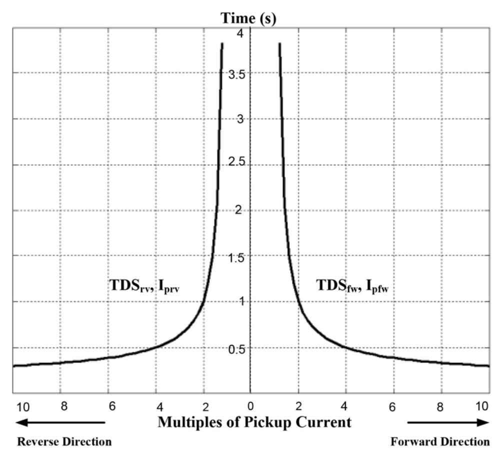

Fig. 3. Time-current characteristics—the dual settings DOCR.

II. DUAL SETTING RELAY AND PROTECTION COORDINATION SCHEME

The relay TDS and the pickup current setting (I_p) define the shape of the relay characteristic. These settings are determined optimally to minimize the overall relay operating time while satisfying the constraints related to the protection coordination scheme. A protection coordination scheme defines which relays operate as a backup for other relays on the system. Fig. 1 shows an example of a 3-bus meshed system with six DOCRs, equipped with the conventional relay characteristic given in Fig. 2. The conventional way of coordinating such relays is presented in Table I. For example, if a fault happens at point A, R1 will be the primary relay and in case of failure R5 acts as its backup. Similarly, for the same fault location, R2 will be the primary relay responsible for isolating the fault and in case of failure, R6 acts as its backup.

The proposed approach takes advantage of the flexibility and capabilities of available dual setting directional relays by proposing a new protection coordination scheme. Dual setting directional relays operate for faults in both directions (forward and reverse) but with two different relay characteristics corresponding to the two possible directions.

Fig. 3 presents the time-current characteristic of the dual setting directional relay. The relay will act as a primary protection when the fault current flows in its forward direction and backup protection for a fault current flowing in the reverse direction. The relay will have two different pairs of settings; TDS_{fw}, I_{pfw} for primary protection operation (forward), and TDS_{rv}, I_{prv} for backup protection operation (reverse).

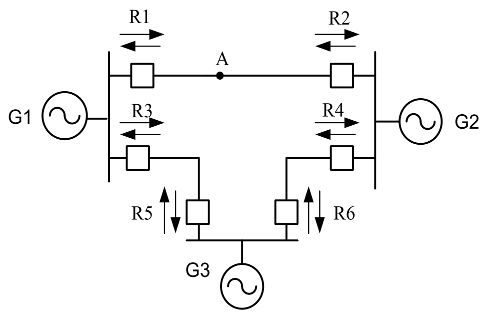

Fig. 4. Protection with dual setting directional relays.

Fig. 4 shows an example of a 3-bus meshed system with six dual setting DOCRs that are equipped with the relay characteristic given in Fig. 3. Each relay has two arrows denoting the two directions of fault current flow for which the relay can operate. The proposed protection coordination scheme using the dual setting DOCR is presented in Table I. For a fault at point *A* (refer to Fig. 4), R3 will be the backup relay for R1 while R4 is the backup relay for R2. In such case, R3 will use the settings associated with the reverse operation (TDS_{rv3} and I_{prv3}) while R1 will use the settings associated with the forward operation (TDS_{fw1} and I_{pfw1}).

III. Protection Coordination Problem Formulation With Dual Setting DOCR

The operating time (t) of a DOCR is an inverse function of the short circuit current flowing through it. In general, the relay time-current characteristic can be expressed as follows:

$$t_{ij} = \mathrm{TDS}_i \frac{A}{\left(\frac{I_{scij}}{I_{pi}}\right)^B - 1} \tag{1}$$

where i is the relay identifier and j is the fault location identifier. The parameters A and B are constants that vary with the type of OCR which are commonly set to 0.14 and 0.02, respectively. The term I_{scij} represents the relay fault current and I_{pi} represents the relay pickup current. As shown in (1), each DOCR has one pair of setting for both primary and backup operation. The optimization objective is to minimize the times of all the relays (primary and backup) while maintaining the conditions of protection coordination. The objective function is taken to be the sum, T, and can be expressed as follows:

$$T = \sum_{j=1}^{M} \left(\sum_{i=1}^{N} t_{fwij} + \sum_{k=1}^{N} t_{rvkj} \right) \ \forall\ (i,k) \in \Omega \tag{2}$$

where Ω is the set of primary/backup pairs of the relays, N represents the total number of relays, and M denotes the total number of fault locations across all feeders. The variables t_{fwij} and t_{rvkj} are the time of operation of relay i, and k for a fault at location j during forward (primary) and reverse (backup) operation, respectively, which can be represented as follows:

$$t_{fwij} = \mathrm{TDS}_{fwi} \frac{A}{\left(\frac{I_{scfwij}}{I_{pfwi}}\right)^B - 1} \tag{3}$$

$$t_{rvkj} = \mathrm{TDS}_{rvk} \frac{A}{\left(\frac{I_{scrvkj}}{I_{prvk}}\right)^B - 1} \tag{4}$$

where TDS_{fwi} and TDS_{rvk} are the relay i and k TDS setting in the forward and reverse directions, respectively. Similarly, the variables I_{pfwi} and I_{prvk} represent relay i and k pickup current setting for both forward and reverse operation. The fault current, due to a fault at location j, passing through relay i in the forward direction is denoted as I_{scfwij}. Similarly, the parameter I_{scrvkj} represents the fault current, due to a fault at location j, passing through relay k in the reverse direction. The coordination constraints must be satisfied while solving the protection coordination problem which can be represented as follows:

$$t_{rvkj} - t_{fwij} \geq CTI\ \forall i,k,j \tag{5}$$

where coordination time interval (CTI) indicates the minimum time between the primary and the backup relay. The CTI usually takes values between 0.2 and 0.5 s and in this paper it was set to 0.3 s. In addition, there are upper and lower bounds on the relay settings which can be represented as follows:

$$I_{pi\_\min} \leq I_{pfwi},\ I_{prvi} \leq I_{pi\_\max} \tag{6}$$

$$\mathrm{TDS}_{i\_\min} \leq \mathrm{TDS}_{fwi},\ \mathrm{TDS}_{rvi} \leq \mathrm{TDS}_{i\_\max} \tag{7}$$

where $I_{pi\_\min}$ and $I_{pi\_\max}$ represent the lower and upper bounds on relay i pickup current setting. The parameters $\mathrm{TDS}_{i\_\min}$ and $\mathrm{TDS}_{i\_\max}$ represent the lower and upper bounds on the TDS for relay i.

The main variables, to be optimized, for the protection coordination problem, are the TDS and I_p in both forward and reverse directions. The short circuit current is considered a parameter within the optimization but the DG location and size will have an effect on fault current levels. For each study in this paper, prior to optimizing the relay settings, fault analysis is conducted to determine the fault currents passing through each relay. As can be seen from (3) and (4), the relationship between the relay operating time and the pickup current setting is nonlinear. Thus, the model is formulated as a constrained NLP problem, integrated with a primary/backup pair scheme (similar to what is presented in Table I) such that the relays closest to the fault are considered.

IV. System and Simulation Setup

The dual setting DOCR along with the new protection coordination scheme is tested on a modified distribution portion of the IEEE 30-bus system shown in Fig. 5. The distribution portion of the IEEE 30-bus test case represents a portion of the American electric power system and its parameters are available in [34]. The system has three 132/33 kV 50 MVA distribution substations, connected at buses 2, 8, and 12, where the 33 kV distribution portion is equipped with 28 DOCRs. Each DG is rated at 5 MVA and operates at unity power factor. The DG units feed the system through a 480 V/33 kV step-up transformer with 5% transient reactance. Nodes are added at midway points of all lines (F15–F30) representing fault locations at which three phase short circuit analysis will be carried out [35]. To highlight the effectiveness of

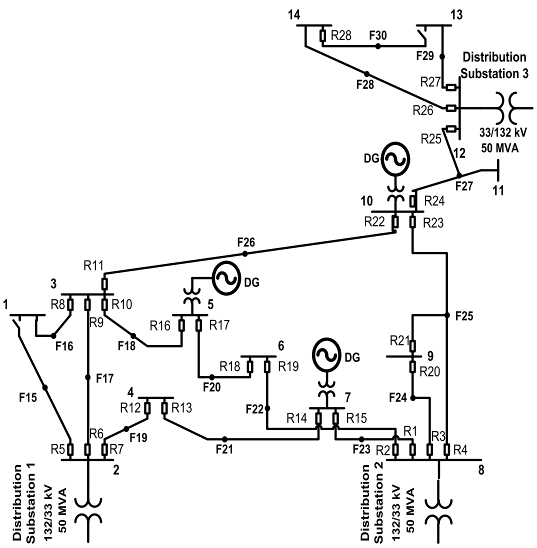

Fig. 5. Modified distribution portion of the IEEE 30-bus system.

the use of dual setting relays, the new protection scheme has been further tested considering different DG sizes and locations.

The proposed as well as the conventional protection coordination problem are implemented for comparison. For the conventional backup scheme, the system is equipped with 28 conventional directional OCR that have one pair of settings (TDS & I_p). As an example, for a fault at node F20, relays R17 and R18 will represent the primary relays. In the conventional protection coordination scheme, the backup relay for R17 is relay R10 while R2 acts as backup for relay R18.

With the proposed scheme, the system is, similarly, equipped with 28 relays where each dual setting DOCR is equipped with one pair of settings (TDS_{fw}, I_{pfw}) for operation in forward direction and another pair (TDS_{rv}, I_{prv}) for operation in the reverse direction. With the proposed scheme, for the same fault at node F20, the primary relays will remain to be R17 and R18 but the backup relays will be changed to be R16 instead of R10 for primary relay R17 and R19 instead of R2 for primary relay R18. The optimization model developed is solved using the MATLAB minimum constrained nonlinear multivariable function. This built-in MATLAB function relies on the reduced gradient approach (first order optimality) for solving constrained nonlinear optimization problems. There are several algorithms available for solving a constrained NLP problem. Sequential quadratic programming (SQP) algorithm is chosen to solve the protection coordination model. Full description of the MATLAB SQP algorithm is provided in [36].

V. Results And Analysis

In this section, the optimal relay settings considering both the conventional and proposed protection scheme are presented for meshed distribution systems with and without DG installation. In addition, a comprehensive analysis in which the DG capacity and location are varied is implemented to highlight the superiority of the proposed scheme.

TABLE II
Optimal Relay TDS and I_p Settings Considering the Conventional Protection Coordination Scheme

Relay	*TDS(s)*	*Ip(p.u)*	*Relay*	*TDS(s)*	*Ip(p.u)*
1	0.1	0.855	15	0.3513	0.0684
2	0.1	0.6811	16	0.2773	0.0605
3	0.1	1.0708	17	0.1	0.4648
4	0.1	0.1395	18	0.1	0.4558
5	0.1	0.0768	19	0.1	0.2412
6	0.1	0.6758	20	0.2888	0.0789
7	0.1	0.7312	21	0.5966	0.0166
8	0.1	0.0196	22	0.2243	0.0961
9	0.1	0.3229	23	0.4176	0.0627
10	0.1	0.5952	24	0.1	0.1661
11	0.1	0.1975	25	0.2836	0.1502
12	0.1	0.2967	26	0.1	0.2174
13	0.1	0.538	27	0.1	0.0622
14	0.1	0.5503	28	0.1	0.0367

A. Proposed Protection Scheme Versus Conventional Scheme With DG

In order to evaluate the performance of the proposed scheme, the conventional protection coordination is modeled and solved optimally. Table II presents the optimized setting TDS and I_p for primary and backup relays for faults at nodes F15–F30. The sum of relay operating times (T) using the conventional protection scheme is 63.27 s. Table III illustrates a breakdown of the optimal operating times of the primary and backup relays for all fault locations. Each primary/backup relay pair satisfies the protection coordination constraint by maintaining a minimum CTI of 0.3 s.

The proposed protection coordination scheme, presented in Section III, is applied on the same test system. As mentioned earlier, each relay is equipped with two pairs of settings, one corresponding to its operation in the forward direction and the other for its operation in the reverse direction. Table IV presents the optimal settings for the dual setting DOCR. As seen from the table, all relays except for relays 5, 8, 27, and 28, have two pairs of settings for forward and reverse operation. For relays 5, 8, 27, and 28, such relays will only have forward settings since fault currents in such relays flow in only one direction (due to the normally open switch).

From Tables II and IV, it can be noticed that the pickup currents settings for the proposed scheme, especially in the forward direction, are lower in values than the conventional scheme. For example, R1 has I_p setting of 0.855 p.u. using the conventional scheme compared to 0.064 p.u. for the proposed scheme. The reason is that R1, in the conventional scheme, is equipped with one pair of setting (I_p and TDS) that needs to satisfy both primary and backup operation (where R1 has to backup R14). For the same relay, with dual setting characteristic, two pairs of settings are available where one is dedicated for primary operation (forward) and the other for backup operation (reverse) and thus allowing the relay to be better tuned for each function.

As mentioned earlier, the dual setting relay will result in a new backup/primary coordination scheme. Table V presents the new protection scheme in addition to the optimal relay operating times using the dual setting relay. For the same

TABLE III
OPTIMAL PRIMARY AND BACKUP RELAY OPERATING TIMES CONSIDERING THE CONVENTIONAL PROTECTION COORDINATION SCHEME

Fault Location	Operating times of relays in sec. (*p* = primary, *b* = backup)				
	p	b_1	b_2	b_3	b_4
F15	*R5*	*R9*	*R12*	-	-
	0.1862	0.8136	0.9223	-	-
F16	*R8*	*R6*	*R16*	*R22*	-
	0.1359	0.9274	0.8168	0.8457	-
F17	*R6*	*R12*	-	-	-
	0.4931	0.7931	-	-	-
	R9	*R16*	*R22*	-	-
	0.4411	0.7411	0.7411	-	-
F18	*R10*	*R6*	*R22*	-	-
	0.5380	0.8380	0.8380	-	-
	R16	*R18*	-	-	-
	0.6214	0.9214	-	-	-
F19	*R7*	*R9*	-	-	-
	0.5544	0.8544	-	-	-
	R12	*R14*	-	-	-
	0.4451	0.7451	-	-	-
F20	*R17*	*R10*	-	-	-
	0.5484	0.8484	-	-	-
	R18	*R2*	-	-	-
	0.5816	0.8816	-	-	-
F21	*R13*	*R7*	-	-	-
	0.6839	0.9839	-	-	-
	R14	*R1*	-	-	-
	0.4753	0.7753	-	-	-
F22	*R2*	*R15*	*R20*	*R21*	*R23*
	0.6136	1.3743	1.8241	1.5297	1.5697
	R19	R17	-	-	-
	0.4283	0.7283	-	-	-
F23	*R1*	*R19*	*R20*	*R21*	*R23*
	0.4942	1.0210	1.0408	1.1631	1.0793
	R15	*R13*	-	-	-
	0.8053	1.1053	-	-	-
F24	*R3*	*R15*	*R19*	*R21*	*R23*
	0.6011	0.9011	0.9011	0.9011	0.9843
	R20	*R4*	*R23*	-	-
	0.6843	0.9843	0.9843	-	-
F25	*R4*	*R15*	*R19*	*R20*	-
	0.3073	0.9495	1.1985	0.6073	-
	R21	*R3*	*R25*	-	-
	0.8317	1.1317	1.2304	-	-
	R23	*R11*	-	-	-
	0.9304	1.2304	-	-	-
F26	*R11*	*R6*	*R16*	-	-
	0.3166	1.1198	0.9365	-	-
	R22	*R4*	*R21*	*R25*	-
	0.5627	1.0324	1.2515	1.4612	-
F27	*R24*	*R4*	*R11*	*R21*	-
	0.3191	0.8111	0.8724	1.1825	-
	R25	-	-	-	-
	0.8182	-	-	-	-
F28	*R26*	*R24*	-	-	-
	0.3416	0.6416	-	-	-
F29	*R27*	*R24*	-	-	-
	0.1963	0.5460	-	-	-
F30	*R28*	*R26*	-	-	-
	0.2179	0.5179	-	-	-

fault location (node F18), the primary relays R10 and R16 will trip after 0.1891 and 0.2241 s, respectively. If R10 fails to trip, its backup relays R9 and R11 (which used to be relays R6 and R22 in the conventional scheme) will operate after 0.4891 and 0.6829 s respectively. Relay R17 will act as a backup for relay R16 with an operating time of 0.5241 s. For a fault at location F18, the fault will be cleared in much less time using the proposed protection scheme.

TABLE IV
OPTIMAL RELAY DUAL SETTINGS WITH THE PROPOSED PROTECTION COORDINATION SCHEME

Relay	$TDS_{FW}(s)$	$Ip_{FW}(p.u)$	$TDS_{RV}(s)$	$Ip_{RV}(p.u)$
1	0.1	0.0684	0.2038	0.0684
2	0.1	0.0929	0.1031	0.1182
3	0.1	0.0789	0.2619	0.0789
4	0.1	0.0856	0.1	0.0856
5	0.1	0.0767		
6	0.1	0.1815	0.1007	0.1815
7	0.1	0.0746	0.1816	0.0746
8	0.1	0.0196		
9	0.1	0.1815	0.153	0.1815
10	0.1	0.0605	0.2321	0.0605
11	0.1	0.0547	0.24	0.0547
12	0.1	0.0746	0.1843	0.1117
13	0.1	0.0395	0.1977	0.1106
14	0.1	0.0395	0.1773	0.102
15	0.1	0.0684	0.2008	0.1107
16	0.1	0.0605	0.1766	0.1011
17	0.1	0.0279	0.1708	0.1041
18	0.1	0.0279	0.1850	0.1137
19	0.1	0.0673	0.1820	0.1061
20	0.1	0.0789	0.1862	0.111
21	0.1	0.0166	0.1754	0.1489
22	0.1	0.0197	0.1443	0.0523
23	0.1	0.0627	0.1761	0.0627
24	0.1	0.0243	0.2637	0.0243
25	0.1	0.0485	0.1	0.1661
26	0.1	0.2174	0.1	0.0716
27	0.1	0.0622		
28	0.1	0.0367		

In general, by comparing Tables III and V, it can be seen that all relays experience a reduction in the relay operating time with the proposed protection scheme. The value of the total operating time for all the relays considering the proposed scheme is 32.047 s which represents a reduction of approximately 50% compared to the conventional scheme. Thus, the proposed protection scheme can reduce significantly the overall sum of relay operating times for meshed distribution systems with DG.

B. Proposed Protection Scheme Versus Conventional Scheme Without DG

The proposed scheme is independent on the presence of the DG and thus can also be extended and applied to meshed distribution system with no DG interconnections. The proposed scheme was tested on the distribution portion of the IEEE 30-bus system without the addition of DGs. For brevity, Table VI shows a sample of the primary/backup relay operating times for faults at nodes F15–F20. It can be seen from the table that all the relays satisfy the protection coordination constraint with at least a CTI of 0.3 s between the primary and backup pairs. The total sum of relay operating times using the proposed scheme is 34.1722 s compared to 64.1725 s for the conventional coordination scheme and thus achieving an overall reduction of 46.7%. In addition, the proposed scheme results in lower relay operating times.

TABLE V
OPTIMAL PRIMARY AND BACKUP RELAY OPERATING TIMES WITH DG-PROPOSED SCHEME

Fault Location	Operating times of relays in sec. (p = primary, b = backup) p	b_1	b_2	b_3
F15	R5	R6	R7	-
	0.1862	0.4862	0.5831	-
F16	R8	R9	R10	R11
	0.1359	0.5083	0.6838	0.6877
F17	R6	R7	-	-
	0.2509	0.5509	-	-
	R9	R10	R11	-
	0.3204	0.6204	0.6204	-
F18	R10	R9	R11	-
	0.1891	0.4891	0.6829	-
	R16	R17	-	-
	0.2241	0.5241	-	-
F19	R7	R6	-	-
	0.1914	0.5005	-	-
	R12	R13	-	-
	0.2321	0.5321	-	-
F20	R17	R16	-	-
	0.1649	0.4649	-	-
	R18	R19	-	-
	0.1688	0.4688	-	-
F21	R13	R12	-	-
	0.1862	0.4862	-	-
	R14	R15	-	-
	0.1644	0.4644	-	-
F22	R2	R1	R3	R4
	0.2174	0.7973	1.6545	1.1806
	R19	R18	-	-
	0.3258	0.5358	-	-
F23	R1	R2	R3	R4
	0.1716	0.5107	0.9441	0.4935
	R15	R14	-	-
	0.2292	0.5292	-	-
F24	R3	R1	R2	R4
	0.1793	0.5228	0.4793	0.5792
	R20	R21	-	-
	0.2370	0.5370	-	-
F25	R4	R1	R2	R3
	0.2508	0.5508	0.5508	0.5508
	R21	R20	-	-
	0.1394	0.4394	-	-
	R23	R22	R24	-
	0.2228	0.5228	0.5228	-
F26	R11	R9	R10	-
	0.1962	0.5426	0.7840	-
	R22	R24	R23	-
	0.1559	0.5651	0.5013	-
F27	R24	R22	R23	-
	0.1651	0.4651	0.4651	-
	R25	-	-	-
	0.1931	-	-	-
F28	R26	R25	-	-
	0.3416	0.6416	-	-
F29	R27	R25	-	-
	0.1962	0.5460	-	-
F30	R28	R26	-	-
	0.2179	0.5179	-	-

As an example, for a fault at F18, primary relays R10 and R16 will operate in 0.538 and 0.6214 s using the conventional relay characteristic. On the other hand, the same relays for the same fault location will have an operating time of 0.1917 and 0.2464 s, respectively, when dual setting relays are utilized. Thus, the proposed scheme can be applied to meshed distribution systems with/without DG.

TABLE VI
OPTIMAL PRIMARY AND BACKUP RELAY OPERATING TIMES WITHOUT DG-PROPOSED SCHEME

Fault Location	Operating times of relays in sec. (p = primary, b = backup) p	b_1	b_2	b_3
F15	R5	R6	R7	-
	0.1889	0.5513	0.5698	-
F16	R8	R9	R10	R11
	0.1380	0.5055	0.7132	0.7198
F17	R6	R7	-	-
	0.2546	0.5546	-	-
	R9	R10	R11	-
	0.3536	0.6536	0.6536	-
F18	R10	R9	R11	-
	0.1917	0.4917	0.7271	-
	R16	R17	-	-
	0.2464	0.5464	-	-
F19	R7	R6	-	-
	0.1946	0.6166	-	-
	R12	R13	-	-
	0.2431	0.5431	-	-
F20	R17	R16	-	-
	0.1741	0.4741	-	-
	R18	R19	-	-
	0.1713	0.4713	-	-

TABLE VII
OVERALL RELAY OPERATING TIME (T) CONSIDERING DIFFERENT DG SIZES AND LOCATIONS WITH SBDG

DG Capacity and Location	Conventional Scheme	Proposed Scheme	Percentage Reduction
DGs rated 2 MVA@ bus 3	64.0842s	33.7388s	47.35%
DGs rated 4 MVA @bus 3	64.0014s	33.3726s	47.85%
DGs rated 6 MVA @bus 3	63.9232s	33.0889s	48.23%
DGs rated 2 MVA @ bus 6	64.3032s	33.9001s	47.28%
DGs rated 4 MVA @ bus 6	64.4239s	33.6779s	47.72%
DGs rated 6 MVA @ buses 6	64.5316s	33.4834s	48.11%
DGs rated 2 MVA @ buses 3,6	64.2495s	33.5030s	47.85%
DGs rated 4 MVA @ buses 3,6	64.2374s	33.0129s	48.6%
DGs rated 6 MVA @ buses 3,6	64.2115s	32.6491s	49.15%
DGs rated 2 MVA @ buses 3,6,10	63.581s	32.9376s	48.19%
DGs rated 4 MVA @ buses 3,6,10	63.1246s	32.1722s	49%
DGs rated 6 MVA @ buses 3,6,10	62.7497s	31.6333s	49.59%

C. Proposed Scheme Considering Various DG Sizes, Locations, and Technologies

To further test the proposed protection scheme, its performance is evaluated considering different DG sizes, technologies (IBDG and SBDG) and locations and compared against the conventional scheme. Several case studies are simulated to test the validity and superiority of the proposed scheme by considering different DG sizes and locations. Table VII summarizes the various case studies implemented and provides the overall relay operating time considering the conventional and

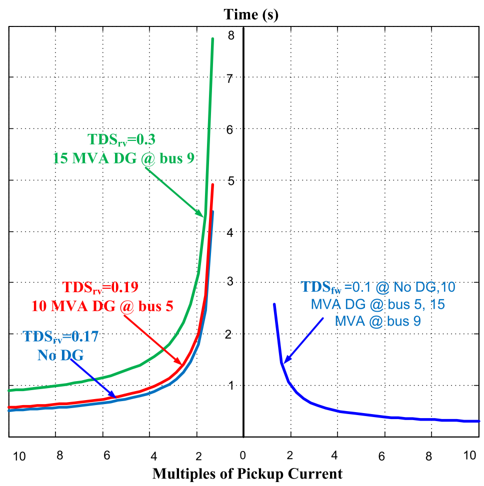

Fig. 6. Change of TDS$_{fw}$ and TDS$_{rv}$ of relay 18 due to DG addition.

TABLE VIII
OVERALL RELAY OPERATING TIME (T) CONSIDERING DIFFERENT DG TECHNOLOGIES

DG Capacity and Location	Conventional Scheme	Proposed Scheme	Percentage Reduction
IBDG rated 2 MVA @ bus 3	63.6874s	34.0498s	46.54%
IBDG rated 4 MVA @ bus 3	63.7283s	33.9322s	46.75%
IBDG rated 2 MVA @ bus 6	63.6819s	34.0468s	46.54%
IBDG rated 4 MVA @ bus 6	63.7207s	33.9306s	46.75%
IBDGs rated 2 MVA @buses 3 & 6	63.7288s	34.0286s	46.6%
IBDGs rated 4 MVA @buses 3 & 6	63.8131s	33.9041s	46.87%
SBDG rated 6 MVA @ buses 3 & 6 and IBDG rated 2 MVA @ bus 10	63.4979s	32.4260s	48.94%
SBDG rated 2 MVA @ buses 3 and IBDG rated 4 MVA @ bus 6&10	63.5247s	33.1553s	47.8%

proposed scheme for a distribution system with SBDG. All the simulated cases prove that the proposed protection scheme is capable of reducing the overall relay operating times compared to the conventional scheme. Fig. 6 illustrates graphically an example of the dual setting relay time-current curves for R18 considering different SBDG location and size. It should be noted that for this case, the forward settings (TDS$_{fw}$ and I_{pfw}) coincide for all considered locations while the reverse settings change with DG location and size. Furthermore, Table VIII presents the relay operating time percentage reduction achieved for systems with IBDG and a mix of IBDG and SBDG taking into account various DG sizes and locations. The results show that irrespective of the DG type, location, and size, the proposed scheme with dual setting relays is capable of achieving significant reduction in relay operating time.

D. Effect of Fault Location and Resistance

Previous results considered bolted three phase faults at the midpoint of the feeders. To further investigate the performance

TABLE IX
SAMPLE OF OPTIMAL PRIMARY AND BACKUP RELAYS OPERATING TIMES CONSIDERING NEAR/FAR POINTS FAULTS

Fault Location	Operating times of relays in sec. (p = primary, b = backup) p	b_1	b_2
F18-Near End (conventional)	*R10*	*R6*	*R22*
	0.5433	0.8433	1.0989
	R16	R18	-
	0.934	1.245	-
F18- Far End (conventional)	*R10*	*R6*	*R22*
	0.8565	1.1565	1.5898
	R16	*R18*	-
	0.857	0.974	-
F18-Near End (proposed)	*R10*	*R9*	*R11*
	0.1699	0.4699	0.6202
	R16	*R17*	-
	0.2501	0.6146	-
F18- Far End (proposed)	*R10*	*R9*	*R11*
	0.2055	0.6414	0.8981
	R16	*R17*	-
	0.2076	0.5076	-

TABLE X
EFFECT OF FAULT RESISTANCE ON TOTAL RELAY OPERATING TIME—CONVENTIONAL AND PROPOSED COORDINATION SCHEME

R_{fault} in ohms	Conventional Scheme	Proposed Scheme
0	63.27s	32.047s
0.01	63.2734s	32.0512s
0.05	63.2763s	32.0681s
0.1	63.2795s	32.09s
0.2	63.2842s	32.1337s
0.5	63.2874s	32.2924s

of the proposed approach, the protection coordination problem is solved considering near-end, midpoint, and far-end faults. For brevity, Table IX shows the relay operating times for both the conventional and proposed protection coordination schemes considering different fault locations within the same feeder with 5 MVA SBDG connected at buses 5, 7, and 10. Similar to the results obtained for midpoint faults, the results show that reduction in relay operating time is achieved at both near and far end fault locations. For the same DG sizes mentioned above, Table X presents the overall relay operating time considering various fault resistance values. The results highlight the superior performance of the proposed scheme.

VI. CONCLUSION

This paper proposes a new protection scheme utilizing dual setting DOCRs that are capable of operating in both forward and reverse directions but with a different setting. Thus, each relay is designed to have two pairs of settings, one for each direction. Such relay will consequently result in a new coordination scheme that varies from the commonly used backup/primary scheme used in previous literature. The proposed protection scheme is formulated as an optimization problem where two optimal pair of settings is determined for each relay. Simulation results show the superiority of the proposed protection scheme, in the presence and absence of DG, over the conventional well-known coordination scheme that uses the DOCR with one pair of settings. A reduction, in the overall relay operating time, of approximately 50% can be achieved with such scheme. Furthermore, the results show that the scheme can achieve reduced relay operating times irrespective of the DG size and location. Dual setting relays can achieve faster fault isolation and thus increasing the chances of DG to ride through fault events. Although this can result in economic and technical benefits, it is worthy to mention that dual setting relays provide additional functionality which can incur additional costs compared to the conventional directional relay.

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