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Non-Communication Based Time-Current-Voltage Dual Setting Directional Overcurrent Protection for Radial Distribution Systems With DG

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ABSTRACT This paper proposes a novel protection scheme equipped with time current voltage dual setting directional overcurrent relays for radial distribution systems with (distributed generation) DG without the need of communication assistance. The proposed protection scheme is formulated as a nonlinear programming problem where the main objective is to determine the optimal relay forward and reverse settings to minimize the relay overall operating times. The proposed scheme, based on the time current voltage dual settings directional overcurrent relay, is applied to the IEEE 33-bus radial distribution system with synchronous-based DG and its performance is compared against the conventional protection schemes that rely on both standard overcurrent relays and time current voltage directional overcurrent relays (proposed in the literature). The results show that, for radial distribution systems, the proposed scheme is capable of mitigating protection coordination failure due to DG reverse fault currents (a limitation in overcurrent relays), does not require communication (a limitation for meshed distribution systems) and does not require additional relays (a limitation in directional overcurrent relays) and thus making such relays more suitable for protecting radial distribution systems with DG.

INDEX TERMS Distributed generations (DGs), directional overcurrent relays, optimization, protection coordination.

I. INTRODUCTION

Protection from faults is a basic necessity in the planning and designing of distribution systems. Protection coordination is a procedure that is employed to ascertain the order of operating the main and backup protective devices for each fault location. An acceptable protection coordination strategy is one that can isolate only the area that is affected by the fault. Distribution systems are commonly designed to operate radially, where power flows in a unidirectional manner. This unidirectional flow of power has enabled relatively uncomplicated protection strategies. Consequently, in conventional distribution systems, simple protection devices such as overcurrent relays, re-closers, and fuses are normally employed [1], [2]. However, the integration of distributed generation has introduced some complexity in protecting distribution systems, as a result of the bidirectional power flow. DG impacts on distribution system protection including changing short circuit levels, relay coordination failure, nuisance fuse tripping, relay under reaching among other problems [3]. Consequently, recent work has focused on proposing new protection schemes and solutions for mitigating DG integration impacts on protection coordination for both radial [4]–[13] and meshed systems [17]–[20].

For radial distribution systems with DG, in [4], the proposed protection scheme relies on equipping each line with two overcurrent relays and is capable of minimizing the overall relay time. In [5], one overcurrent relay is added on the feeder to which the DG is connected in order to mitigate protection coordination failure and is coordinated with other

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relays on the system. In [6], a communication based multi-agent approach, which utilizes overcurrent relays for protecting radial distribution systems with DG is implemented. In [7], a stochastic mixed integer linear program capable of determining faster relay operating times is proposed to determine the optimal settings of overcurrent relays in radial distribution systems with DG. All of the above methods, relying on overcurrent relays, either do not consider the effect of the reverse DG fault contribution on protection coordination or require communication. Similarly, protection schemes, proposed in [8]–[11], mainly rely on overcurrent relays and thus as the system becomes larger, the impact of reverse fault current becomes more critical. Given the fact that coordination of overcurrent relays is lost in the presence of DG, one of the effective solutions proposed for restoring overcurrent relay coordination is through the use of Fault Current Limiter (FCL) [12]. In [13], the impact of DG reverse fault current contribution on overcurrent relay coordination is analyzed and it has been shown that the size and location of DG can adversely affect protection coordination.

To mitigate this impact, in [14], [15], and [24], directional overcurrent relays were proposed and optimally set at both ends of every line where the proposed scheme is capable of handling DG reverse fault current contribution. In [16], the directional overcurrent relay protection scheme is further enhanced by equipping each relay with a blocking signal that is transmitted to other relays. The aforementioned methods either require an additional relay to be located in each line or require a communication infrastructure to avoid coordination failure [23].

Similarly, several protection schemes have been proposed for meshed distribution systems with DG [17]–[20]. One approach proposed, in [17], [18], is to utilize Fault Current Limiters (FCL) to locally limit the DG fault current. However, the costs associated with such approach will increase with the increase in DG penetration. In [19], relays are installed at each line end having a combined feature of standard time inverse over current and distance relays. In order to reduce the protection scheme operating time, dual setting directional overcurrent relays were proposed for meshed distribution systems equipped with DG [20], [25]. This method can reduce the relay operating time but requires a communication infrastructure. In general, protection schemes developed for meshed distribution systems are capable of handling reverse fault contribution.

This paper proposes a dual setting time current voltage directional overcurrent relays (TCV-DOCR) protection scheme for radial distribution systems with high DG penetration. The proposed protection scheme is designed such that it can reduce the overall relay operating time, handle reverse DG fault contribution, and minimize the number of installed relays, and yet without the need for either a communication infrastructure or FCL. The proposed scheme is formulated as a nonlinear programming problem where the main objective is to minimize the relay operating time while maintaining adequate protection coordination for both upstream and downstream faults. The scheme is applied on the IEEE 33 bus radial network and is compared against the conventional overcurrent and time voltage current directional overcurrent relay schemes presented in [26].

II. PROBLEM FORMULATION

Generally, the overcurrent relay (OCR) operation time is determined by an inverse function of the fault current passing through it. The characteristic equation controlling the relay operating time differs depending on the manufacturer and type of OCR used. In this paper, identical OCRs are used with IEC255-3 standard characteristic equation as in [21]:

$$t_{ij} = TDS_i \frac{A}{\left(\frac{Isc_{ij}}{I_{p,i}}\right)^B - 1} \tag{1}$$

where i identifies the relay and j represents the fault location; t_{ij} is the required time for relay i to trip in sec for a fault at location j; Isc_{ij} is the short circuit current measured at the primary winding of the current transformer of relay i for a fault at location j; A and B are constants set to 0.14 and 0.02, respectively, based on the IEC standard normal inverse characteristic [21]; $I_{p,i}$ is the pickup or the threshold current (above the rated current) at which relay i will operate; TDS_i is the time dial setting of relay i and it is used as a tuning parameter. Such relays typically have one pair of settings, which include $I_{p,i}$ and TDS_i [8]–[11].

In [26], a time current voltage DOCRs for meshed distribution systems is proposed where this scheme is capable of reducing the total operating time of the relays compared to the conventional time-current characteristic. Equation (2) describes the operating time characteristic for time current voltage relays:

$$t_{ij} = TDS_i \frac{A}{\left(\frac{Isc_{ij}}{I_{p,i}}\right)^B - 1} \times \left(\frac{1}{e^{1-v_{f_{ij}}}}\right)^{\propto} \tag{2}$$

where $\propto$ is a constant parameter. On the other hand, a dual setting directional OCR with two pairs of settings was proposed in [20]. Unlike the conventional directional relays; which operates only in one forward direction; the dual setting directional overcurrent relays are capable of operating in the two directions (forward and reverse) but with a different pair of settings.

This paper combines both the time current voltage characteristics with the dual setting feature and proposes a dual setting time current voltage directional overcurrent relay to be applied for the protection of radial system with DGs.

Fig. 1 shows the forward characteristic of a dual setting TCV-DOCR. The relay will have two different pairs of (TDS and I_p) settings: $TDS_{fw}, I_{p,fw}$ for forward protection operation, and $TDS_{rv}, I_{p,rv}$ for reverse protection operation.

Two main differences appears in the application of dual setting relays for radial distribution systems introduced in this work when compared to [20]: dual settings DOCRs don't need any communication assistance in radial systems and the forward and reverse pair of settings can be utilized

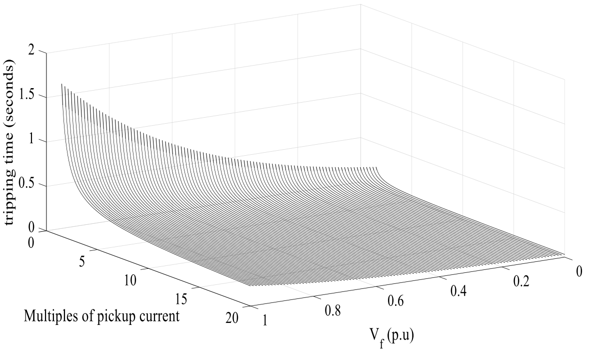

FIGURE 1. Time-Current-Voltage dual setting directional overcurrent relay forward characteristic.

for either primary or backup operation. On the contrary, for meshed distribution systems, the dual settings DOCRs needed communication features and the forward settings were used only for primary operation while the reverse settings were dedicated for backup operation.

The relay time-current-voltage characteristics can be expressed as follows:

$$t_{fw\_ij} = TDS_{fwi} \frac{A}{\left(\frac{Isc_{ij}}{I_{p,fwi}}\right)^{B} - 1} \times \left(\frac{1}{e^{1-v_{f_{ij}}}}\right)^{\propto} \quad (3)$$

$$t_{rv\_ij} = TDS_{rvi} \frac{A}{\left(\frac{Isc_{ij}}{I_{p,rvi}}\right)^{B} - 1} \times \left(\frac{1}{e^{1-v_{f_{ij}}}}\right)^{\propto} \quad (4)$$

where t_{fw_ij}, TDS_{fwi} and $I_{p,fwi}$ represent the relay operating time, relay time dial setting, relay pickup current setting for relay forward operation while t_{rv_ij}, $TDS_{rvi} I_{p,rvi}$ are the relay operating time, relay time dial setting, and relay pickup current settings parameters for the relay reverse operation. $v_{f_{ij}}$ is the per unit phase voltage magnitude measured at relay i at fault location j.

As mentioned earlier, the forward and reverse time-current-voltage characteristics for dual setting directional OCR have been modified (compared to [20]) such that (3) and (4) can be utilized for both primary and backup operation. Utilizing the voltage for the protection of distribution systems has been recently proposed in [26]. Since the conventional protective devices are current based, this method would require the installation of a voltage sensor within the relays.

The main objective of the protection coordination problem is to minimize the sum of primary and backup relay operating time (T) while maintaining the conditions of protection coordination. Thus, the objective function can be expressed as follows:

$$\text{Minimize T} = \sum\nolimits_{i=1}^{N} \Big(\sum\nolimits_{j=1}^{M} \big(t^{p}_{fw_{ij}} + \sum\nolimits_{k=1}^{K} (t^{bk}_{fw_{ij}} + t^{bk}_{rv_{ij}}) + (t^{p}_{rv_{ij}} + \sum\nolimits_{k=1}^{K} t^{bk}_{rv_{ij}}\big)\Big) \quad (5)$$

where i is the fault location identifier, N is the total number of fault locations considered, j is the relay identifier and M is the total number of relays. The superscript p refers to primary relays, while b_k refers to backup relay k, and K is the number of backup relays for each primary relay. In order to achieve the optimal feasible solution for forward and reverse operation for each relay, the protection coordination optimization (PCO) model considers three sets of constraints that must be satisfied.

The first set of constraints is imposed on the relay settings which represent the upper and lower bound on settings. The TDS_i value of each dual setting relay is constrained by lower and upper limits ($TDS_{i,min}$ & $TDS_{i,max}$), which are set to 0.05 and 5, respectively, as given in (6). Similarly, the pickup current setting $I_{p,i}$ for each dual setting relay is limited between $I_{p\ min,i}$ and $I_{p\ max,i}$ as indicated in (7). $I_{p\ min,i}$ for each relay in both operation (forwarded and reversed) is selected to be 1.6 times the rated load current of the line that it protects to ensure that each relay will trip only if a fault happens. Moreover, the lower and the upper boundaries of the constant parameter $\propto$ for both schemes (proposed and directional) are set to $\propto_{min} = 0$ and $\propto_{max} = 5$ respectively, as in (8).

$$TDS_{i,min} \leq TDS_{fwi}, TDS_{rvi} \leq TDS_{i,max} \quad \forall i \quad (6)$$

$$I_{p\ min,i} \leq I_{p,fwi}, I_{p,rvi} \leq I_{p\ max,i} \quad \forall i \quad (7)$$

$$\propto_{min} \leq \propto \leq \propto_{max} \quad \forall i \quad (8)$$

Finally, the backup relay should operate after a specific time interval in coordination with the primary relay operating time. This operating time difference, between primary and backup operation, is referred to as the Coordination Time Interval (CTI) and it is set to 0.2 sec in this study [11]. The described relation is expressed as follows:

$$\left.\begin{aligned} t^{b_k}_{fw_{ij}} - t^{p}_{fw_{ij}} &\geq CTI \\ t^{b_k}_{fw_{ij}} - t^{p}_{rv_{ij}} &\geq CTI \\ t^{b_k}_{rv_{ij}} - t^{p}_{rv_{ij}} &\geq CTI \end{aligned}\right\} \forall j \quad (9)$$

For example, for a fault at F51 in Fig. 2, it can be seen that the primary relays will be R18 (forward operation) and R19 (reverse operation). The backup relays in this case will be R1 (forward operation) and R2 (reverse operation) for relay R18 and R20 (reverse operation) for relay R19. The relay operating times are constrained using a lower bound of 0.1 seconds, and maximum time of 2.5 sec. The aforementioned problem is solved using the built in MATLAB optimization toolbox utilizing sequential quadratic programming. Single setting relays in the presence of DG can result in protection coordination failure. On the other hand, dual setting relays, proposed in the literature, require communication and are current based resulting in larger clearing times. The proposed dual setting relay scheme relies on both current and voltage and achieves twofold: 1) does not require communication and 2) can result in low relay operating times

III. SYSTEM AND SIMULATION

The IEEE 33 bus radial distribution system, in Fig. 2, is modeled to analyze the performance of the proposed time

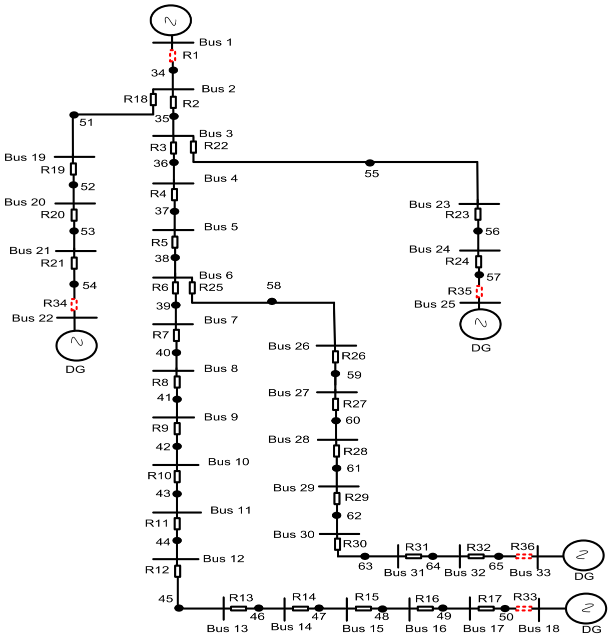

FIGURE 2. **33-bus Radial Distribution System equipped with the proposed protection scheme using Time-Current-Voltage dual setting directional overcurrent relay.**

current voltage dual setting directional overcurrent scheme. Moreover, a comparative analysis is conducted with other protection schemes relying on overcurrent and time current voltage directional overcurrent relays. For the protection scheme which depends on the conventional overcurrent relays, only 32 relays are required and are positioned at one end of the line, as shown in Fig. 2. The total demand for the given system is 5.084 MW and 2.547MVAR.

The IEEE 33 bus system is modified by integrating DG at various locations and thus the total demand is supplied by the primary distribution substation, as well as all DGs. Each DG is rated at 1 MVA and operates at unity power factor with a 10% sub-transient reactance. Each DG is connected at the end of each feeder through a 0.48/12.66kV step up transformer with an impedance of 5%. At each line, a bolted three-phase midway fault is considered where the fault locations are denoted as F34 to F65. Further system details are given in [22]. Typically, for fault analysis, all loads and shunt elements are neglected.

It is worthy to note that the proposed protection scheme relies on a combination of overcurrent as well as dual setting TCV-DOCR.

The choice of using a dual setting versus a conventional overcurrent relay depends primarily on the DG location. For example, all relays upstream of the DG would need to be dual setting relays while overcurrent relays are sufficient for relays downstream of the DG location. As stated earlier, all DGs are positioned at the end of the feeder which represents the most challenging case for protection coordination. Nevertheless, the proposed protection scheme is effective irrespective of the DG location.

For the conventional overcurrent protection scheme in Fig. 2, each relay is equipped with 2 settings (TDS and I_p). Thus, the overall number of settings to be optimized for the IEEE 33 bus system is 64. For the proposed protection scheme, the overcurrent relays in Fig. 2 (except for R_1) are replaced with dual setting TCV-DOCR. Each relay will be equipped with four settings two for forward operation ($TDS_{fwi} I_{p,fwi}$) and two for reverse operation ($TDS_{rvi} I_{p,rvi}$). In addition, relays connected to generation sources, such as Relay R_1 as well as the four additional relays R_{33}, R_{34}, R_{35} and R_{36} (shown in red in Fig. 2), are modeled as time current voltage overcurrent relays (without the dual settings feature).

These overcurrent relays are positioned to provide protection against fault current contribution by the DG at the feeder at which they are connected to. For example, for a fault at F50 on the feeder to which the DG is connected, overcurrent relay R33 and dual setting relay R17 (forward operation) will act as the primary relays and will isolate the fault. Relay R_{16} forward operation acts as a backup for R17. On the other hand, other feeders will be protected primarily by dual settings TCV-DOCR relays for both primary and backup operation. For example, for fault location F36, Relay R3 (*Fw*) and Relay R4 (*Rev*) will act as the primary relays. The backup relays for R3 are Relay R2(*Fw*) and Relay R22 (*Rev*), while Relay R5 (*Rev*) acts as the backup for relay R4 (*Rev*). For the proposed protection scheme, the total number of settings to be optimized is 170 (155 for the dual setting relays and 15 for the time current voltage overcurrent relays).

The proposed scheme is further compared with the time current voltage directional overcurrent relay scheme proposed in [26]. For each fault location, this protection scheme relies on allocating two directional overcurrent relays at each line end as shown in Fig. 3. Thus, this scheme is equipped with 64 DOCRs with an overall number of settings to be optimized equal to 192.

IV. RESULTS AND ANALYSIS

In this section, the simulation results for the 3 protection schemes using: conventional overcurrent relays, time current voltage directional overcurrent relays and time current voltage dual settings directional overcurrent relays are presented and compared when applied to the IEEE 33-bus radial distribution system.

A. CONVENTIONAL OVERCURRENT RELAY PROTECTION SCHEME

As indicated earlier, many recent work have considered the use of overcurrent relays for radial distribution systems with DG. Such approach would require minimal changes to the protection system but, as will be seen, it might not be effective when considering upstream faults. In this section, the optimal protection coordination will be studied in case of using overcurrent relays. For brevity, Table 1 presents the relay operating times for a sample of relays considering both downstream and upstream faults.

TABLE 1. Protection coordination for Both Downstream and Upstream Faults at different fault locations using the OCR scheme.

Fault Location	Operating times of relays in sec			
	Downstream		Upstream	
	Primary	Backup	Primary	Backup
F48	R15 0.407	R14 0.607	R16 0.612	R17 0.103
F63	R30 0.420	R29 0.62	R31 2.185	R32 0.132

As shown in Table 1, the overcurrent relays are well coordinated for all downstream faults (faults downstream of the relay under consideration).

For example, for a fault at 48, relay R15 will be the primary relay with an operating time of 0.4071s and is backed up by R14 which operates in 0.607s. On the contrary, all relays experience loss of coordination (where the backup relay will operate before the primary) for faults that are upstream with respect to the relay.

This will lead to protection coordination failure and for the system under study, the total number of protection coordination violation is 28. For example, for the same fault location, the backup relay R17 will come into operation at 0.103s while the primary relay R16 (which should operate before the backup) takes 0.612s.

B. TIME-CURRENT-VOLTAGE DIRECTIONAL RELAY PROTECTION SCHEME

In order to mitigate the coordination violation for downstream faults when depending on overcurrent relays in the presence of DG, TCV-DOCRs were proposed, where directional overcurrent relays are positioned at the two ends of each line. Fig. 3 highlights the locations of the TCV-DOCRs for a radial distribution system equipped with DG. Similarly, the main objective is to minimize the overall relay operating time while maintaining adequate protection coordination. Table 2, for brevity, presents the relay operating time for a selected list of faults while Table 3 presents the optimal relay settings.

By comparing to the overcurrent relay scheme, it can be seen that for a fault at F48, the downstream relay R27 will be the backup for relay R29 while the upstream relay R32 will act as the backup for relay R30 for the same fault. The optimal settings results in a relay operating time of 0.1s and 0.3s for R29 and R27, respectively. Similarly, the optimal relay operating time for R30 and R32 are 0.1s and 0.3s, respectively. As can be seen, time-current-voltage DOCRs are capable of providing adequate protection coordination for both upstream and downstream faults without any protection coordination violations.

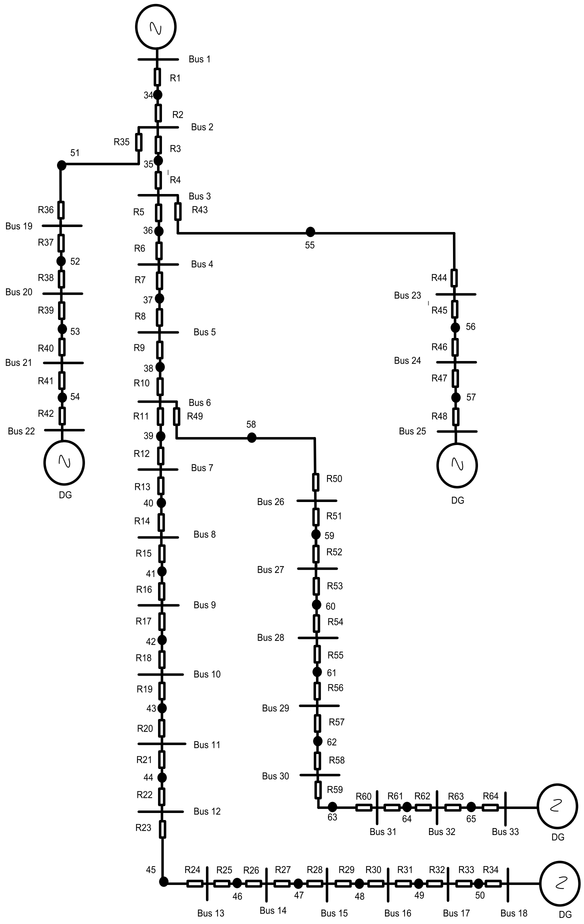

FIGURE 3. 33-bus Radial Distribution System equipped with time current voltage directional overcurrent relays.

In the next subsection, a protection scheme which relies on dual setting TCV-DOCR is proposed to mitigate the shortcomings in both the overcurrent and directional overcurrent protection schemes. The proposed protection scheme requires minimal additional relays, does not require a communication infrastructure and relies on modifying the existing relays with the characteristic of the dual setting time-current-voltage relay. Thus, the proposed scheme is a cost effective solution for protecting distribution systems with DGs. On the contrary, protection schemes relying on, for example, directional relays shown in Fig. 3 would require a significant amount of additional relays, which will in turn result in additional costs.

C. PROPOSED TIME CURRENT VOLTAGE DUAL SETTING DIRECTIONAL RELAY SCHEME

In this subsection, a protection scheme that relies on dual setting TCV-DOCR is optimally designed to provide adequate protection for radial distribution systems with DG. The method relies on a combination of dual setting relays as well as time current voltage overcurrent relays. Fig. 2 presents the locations of the dual settings relays (shown in black). The proposed scheme relies on converting all feeder overcurrent relays into dual setting time current voltage directional relays capable of operating in both forward and reverse direction but with a different set of settings. For any bus with a DG or grid connection, a TCV overcurrent relay is installed since fault current will flow in only one direction (from the generation

TABLE 2. **Optimal primary and backup relay operating times of the time-current- voltage directional overcurrent relay scheme.**

Fault Loc.	$T_{operating}$ of relays (sec.)			Fault Loc.	$T_{operating}$ of relays (sec.)		
	p	b_1	b_2		p	b_1	b_2
F34	R1 0.192 R2 0.1	- - R4 0.3	- - R36 0.3	F51	R35 0.1 R36 0.28	R4 0.62 R38 0.48	R1 0.3
F35	R3 0.1 R4 0.19	R1 0.4 R6 0.39	R36 0.5 R44 0.39	F52	R37 0.1 R38 0.1	R35 0.53 R40 0.3	- -
F36	R5 0.1 R6 0.32	R3 0.3 R8 0.52	R44 0.5 - -	F53	R39 0.1 R40 0.1	R37 0.3 R42 0.3	- - - -
F37	R7 0.1 R8 0.11	R5 0.3 R10 0.31	- - - -	F55	R43 0.1 R44 0.3	R3 0.386 R46 0.5	R6 0.591 - -
F46	R25 0.1 R26 0.1	R23 0.3 R28 0.3	- - - -	F59	R51 0.1 R52 0.21	R49 0.3 R54 0.41	- - - -
F48	R29 0.1 R30 0.1	R27 0.3 R32 0.3	- - - -	F61	R55 0.18 R56 0.1	R53 0.38 R58 0.3	- - - -

source and towards the system). The role of the overcurrent relays, shown in red in Fig. 2, is to provide protection against fault contribution by the generation sources.

The proposed protection scheme, is optimally solved to determine the relay settings for both the TCV dual setting DOCR and overcurrent relays. As mentioned earlier, each dual setting relay is equipped with two settings, one corresponding to its operation in the forward direction and the other for its operation in the reverse direction. Table 4 presents the optimal settings for the time current voltage dual setting DOCRs. As seen from Table 4, all relays have two pairs of settings for forward and reverse operation except for relays R1, R33, R34, R35 and R36, respectively, which are all overcurrent relays as indicated earlier. The time current voltage dual setting DOCRs will lead to a new backup/primary coordination scheme. Table 5 presents the new protection scheme in addition to the optimal relay operating times for a selected locations of faults. As can been seen from the results, all constraints are satisfied including the protection coordination constraint where the backup relays operate after the primary relay by a CTI. Moreover the optimal value of $\propto$ is found to be 5 for both the time current voltage DOCR scheme as well as the proposed protection scheme.

By referring to the same fault location, F48, it can be seen that the primary relays will be $R15_{fw}$ and $R16_{rv}$. The backup relays in this case will be $R14_{fw}$ for relay R15 and R17*rv* for relay R16. As seen from Table 5, the operating times for primary operation will be 0.1s for R15 and R16. On the contrary both the time current voltage directional overcurrent and proposed scheme result in a primary operation time of 0.1s,

TABLE 3. **Optimal primary and backup relay settings of time-current-voltage directional overcurrent relay scheme.**

Relay	TDS	$I_{p\ (per\ unit)}$	Relay	TDS	$I_{p\ (per\ unit)}$
1	1.005	3.792	33	0.05	1.048
2	0.05	2.045	34	0.166	0.605
3	0.406	3.892	35	5	0.358
4	0.325	1.4112	36	5	0.254
5	0.353	4.245	37	2.537	03664
6	5	0.439	38	0.072	0.586
7	1.216	2.234	39	0.899	1.884
8	0.05	0.962	40	0.132	0.594
9	0.747	2.27	41	0.05	2.747
10	0.108	0.96	42	0.09	0.623
11	0.464	2.792	43	5	0.145
12	0.111	0.465	44	5	0.287
13	1.008	1.676	45	3.856	0.093
14	0.0517	0.487	46	0.053	0.62
15	1.028	1.226	47	1.967	0.641
16	0.068	0.492	48	0.096	0.624
17	0.272	1.918	49	0.186	3.629
18	0.0995	0.5	50	2.5	0.339
19	0.11	2.019	51	1.299	1.823
20	0.0576	0.521	52	0.05	0.562
21	0.642	1.466	53	1.077	1.155
22	0.05	0.531	54	0.0584	0.563
23	0.458	1.257	55	0.378	1.959
24	0.07	0.532	56	0.112	0.568
25	0.252	1.354	57	0.539	1.677
26	0.1271	0.538	58	0.066	0.596
27	0.238	1.271	59	0.326	1.59
28	0.077	0.565	60	0.0782	0.603
29	0.49	1.024	61	0.20	1.622
30	0.065	0.580	62	0.091	0.619
31	0.331	0.951	63	0.05	1.655
32	0.137	0.578	64	0.058	0.64

respectively, for upstream fault currents resulting from DG contribution. Both time current voltage directional and dual setting time current voltage schemes are able to mitigate protection coordination failure.

For the dual setting time current voltage relays, the backup scheme for F48 will operate in 0.3s for both $R14_{fw}$ and $R17_{rv}$. The proposed scheme requires approximately 45 % less number of relays when compared to the DOCR case. Furthermore, in comparison to the overcurrent relay scheme, the proposed scheme would require 4 additional overcurrent relays (one per each DG). With the availability of microprocessor based relays, a simple modification to the 32 existing overcurrent relays can be achieved by updating the relays with the dual characteristic. On the other hand, the directional overcurrent relay scheme would require 32 additional relays and this is in addition to modifying all 64 relay characteristics with the directional overcurrent relays. Moreover, the total sum of relay operating times using the proposed scheme is 30.84s compared to 32.1s for the time current voltage DOCRs.

When applying the dual setting relays in meshed systems, they require a communication infrastructure [20] in order

TABLE 4. **Optimal settings for the proposed scheme with dual settings-TCV DOCRs.**

Relay	TDS_{fw}	$I_{p\ (per\ unit)}$	TDS_{rv}	$I_{p\_\ rv}$ (per unit)
1	0.918	3.868	-	-
2	0.406	3.892	0.101	1.439
3	0.358	4.232	5	0.324
4	1.217	2.222	0.069	0.933
5	0.754	2.264	0.055	0.956
6	0.463	2.790	5	0.193
7	1	1.677	0.1	0.467
8	1.026	1.228	0.052	0.487
9	0.272	1.918	0.068	0.493
10	0.111	2.018	0.099	0.499
11	0.641	1.466	0.057	0.521
12	0.462	1.255	0.05	0.531
13	0.253	1.352	0.07	0.531
14	0.238	1.27	0.127	0.538
15	0.48	1.023	0.077	0.565
16	0.33	0.950	0.065	0.580
17	0.05	1.047	0.138	0.579
18	5	0.357	0.184	0.538
19	2.536	0.036	0.05	0.583
20	0.899	1.885	0.083	0.583
21	0.582	1.802	0.131	0.594
22	5	0.144	0.105	0.583
23	3.856	0.093	0.076	0.601
24	0.347	2.554	0.067	0.615
25	0.186	3.626	0.298	0.493
26	1.295	1.824	0.095	0.540
27	1.075	1.157	0.05	0.561
28	0.377	1.958	0.061	0.563
29	0.538	1.676	0.111	0.568
30	0.327	1.591	0.066	0.594
31	0.2	1.621	0.078	0.603
32	0.05	1.654	0.091	0.618
33	-	-	0.165	0.604
34	-	-	0.09	0.623
35	-	-	0.096	0.624
36	-	-	0.058	0.64

to avoid the operation of relays for faults outside of their zone prior to the primary relay and thus maintaining proper protection coordination. On the contrary, no communication is needed when applied in a radial systems as the work in this paper.

In order to validate that the proposed scheme does not require a communication infrastructure, Table 6 presents the operating times of a selected group of relays for different fault locations.

For example, for a fault at F47, the primary downstream relay is R14fw and Relay R13fw forward operation acts as a backup for R14 and R12 acts as a second backup. The operating times for primary operation will be 0.1s for R14 and 0.3s for backup1 (R13) whereas relay R12 will operate at 0.6s.

TABLE 5. **Relay operating times for the proposed scheme with dual settings- TCV DOCRs.**

Fault Loc.	$T_{operating}$ of relays (sec.) p	b		Fault Loc.	$T_{operating}$ of relays (sec.) p		
		b_1	b_2			b_1	b_2
F34	$R1_{fw}$ 0.188 $R2_{rv}$ 0.1 $R18_{rv}$ 0.1	- - $R3_{rv}$ 0.3 $R19_{rv}$ 0.3	- $R22_{rv}$ 0.3	F51	$R18_{fw}$ 0.1 $R19_{rv}$ 0.151	$R2_{rv}$ 0.62 $R20_{rv}$ 0.35	R1 0.3
F35	$R2_{fw}$ 0.1 $R3_{rv}$ 0.25 $R22_{rv}$ 0.13	$R1_{fw}$ 0.41 $R4_{rv}$ 0.45 $R23_{rv}$ 0.33	$R18_{rv}$ 0.3 - - - -	F52	$R19_{fw}$ 0.1 $R20_{rv}$ 0.1	$R18_{fw}$ 0.53 $R21_{rv}$ 0.3	- -
F36	$R3_{fw}$ 0.1 $R4_{rv}$ 0.1	$R2_{fw}$ 0.3 $R5_{rv}$ 0.3	$R22_{rv}$ 0.5 - -	F53	$R20_{fw}$ 0.1 $R21_{rv}$ 0.1	$R19_{fw}$ 0.3 $R34_{rv}$ 0.3	- - - -
F37	$R4_{fw}$ 0.1 $R5_{rv}$ 0.1	$R3_{fw}$ 0.3 $R6_{rv}$ 0.4	- - $R25_{rv}$ 0.3	F55	$R22_{fw}$ 0.1 $R23_{rv}$ 0.1	$R2_{fw}$ 0.386 $R24_{rv}$ 0.3	$R3_{rv}$ 0.37 - -
F47	$R14_{fw}$ 0.1 $R15_{rv}$ 0.1	$R13_{fw}$ 0.3 $R16_{rv}$ 0.3	- - - -	F61	$R28_{fw}$ 0.1 $R29_{rv}$ 0.1	$R27_{fw}$ 0.3 $R30_{rv}$ 0.3	- - - -
F48	$R15_{fw}$ 0.1 $R16_{rv}$ 0.1	$R14_{fw}$ 0.3 $R17_{rv}$ 0.3	- - - -	F62	$R29_{fw}$ 0.1 $R30_{rv}$ 0.1	$R28_{fw}$ 0.3 $R31_{rv}$ 0.3	- - - -
F50	$R17_{fw}$ 0.1 $R33_{rv}$ 0.1	$R16_{fw}$ 0.3	- - - -	F65	$R32_{fw}$ 0.18 R36 0.1	$R31_{fw}$ 0.38 -	- - - -

TABLE 6. **Validating the performance of the proposed scheme with dual settings- TCV DOCRs for out of zone faults.**

Fault Loc.	$T_{operating}$ of relays (sec.)					
	Downstream			Upstream		
	p	b_1	b_2	p	b_1	b_2
F36	R3 0.1	R2 0.3 $R22_{rv}$ 0.412	R1 1.63	$R4_{rv}$ 0.1	$R5_{rv}$ 0.3	$R6_{rv}$ 0.47 $R25_{rv}$ 0.45
F47	R14 0.1	R13 0.3	R12 0.61	$R15_{rv}$ 0.1	$R16_{rv}$ 0.3	$R17_{rv}$ 0.83
F61	R28 0.1	R27 0.3	R26 1.08	-	-	-

By referring to the same fault location, the upstream relay $R16_{rv}$ will be the first backup for relay $R15_{rv}$ and the relay $R17_{rv}$ will act as the second backup for relay $R15_{rv}$. The optimal settings results in a relay operating time of 0.1s for $R15_{rv}$, 0.3s for R16 and 0.8296s for $R17_{rv}$. Thus, a blocking communication signal is not required for the second backup as in the case of meshed distribution systems [20].

It is worthy to note that the current trend in intelligent distribution networks is the use of communication given that communication latency and failure does not significantly affect the operation of the protection scheme. For distribution

TABLE 7. Optimal settings for the proposed scheme with dual settings-TCV DOCRs in presence of inverter based DGs.

Relay	TDS_{fw}	I_{p} (per unit)	TDS_{rv}	I_{p_rv} (per unit)
1	0.9426	3.8483	-	-
2	0.4073	3.889	0.09	1.44
3	0.3586	4.231	5	0.325
4	1.2247	2.212	0.069	0.934
5	0.745	2.274	0.055	0.956
6	0.464	2.790	5	0.193
7	1	1.676	0.1	0.467
8	1.0278	1.228	0.052	0.487
9	0.272	1.916	0.068	0.493
10	0.111	2.017	0.099	0.499
11	0.642	1.465	0.057	0.521
12	0.462	1.253	0.05	0.531
13	0.253	1.351	0.07	0.531
14	0.238	1.27	0.127	0.538
15	0.49	1.022	0.077	0.565
16	0.33	0.95	0.065	0.580
17	**4.99**	**0.0738**	0.137	0.579
18	5	0.357	0.18	0.539
19	2.5391	0.036	0.05	0.584
20	0.9	1.882	0.082	0.584
21	**4.6529**	**0.08**	0.13	0.595
22	5	0.145	0.103	0.583
23	3.855	0.093	0.075	0.601
24	**0.058**	**3.2794**	0.067	0.615
25	0.186	3.625	0.31	0.492
26	1.295	1.824	0.095	0.540
27	1.075	1.155	0.05	0.561
28	0.377	1.956	0.061	0.563
29	0.539	1.674	0.11	0.568
30	0.327	1.589	0.066	0.594
31	0.2	1.619	0.078	0.603
32	**0.096**	1.61	0.091	0.618
33	-	-	0.165	0.604
34	-	-	0.09	0.623
35	-	-	0.095	0.624
36	-	-	0.058	0.64

systems equipped with DG, which lack a communication infrastructure, the proposed protection scheme would provide timely and effective fault detection and isolation using dual setting directional overcurrent relays.

The proposed scheme relies on one relay in each line to perform both forward and reverse fault detection. This results in a reduced number of relays and costs but results in a loss of an additional load. For example, for a fault at F59 in Fig.2, load on bus 27 will be lost. On the contrary, using two directional relays at both ends of the line, increases the number of relays but results in less loads to be lost due to faults. For example, for the same fault F59 in Fig. 3, the relays would isolate the fault and load at bus 27 would continue to operate. There is a tradeoff between the number of relays, consequently cost, and the reliability of the system.

TABLE 8. Optimal settings for the proposed scheme with dual settings-TCV DOCRs under dynamic operation.

Relay	TDS_{fw}	I_{p} (per unit)	TDS_{rv}	I_{p_rv} (per unit)
1	0.56	3.781	-	-
2	0.1865	4.086	0.05	1.19
3	0.1723	4.344	0.05	0.275
4	0.5524	2.519	2.37	0.671
5	0.3198	2.412	0.05	0.684
6	0.174	2.737	0.05	0.693
7	4.2864	0.1	0.0758	0.71
8	0.3652	1.54	0.05	0.743
9	1	0.578	0.06	0.756
10	5	0.3	0.09	0.771
11	0.27	1.46	1.3	0.527
12	0.214	1.258	0.394	0.61
13	0.1219	1.297	0.076	0.853
14	0.1148	1.22	0.127	0.876
15	0.2239	1	0.076	0.967
16	0.1619	0.935	0.066	1
17	3.63	0.0272	0.136	0.995
18	4.82	0.0394	0.09	0.54
19	0.5	0.966	0.05	0.579
20	0.38	2.0961	0.05	0.583
21	3.156	0.0378	0.065	0.59
22	0.899	1.591	0.1	0.576
23	0.753	1.147	0.05	0.6
24	2.5239	0.0815	0.05	1.063
33	-	-	0.1886	1.063
34	-	-	0.05	0.623
35	-	-	0.05	0.626

D. PERFORMANCE of THE PROPOSED METHOD WITH INVERTER BASED DG

In order to further validate the proposed protection scheme, the distribution system given in Fig. 2 is equipped with four inverter-based DGs each rated at 0.5 MVA and located at buses 18, 22, 25 and 33. The system also includes the synchronous-based DG shown in Fig. 2. The optimal settings are determined and for brevity, the optimal settings of the relays are presented in Table 7. As can be seen, the presence of inverter-based DG has minimal impact on the relay settings when compared to the results presented in Table 4. Significant changes in settings can be seen for relays 17, 21, 24, and 32 (highlighted in bold in Table 7). This is due to the low fault current contribution of inverter-based DG in comparison to synchronous-based DG. It is also noticed that the optimal value of $\propto$ is found to be 5 which is similar to the results obtained for the synchronous based DG case.

E. PERFORMANCE of THE PROPOSED METHOD CONSIDERING DYNAMIC CHANGES

This subsection investigates the impact of dynamic changes in the distribution system on the optimal relay settings. Dynamic changes in the system can impact the system overall configuration resulting in changes in the fault current magnitudes. This in turn would have an impact on protection coordination. The optimal relay settings for the distribution system presented in Fig. 2 is determined for the proposed protection scheme considering outages in line between Bus 3 and Bus 23, line between Bus 2 and Bus 19 and line between Bus 6 and Bus 26, respectively. For brevity, Table 8 presents the optimal settings for the case where the line between Bus 6 and Bus 26 is open. Compared to the settings provided in Table 4, dynamic changes in the distribution system can have a significant impact on the optima relay settings. For systems equipped with a reliable communication infrastructure and a central protection unit, the relay settings can adaptively change with changes in system configuration. The optimal value of $\propto$ is found to be 4.34.

V. CONCLUSION

This paper proposes a protection scheme for radial distribution systems equipped with DG that relies on a combination of time current voltage dual setting and overcurrent relays. The proposed scheme does not rely on communication or the use of fault current limiters. The protection coordination problem is formulated in an optimization framework where the optimal settings are determined for each dual setting relay (pick-up current and time dial setting for forward and reverse directions).

A comparative study is conducted considering three protection schemes, namely, overcurrent, time-current-voltage directional overcurrent and the proposed combined dual setting time-current-voltage directional overcurrent and overcurrent scheme. The proposed scheme is tested on a typical radial distribution system on the IEEE 33-bus system equipped with DG and the results for both systems highlight the effectiveness of the proposed method. The results show that the operating time of the dual-setting time-current voltage directional relays and the time-current voltage directional relays are nearly equal. However, the number of relays required for the proposed scheme is approximately half of that needed for the DOCR scheme and thus providing a cost effective solution for radial distribution system protection. Future work will explore the application of dual setting relays and its coordination with re-closers and fuses.

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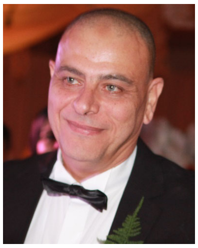

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