IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 4, 2021, accepted April 16, 2021, date of publication April 20, 2021, date of current version April 30, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3074426

User-Defined Dual Setting Directional Overcurrent Relays with Hybrid Time Current-Voltage Characteristics-Based Protection Coordination for Active Distribution Network

LUCHENG HONG[1], (Member, IEEE), MIAN RIZWAN[1,2], MUHAMMAD WASIF[2], SHAFIQ AHMAD[3], MAZEN ZAINDIN[4], AND MUHAMMAD FIRDAUSI[3]

[1]Jiangsu Provincial Key Laboratory of Smart Grid Technology and Equipment, Southeast University, Nanjing 210000, China
[2]Department of Electrical Engineering, University of Gujrat, Gujrat 50700, Pakistan
[3]Industrial Engineering Department, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
[4]Department of Statistics and Operations Research, College of Science, King Saud University, Riyadh 11451, Saudi Arabia

Corresponding author: Mian Rizwan (rizwan.nazeer26@uog.edu.pk)

This work was supported by the Deanship of Scientific Research at King Saud University for funding this work through Research Group under Grant RG-1438-089.

ABSTRACT With the penetration of renewable energy sources based distributed generation (RES-DG) in the distribution network (DN), the operating time of protection relays becomes a major concern to avoid the mis-coordination and nuisance tripping of RES-DG. It is due to the bidirectional flow of current, variance in the fault current level, i.e. high fault current in case of Squirrel cage induction generator (SCIG) based RES-DG, and low fault current for an inverter-based RES-DGs. This paper proposes a novel User-defined dual setting direction overcurrent relay with hybrid time current-voltage (UDDOR-TCV) characteristics to intensify the proposed scheme's flexibility without any communication assistance for radial DN. The proposed model is formulated in a constrained non-linear optimization fashion and solved with the MINLP solver of general algebraic modelling system(GAMS) software to determine the optimal relay settings. The propounded protection scheme is simulated on IEEE-33 bus radial distribution system and a local 40-bus system hosting the multiple SCIG and PV based RES-DGs at optimal locations. Detailed numerical studies are carried out to show the performance of the proposed scheme. 66.848% and 68.26% reduction in relay operation time with zero mis-coordination is achieved with SCIG-WTG case and PV-units case for the IEEE-33 bus system and a similar reduction in operation time is 68.937% and 66.563% for Local-40 bus system. Moreover, the relays numbers are reduced by 32.692% and 39.7% for IEEE-33 and Local-40 bus systems, respectively, due to the forward/reverse characteristics capability of the proposed UDDOR-TCV. The performance of the proposed scheme is also evaluated on IEEE-8 bus meshed DN. The results are compared with the existing protection schemes in recent literature.

INDEX TERMS Distributed generation, dual setting directional overcurrent relay, hybrid TCV characteristics, GAMS, protection coordination, optimization, user-defined relay settings, fault currents.

I. INTRODUCTION

Renewable energy source based DGs (RES-DGs) such as wind turbine Generator (WTG) and Photovoltaic (PV) have been increased in the distribution network (DN) due to their low-cost green energy production and low maintenance [1].

The associate editor coordinating the review of this manuscript and approving it for publication was Padmanabh Thakur.

Some RES-DG such as the synchronous generator, squirrel cage induction generator (SCIG), and doubly fed SCIG based WTG can be directly connected to the DN. In contrast, some RES-DGs such as PVs can be integrated through inverter circuits [2]. Integration of RES-DGs transforms the conventionally designed radial DN into meshed DN. Bidirectional power flow in meshed DN complicates the protection schemes designed to protect radial distributed network where the current flow is unidirectional. Moreover, the addition of RES-DGs increases the fault current level (FCL), which depends on specific technology of RES-DG and disturbs the conventional protection scheme. Directly connected RES-DGs significantly increase fault current level, whereas the inverter based RES-DGs limit the fault currents from 1 to 2 per unit of rated currents [3]. This variation in fault current contribution from RES-DGs and bidirectional flow lead towards delayed operation of OCR, protection mis-coordination, nuisance tripping of DGs, and malfunctioning [4], [5]. Researchers have strived in numerous ways to mitigate the impact of RES-DGs integration on protection coordination of overcurrent relays.

Optimization algorithms (OAs) are proposed in the literature for sustainable protection coordination for radial and meshed DN. The main objective of OAs is to find the optimal settings of relay variables such as time dial settings (TDS) and pickup current (Ip) to reduce the relay overall operating time. The trial and error approach proposed in [6] constitutes high computation and time-consuming. For optimal coordination of OCR the- mixed-integer non-linear programming (MINLP) technique is applied based on particle swarm optimization(PSO) for unknown relay variables in [7]. The non-linear OCR coordination problem is formulated as mixed-integer linear programming(MILP) in [8] by linearizing the bilinear terms. One of the variables in each bilinear term is discretized over its interval into a fixed number of steps. The resulting terms after assigning binary variables are written in disjunctive inequalities. An indistinguishable approach hybrid GA-NLP unfolds in [9] to handle the non-linear (NL) nature of the coordination process. Although it exhibited good results which still can be improved in terms of decrease in mis-coordination and relay tripping time. The mis-coordination in a primary backup relay pair points out the case where the backup relay operates before the primary relay or both operate simultaneously [10]. In [8] pre-solution filtering simplification techniques are used and the NL protection coordination problem is linearized to formulate a linear programming problem. An intelligent genetic algorithm (GA) is deployed to deal with the non-linear nature of protection coordination(PC) problem [11]. A multi-population based GA was used in order to reduce the number of mis-coordinations and operating time [12]. An number of hybrid algorithms are developed to solve the complex and non-convex PC problem such as hybrid quadratic programming with quadratic constraints (QCQP) [13], hybrid fuzzy evaluation algorithm [14], and hybrid particle swarm optimization (H-PSO) [15].

The relay operating time can also be reduced drastically by modifying standard time-current characteristics (TCC) of OCR. This is only possible due to the invention of numerical/microprocessor-based relays, i.e., ARGUS2 [16] and GRD110-GRD150 [17], as the TCC equation can be modified by reprograming the relay microprocessor. In [18], the authors remarkably reduced the relay OT by considering the relay constants as variables and optimizing their values within a specific range termed as non-standard DS-DOCR(nst-DS-DOCR). Authors in [19] used double-setting DOCR(DS-DOCR) of TDS and IP for the forward and the reverse directions in order to cope with the effect of reverse DG fault current contribution. DS-DOCR has different settings of TDS and IP for forward and reverse directions. The protection coordination scheme using DS-DOCR for both operating modes of microgrid i.e. grid-connected and islanded was presented in [20] but it is applicable with communication assistance. A protection scheme with DS-DOCR without assistance of communication infrastructure was proposed in [21]. Each relay has one pickup setting and two TDS settings and operates as backup relay only in forward direction. The relay operating time was reduced with DS-DOCR using a hybrid cuckoo-linear algorithm in optimizing fault current limiter oriented protection scheme in [22] and using adaptive modified firefly algorithm in [23]. In [24], the authors with integration of the voltage component in the relay equation proposed new time current-voltage characteristics of DOCR for DG hosting meshed DN. Although, the scheme has a significant impact on the reduction of the relay operating time, however, the proposed scheme can be further extended with dual setting of directional overcurrent relays, as the numeric/microprocessor relays are furnished with the flexibility of easily reprogrammable by the user due to their mature design. This feature enables the user to implement the user-defined non-standard relay characteristics through the optimized parameters.

This paper presents a user-defined dual setting direction overcurrent relay with hybrid time and current-voltage characteristics (UDDOR-TCV) protection scheme for the radial distribution system. The proposed model is formulated in a constrained non-linear optimization fashion, which is tackled by mixed-integer non-linear programming (MINLP) solver of general algebraic modelling systems (GAMS) software. The propounded protection scheme is simulated on IEEE-33 bus radial distribution system and a local 40-bus system. The main contributions of the proposed scheme are listed as follows.

- A novel protection coordination scheme is devised by deploying user-defined dual setting directional overcurrent relays with hybrid time current-voltage characteristics.
- A potential transformer (PT) with pre-equipped DOCR is used for voltage data making it cost-effective as no new device is added.
- The total number of relays reduces as compared to the conventional DOCR for protecting the same RD; hence it also provides an economical solution.
- Having both the forward and the reverse characteristics of the proposed relay can be used as either primary or backup relay without any communication as in the meshed DN.
- The relay characteristics constants, voltage parameter along with TDS and Ip are treated as variables and

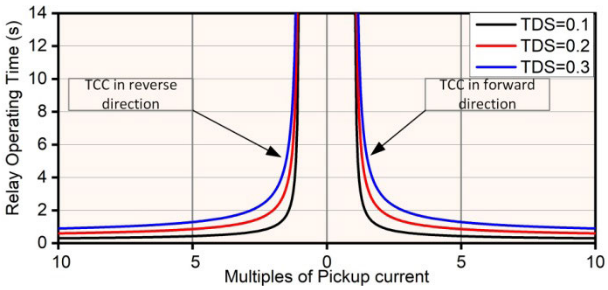

FIGURE 1. Relay time-current characteristics in forward and reverse direction for dual setting direction overcurrent relay.

included in the optimization model to reduce the overall relay operating time.

- SCIG and inverter-based PV RES-DGs are used due to their high and low fault current contributions to demonstrate that the scheme outperforms irrespective of fault current contribution from RES-DGs.
- A remarkable reduction in total operation time of relays is achieved with zero miscoordination.
- The proposed strategy does not jeopardize the relay sensitivity.

The ongoing paper is organized as follows: Section II describes the proposed UDDOR-TCV and problem formulation. Section III addresses the test systems under consideration and the results of case studies. Finally, the conclusions are drawn in Section IV.

II. PROPOSED PROTECTION SCHEME

A. ILLUSTRATION OF UDDOR-TCV

A reliable protection scheme isolates the least faulted section in a minimum time. Typically, the DOCR follows the standard inverse time-current characteristics defined in (1), and operates uni-directionally. A mature and flexible design of numerical/microprocessor relays enables the users to modify the relay characteristics according to the desired requirements in order to achieve minimum relay operating time. As a result, DOCR with double inverse TCC has evolved recently, operating in forward and reverse both directions. It comprises a separate setting of TDS and Ip in forward and reverse direction denoted as TDS_{fw}, $I_{pf}w$, TD_{Srev}, and I_{prev}. The TCC of double setting DOCR (DS-DOCR) is shown in Fig. 1.

$$T_{op} = \left(\frac{A}{M^B - 1}\right) \times TDS$$
$$M = \left(\frac{I_f}{I_p}\right) \tag{1}$$

T_{op} is the relay operation time; M is the pickup current multiplier and defined as the ratio of fault current to pickup curren; TDS is the relay time dial settin; A and B are relay characteristic parameters and have constant values for each standard inverse, normally inverse, and extremely inverse overcurrent relay.

The functionality of DS-DOCR in a meshed and radial distribution network is illustrated here. DS-DOCR constitutes different primary-backup relay pairs from conventional DOCR. Consider a meshed DN showed in Fig. 2(a) equipped with a conventional DOCR. For a fault F-1at line-1, the primary relays to isolate the fault are R1 and R3, with R5 and R6 as backup relays, respectively. In the case of same fault with a DS-DOCR as shown in Fig. 2(b), R1 operates in the forward direction ($R1_{fw}$) as the primary relay and R2 operates in the reverse direction (R2rev) to provide the backup protection. However, a signal through a communication link is sent to block the operation of R5 in the forward direction ($R5_{fw}$) on behalf of $R2_{rev}$. As a result, the relay operating time decreases considerably. If the communication link is removed, the relay R5fw needs to coordinate with R2rev through a coordination time interval (CTI). The total number of CTI for the operation of R5fw as a backup relay for R1fw will be 2∗CTI. This approach also increases the operation time of R5fw in its own protection zone. Therefore, in a meshed DN, the DS-DOCR is used as a primary relay in the forward direction and as a backup relay in the reverse direction, but it needs communication assistance. Otherwise, it will induce a delay in the fault clearance and increased chances of equipment damage.

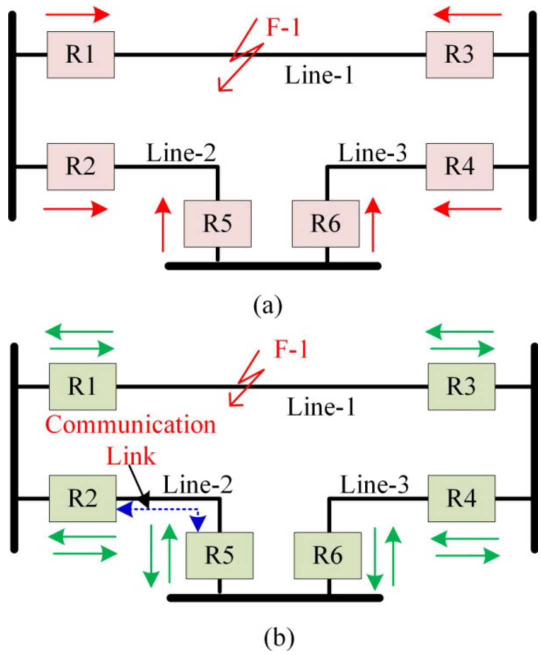

FIGURE 2. Three bus meshed distribution network equipped with (a) DOCR (b) DS-DOCR.

Now consider a radial distribution network equipped with normal DOCR shown in Fig. 3(a) and DS-DOCR shown in Fig. 3(b). A fault is introduced at the same location on line-3 in both networks. R5 and R6 provide the primary protection in the first network, whereas R3 and R8 provide the backup protection respectively. In the second network for the same fault, $R3_{fw}$ in the forward direction and R4rev in the reverse direction function as primary relays, whereas R2fw and R5rev operate as backup relays for R3fw and R4rev respectively. $R2_{fw}$ coordinates with $R3_{fw}$ with only

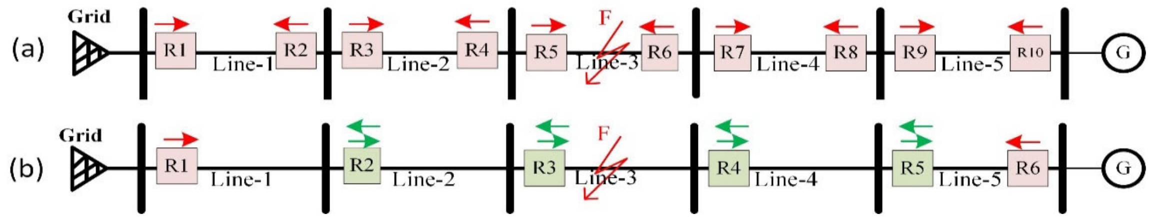

FIGURE 3. Radial distribution network equipped with (a) DOCR (b) DS-DOCR.

one CTI, which also reduces the operation time of $R2_{fw}$ when operating as primary relay in the forward direction in its own protection zone. Therefore, no communication is required in RDN for deploying DS-DOCR and it can be used as primary or backup protection in both the forward and the reverse direction. Furthermore, it is observed that with the deployment of DS-DOCR in a RDN, the number of relays decreased. This is not possible in case of a meshed DN, which reduces equipment and maintenance costs. A simple DOCR can be deployed for the line segments where the current remains unidirectional, reducing the burden of computation.

A DOCR with normal or double setting exhibits the standard time-current characteristics (TCC). The authors in [24] modified the standard TCC by integrating the fault voltage effect, which reduces the relay operation time. This is also possible with numerical relays. The modified TCC with fault voltage is given in (2)

$$T_{op} = \left(\frac{A \times TDS}{M^{B} - 1}\right)\left(\frac{1}{e^{1-V_f}}\right)^{K} \tag{2}$$

where V_f is the fault voltage measured at the relay and K is a relay constant parameter that can have different values for different relays.

In this paper, a novel user-defined dual setting DOCR is proposed with hybrid time-current-voltage characteristics. It combines the features of dual setting DOCR and TCV relays. Furthermore, the relay characteristics parameters A, B, C, and K are treated as variable instead of constants and tuned separately with an optimization model for both directions. Fig. 4 represents the proposed relay characteristics in the forward direction. The characteristics equations of the proposed UDDOR-TCV are given in (3) and (4) for the forward and the reverse relay characteristics respectively.

$$T_{fwi} = \left(\frac{TDS_{fwi} \times A_{fwi}}{\left(\frac{I_f}{Ip_{fwj}}\right)^{B_{fwi}}}\right) \times \left(\frac{1}{e^{1-V_{fi}}}\right)^{K_{fwi}} \tag{3}$$

$$T_{revi} = \left(\frac{TDS_{revi} \times A_{revi}}{\left(\frac{I_f}{Ip_{revi}}\right)^{B_{fwi}}}\right) \times \left(\frac{1}{e^{1-V_{fj}}}\right)^{K_{revi}} \tag{4}$$

where T_{fwi} and T_{revi} are the operating times of the i^{th} relay in the forward and the reverse directions; TDS_{fwi}, TDS_{revi}, Ip_{fwi}, and Ip_{revi} represent relay settings in the forward and the reverse directions; V_{fi} is the voltage measured at the j^{th} relay

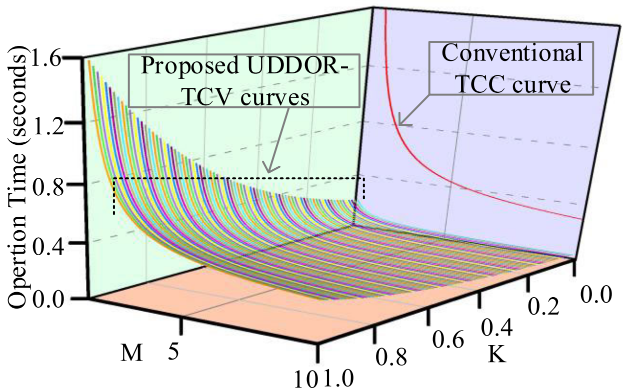

FIGURE 4. Conventional TCC curve and Time current-voltage characteristics of the proposed UDDOR-TCV in the forward direction.

during a fault; A, B and K represent the UDDOR-TCV relay characteristics parameters for the forward and the reverse characteristics.

The proposed protection scheme's main objective using UDDOR-TCV is to minimize the overall operating time of relays for fast fault clearance. The proposed relay can operate as a primary or backup relay in the forward or the reverse direction in a RDN. The objective function (OF) to be minimized is given in (5),

$$OF = \text{Min}\ T = \sum_{i=1}^{N}\sum_{j=1}^{M}\left[\begin{array}{l}\left\{t^{p}_{fw_{ij}} + \sum_{x=1}^{X}\left(t^{bx_{ij}}_{fw_{ij}} + t^{bx_{ij}}_{rv_{ij}}\right)\right\} \\ + \left\{t^{p}_{rv_{ij}} + \sum_{x=1}^{X} t^{bx_{ij}}_{rv_{ij}}\right\}\end{array}\right] \tag{5}$$

In this equation, i denotes the relay number; N is the total number of relays; index j represents the fault location out of total M fault locations; t^{p}_{fwi}, and t^{p}_{revi} represent the i^{th} primary relay operating in the forward and the reverse directions for a fault at a location j; X number of backup relays; t^{b}_{fwi}, t^{b}_{revi}, indicate the x^{th} backup relay operating in the forward and the reverse directions for the i^{th} primary relay and a fault at a location j.

B. RELAY COORDINATION CONSTRAINTS

The protection coordination problem is formulated as a non-linear constrained optimization problem, which should strictly observe the relay effective technical constraints. The most important constraint is that the backup relay (forward/reverse) must operate after a specific discrimination time from the primary (forward/reverse) relay. This discrimination time is called coordination time interval (CTI). These CTI constraints can be written as in (6)-(8)

$$t_{fwij}^{bx} - t_{revij}^{p} - CTI \geq 0 \tag{6}$$
$$t_{revij}^{bx} - t_{fwij}^{p} - CTI \geq 0 \tag{7}$$
$$t_{revij}^{bx} - t_{revij}^{p} - CTI \geq 0 \tag{8}$$

The values of CTI can range from 0.2 to 0.5s. The value of CTI is set to 0.2s in this article.

The relay parameters, i.e., pickup current Ip and time dial setting (TDS) should be regulated within their specified range. The lower and upper bounds of Ip depend on the system's maximum load current and minimum short circuit capacity, and its value is set between 1× ILoad to 1.5×ILoad for the operation in both forward and reverse directions. The lower and upper limits for TDS are capped within a permissible range i.e., 0.1 to 3 [25]. These constraints are given in Eqs. (9)-(10).

$$Ip_{\min} \leq Ip_{fwi}, Ip_{revi} \leq Ip_{\max} \tag{9}$$
$$TDS_{\min} \leq TDS_{fwi}, TDS_{revi} \leq TDS_{\max} \tag{10}$$

The relay parameter K includes the effect of voltage and is also kept within limits. The value of the term $(1/e^{1-vf})^k$ mainly depends on K, as it is directly multiplied to the original TCC equation; hence its value should be less than one. The effect of K on the term $(1/e^{1-Vf})$ is shown in Fig. 5. It shows that with a negative value of K the value of the term increases above one and with a greater than one positive value of K this term decreases but remains to one if k equals to zero. Therefore, the lower limit of k is set to zero and the upper limit can take any suitable positive value greater than one. In this work, the upper limit is taken as 4. The relay parameters A, B, and C are also capped within their permissible limit range. The upper bounds for A and B are taken as 13.5 and 1 respectively, whereas the lower bound is fixed at 0.14 and 0.02 for both the forward and the reverse direction operation. The described parameters constraints are expressed in (11)-(13)

$$K_{\min} \leq K_{fwi}, K_{revi} \leq K_{\max} \tag{11}$$
$$A_{\min} \leq A_{fwi}, A_{revi} \leq A_{\max} \tag{12}$$
$$B_{\min} \leq B_{fwi}, B_{revi} \leq B_{\max} \tag{13}$$

The relay operating time in the forward and the reverse direction is also set to its lower and upper limits i.e., 0.1s and 2.5s respectively. It is given in (14).

$$t_{\min} \leq t_{fwi}, t_{revi} \leq t_{\max} \tag{14}$$

C. SIMULATION RESULTS

The performance of the proposed user-defined dual setting direction overcurrent relay having hybrid time-current-voltage characteristics (UDDOR-TCV) for fast and reliable protection coordination was evaluated with two standard radial test systems: IEEE-33 bus system and local-40 bus system. Fault analysis was carried out using electrical transient analysis program (ETAP). Non-linear programming problem of the protection coordination was optimally solved with GAMS Studio 28.2.0 registered under community license. The personal computer used for the simulations had the following specifications: HP- processor Intel(R) Core(TM) i5-4210 CPU @ 1.70GHz 2.4 GHz, RAM of 4.0 GB with a 64-bit operating system.

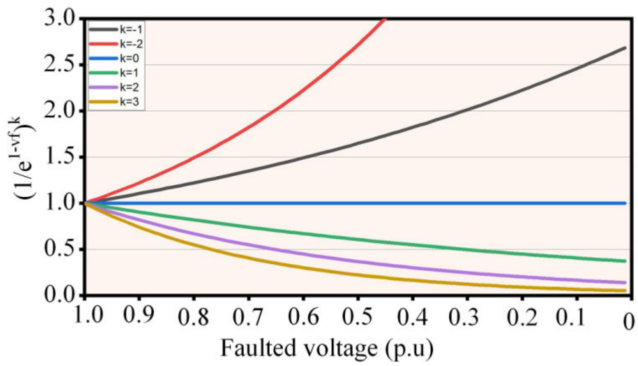

FIGURE 5. Effect of cha1nge in K values on the factor(1/e1-vf).

D. CASE STUDIES

The variation in fault current level (FCL) and the direction of current flow from unidirectional to bidirectional disturb the protection coordination of relays in a conventional radial distribution network (RDN). The FCL variation mainly depends on the RES-DG technology integrated with a RDN. For example, a synchronous generator and SCIG based RES-DG provide high fault current, whereas the inverter-based RES-DGs such as PV units are limited to 1-2(p.u) times of their rated current. To validate the proposed protection scheme with a UDDOR-TCV for low to high level variation of FCL, the following two cases are studied with both radial test systems.

- Case-1. SCIG based RES-DGs integrated into RDN
- Case-2. Impact of PV based RES-DG integrated to RDN

E. IEEE-33 BUS SYSTEM

The IEEE-33 bus system is a standard radial distribution network developed by Baran and Wu in 1989. It has 33 buses and 32 branches. Power was supplied from a source grid at only bus one. The total active and reactive load was 3715kW and 2300 kVAR respectively, similar as in [26]. In normal operation this system was radial and current flow was unidirectional from source to load, and the fault current was supplied by the grid only.

In this paper, the conventional IEEE-33 bus system was modified by connecting the SCIG based WTGs and inverter-based PV units, which caused the current to flow bidirectional and alters the FCL. The details of WTG and PV are given in Appendix (A.1) and (A.2) respectively. From now onward modified IEEE-33 bus system will be referred as the IEEE-33 bus system. The location and size for the integration of single, double and triple RES-DGs were found optimally to reduce the power loss and voltage drop [27]. The integration of three RES-DGs case is considered here to evaluate the proposed protection coordination scheme with a UDDOR-TCV.

F. PERFORMANCE EVALUATION WITH SCIG-WTG INTEGRATION

In this case, three SCIG based WTG with sizes 870kVA, 1064 kVA, and 1481KVA were integrated with the standard IEEE-33 bus system at bus numbers 14, 24, and 30 respectively. The protection coordination problem with a conventional DOCR, TCV-DOCR, dual setting DOCR (DS-DOCR), non-standard DS-DOCR, and the proposed user-defined dual setting direction overcurrent relays with hybrid time-current-voltage characteristics (UDDOR-TCV) is presented and compared. The IEEE-33bus system equipped with a conventional DOCR shown in blue color in Fig. 6(a) and equipped with a DS-DOCR shown in green color in Fig. 6(b). In downstream branches with reference to RES-DGs the current flow is bidirectional and in upstream branches, current flow was unidirectional. The branches with the bidirectional current flow were protected with two DOCR placed one at each end and branches with unidirectional flow were protected with one DOCR set at the sending end as shown in Fig. 6(a). In contrast to this approach, only one DS-DOCR provided protection for the bidirectional current flow branches due to its forward and reverse characteristics capability as shown in Fig. 6(b).

A three-phase bolted fault was introduced at the mid-point of each line represented as F1-F32. The DOCR and DS-DOCR constituted different primary-backup relay pairs. Each fault was associated with two primary relays: one from each side and two backup relays, one for each primary relay. For example, consider the fault F7 in Fig. 6(a). In the upstream side with reference to F7, the R13 operated as primary relay and R11 operated as backup relay. On the downstream side R14 was the primary relay with R16 as a backup relay. Whereas for the same fault F7 with DS- DOCR, $R7_{fw}$ and $R8_{rev}$ operated as primary relays in the forward and reverse directions. $R6_{fw}$ operated as backup relay of $R7_{fw}$ and R9rev operated as backup relay of R8rev. Hence, both DOCR and DS-DOCR had different primary-backup relay pairs for the same fault at the same location. For all the 32 fault locations, the primary-backup relay pairs for DOCR and DS-DOCR are provided in Table 1. It can be seen that the DOCR established 59 primary-backup relay pairs, whereas DS-DOCR established 61 relay pairs for the same fault conditions. The information of fault currents through the primary and backup relay pairs for DS-DOCR are given in Fig. 7.

The protection coordination problem was simulated with the conventional DOCR after integration with three SCIG-WTGs at optimal locations. With DOCR, the total operation time of primary and backup relays pairs for all

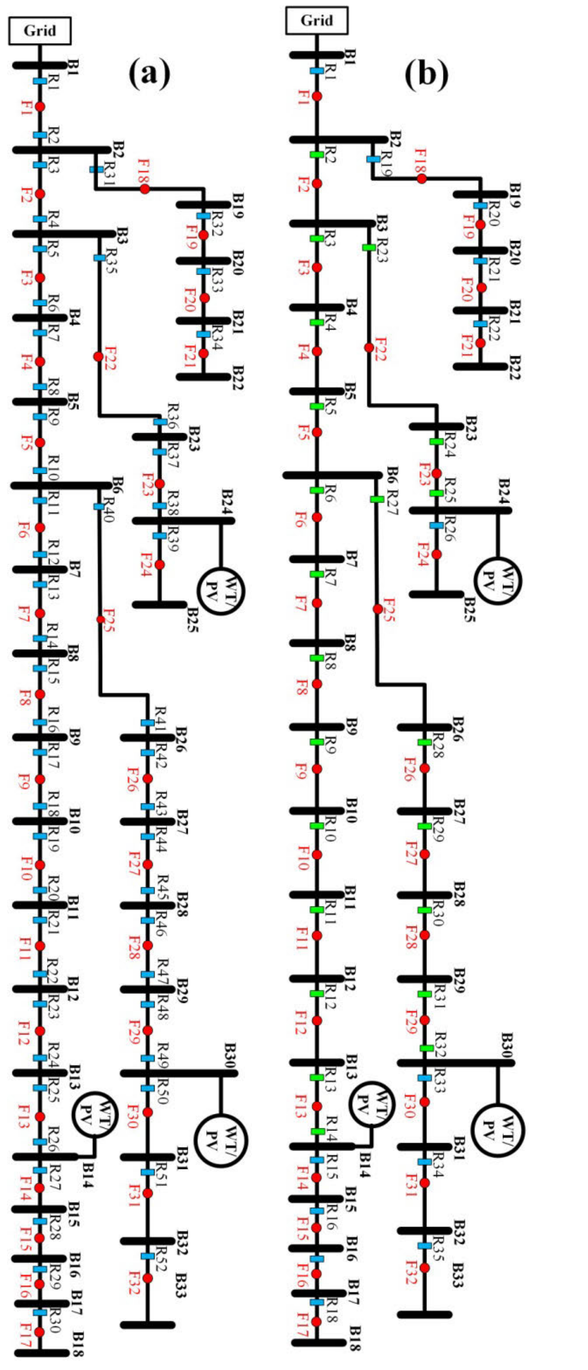

FIGURE 6. Standard IEEE-33 bus system hosting RES-DG such as WTG and PV protected with (a) DOCR shown with blue in color (b) DS-DOCR shown with green in color.

faults was 102.851s. From the results of this case, two violations of CTI were observed. As in the case of Fault F6 in the relay pair number 16, the primary relay was R12 and the backup relay was R14. The operations times of both primary and backup relays were 1.07s and 1.027s with a CTI of −0.043.

Similarly, for the fault F14 corresponding to the relay pair number 31, the operation time of the primary relay R27 was 0.741s and backup relay was 0.260 with a CTI of -0.211.

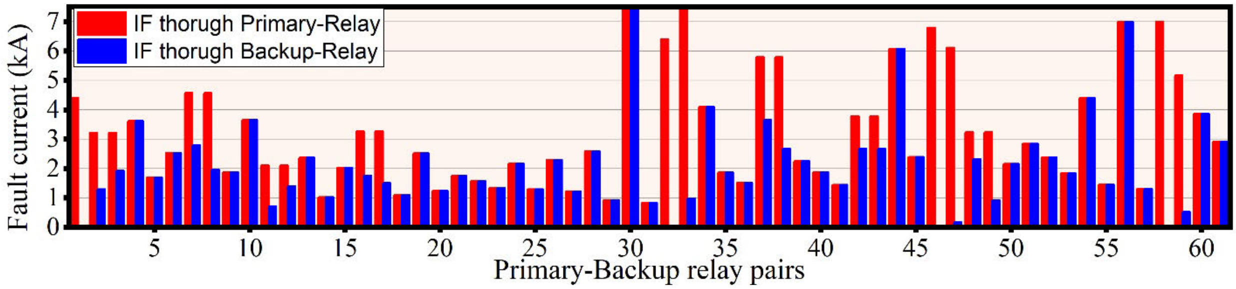

FIGURE 7. Fault currents through the primary and backup relay pairs for IEEE-33 bus system protected with UDDOR-TCV and hosting SCIG-WTG.

TABLE 1. Primary backup relay pairs for all faults with DOCR and UDDOR-TCV for IEEE-33 radial distribution network.

Pair No	P/B relay pairs with DOCR			P/B relay pairs with UDDOR-TCV			Pair No	P/B relay pairs with DOCR			P/B relay pairs with UDDOR-TCV		
	Fault	PR	BR	Fault	PR	BR		Fault	PR	BR	Fault	PR	BR
1	F1	R1	--	F1	R1	--	31	F14	R27	R25	F13	$R14_{fw}$	--
2		R2	R4		$R2_{rev}$	$R3_{rev}$	32	F15	R28	R27		$R13_{fw}$	$R12_{fw}$
3	F2	R3	R1		$R2_{rev}$	$R23_{rev}$	33	F16	R29	R28	F14	15	$R14_{rev}$
4		R4	R6	F2	$R2_{fw}$	R1	34	F17	R30	R29	F15	16	15
5		R4	R36		$R3_{rev}$	$R4_{rev}$	35	F18	R31	R1	F16	17	16
6	F3	R5	R3		$R23_{rev}$	$R24_{rev}$	36		R31	R4	F17	18	17
7		R5	R36	F3	$R3_{fw}$	$R2_{fw}$	37	F19	R32	R31	F18	19	1
8		R6	R8		$R3_{fw}$	$R23_{rev}$	38	F20	R33	R32		19	$R2_{rev}$
9	F4	R7	R5		$R4_{rev}$	$R5_{rev}$	39	F21	R34	R33	F19	20	19
10		R8	R10	F4	$R4_{fw}$	$R3_{fw}$	40	F22	R35	R3	F20	21	20
11	F5	R9	R7		$R5_{rev}$	$R6_{rev}$	41		R35	R6	F21	22	21
12		R10	R12		$R5_{rev}$	$R27_{rev}$	42		R36	R38	F22	$R23_{fw}$	$R2_{fw}$
13		R10	R41	F5	$R5_{fw}$	$R4_{fw}$	43	F23	R38	--		$R23_{fw}$	$R3_{rev}$
14	F6	R11	R9		$R6_{rev}$	$R7_{rev}$	44		R37	R35		$R24_{rev}$	$F25_{fw}$
15		R11	R41		$R27_{rev}$	$R28_{rev}$	45	F24	R39	R37	F23	$R25_{fw}$	--
16		R12	R14	F6	$R6_{fw}$	$R5_{fw}$	46	F25	R40	R9		$R24_{fw}$	$R23_{fw}$
17	F7	R13	R11		$R6_{fw}$	$R27_{rev}$	47		R40	R12	F24	26	$R25_{rev}$
18		R14	R16		$R7_{rev}$	$R8_{rev}$	48		R41	R43	F25	$R27_{fw}$	$R5_{fw}$
19	F8	R15	R13	F7	$R7_{fw}$	$R6_{fw}$	49	F26	R42	R40		$R27_{fw}$	$R6_{rev}$
20		R16	R18		$R8_{rev}$	$R9_{rev}$	50		R43	R45		$R28_{rev}$	$R29_{rev}$
21	F9	R17	R15	F8	$R8_{fw}$	$R7_{fw}$	51	F27	R44	R42	F26	$R28_{fw}$	$R27_{fw}$
22		R18	R20		$R9_{rev}$	$R10_{rev}$	52		R45	R47		$R29_{rev}$	$R30_{rev}$
23	F10	R19	R17	F9	$R9_{fw}$	$R8_{fw}$	53	F28	R46	R44	F27	$R29_{fw}$	$R28_{fw}$
24		R20	R22		$R10_{rev}$	$R11_{rev}$	54		R47	R49		$R30_{rev}$	$R31_{rev}$
25	F11	R21	R19	F10	$R10_{fw}$	$R9_{fw}$	55	F29	R49	--	F28	$R30_{fw}$	$R29_{fw}$
26		R22	R24		$R11_{rev}$	$R12_{rev}$	56		R48	R46		$R31_{rev}$	$R32_{fw}$
27	F12	R23	R21	F11	$R11_{fw}$	$R10_{fw}$	57	F30	R50	R48	F29	$R32_{fw}$	--
28		R24	R26		$R12_{rev}$	$R13_{rev}$	58	F31	R51	R50		$R31_{fw}$	$R30_{fw}$
29	F13	R26	--	F12	$R12_{fw}$	$R11_{fw}$	59	F32	R52	R51	F30	33	$R32_{rev}$
30		R25	R23		$R13_{rev}$	$R14_{fw}$	60				F31	34	33
							61				F32	35	34

For both faults F6 and F14, the CTI values were negative, which means that the backup came into operation before the operation of the primary relay which caused miscoordination between relays. From now onward, the case with DOCR will be referred as the base case.

The authors in [24] modified the conventional time-current characteristics equation of DOCR with time-current-voltage characteristics (DOCR-TCV) which took into account voltages' effect during fault along with the fault current. They applied DOCR-TCV in a meshed distribution network to reduce the overall relay operating times. For brevity, the base case was simulated with DOCR-TCV to mitigate the CTI violations while reducing relay operating times. The optimal value of DOCR-TCV settings i.e. TDS and Ip are reflected in Table 2. The optimal value of K for all relays was found to be equal to 2

The protection coordination problem was accompanied by the proposed UDDOR-TCV which relied on a combination of the user-defined dual-setting DOCR and time-current-voltage hybrid characteristics. Furthermore, the relay constant parameters were considered as variables and were involved in the optimization problem. As mentioned earlier, UDDOR-TCV constitutes two different relay settings for the forward and the reverse direction. The relay characteristics in the forward and the reverse directions can be tuned separately. The relay settings for both directions are reflected

TABLE 2. Optimal settings of TDS and Ip of DOCR-TCV for IEEE-33 bus system.

Relay No.	TDS	Ip(kA)	Relay No.	TDS	Ip(kA)	Relay No.	TDS	Ip(kA)	Relay No.	TDS	Ip(kA)	Relay No.	TDS	Ip(kA)
1	0.669	0.389	12	0.702	0.179	23	0.200	0.254	34	0.050	0.201	45	0.788	0.153
2	0.050	0.197	13	0.592	0.218	24	0.446	0.233	35	0.218	0.389	46	0.280	0.179
3	0.586	0.218	14	0.715	0.245	25	0.157	0.124	36	0.541	0.269	47	0.376	0.218
4	0.427	0.191	15	0.510	0.254	26	0.209	0.179	37	0.192	0.160	48	0.050	0.237
5	0.714	0.179	16	0.831	0.177	27	0.169	0.225	38	0.222	0.140	49	0.196	0.186
6	0.644	0.186	17	0.560	0.275	28	0.211	0.153	39	0.050	0.131	50	0.118	0.177
7	0.590	0.233	18	0.477	0.389	29	0.150	0.179	40	0.700	0.254	51	0.083	0.275
8	0.935	0.170	19	0.578	0.269	30	0.050	0.160	41	1.060	0.171	52	0.050	0.201
9	0.585	0.179	20	1.007	0.218	31	0.287	0.245	42	0.501	0.170			
10	0.703	0.225	21	0.414	0.191	32	0.189	0.254	43	1.140	0.245			
11	0.750	0.153	22	1.285	0.179	33	0.263	0.177	44	0.292	0.225			

TABLE 3. Optimal settings for TDS, Ip, A, B and K for both in the forward and the reverse directions operation of UDDOR-TCV for IEEE-33 bus system.

Relay No	Forward characteristics settings					Reverse characteristics settings				
	TDS_{fw}	Ip_{fw}(kA)	A_{fw}	B_{fw}	K_{fw}	TDS_{rev}	Ip_{rev}(kA)	A_{rev}	B_{rev}	K_{rev}
1	0.24	0.28	0.14	0.02	1.00	--	--	--	--	--
2	0.54	0.27	0.41	0.06	2.14	0.26	0.20	0.14	0.02	1.00
3	0.43	0.17	0.14	0.03	1.26	1.89	0.22	0.23	0.03	3.86
4	1.61	0.19	0.14	0.02	4.00	3.00	0.14	0.22	0.02	4.00
5	3.00	0.18	13.0	0.98	4.00	3.00	0.18	13.0	0.55	4.00
6	3.00	0.25	1.00	0.38	3.20	2.90	0.25	12.2	1.00	4.00
7	1.68	0.23	0.61	0.13	4.00	3.00	0.23	13.0	0.87	4.00
8	3.00	0.17	1.31	0.34	4.00	3.00	0.17	13.0	0.68	4.00
9	3.00	0.24	7.97	1.00	4.00	2.91	0.24	0.14	0.02	4.00
10	3.00	0.23	13.0	0.87	4.00	2.14	0.23	0.14	0.02	4.00
11	2.92	0.15	11.2	1.00	4.00	2.27	0.15	0.16	0.02	3.28
12	3.00	0.18	5.74	1.00	4.00	2.64	0.18	11.1	0.43	4.00
13	0.06	0.16	0.14	0.02	1.00	0.26	0.16	0.14	0.02	1.00
14	0.22	0.18	0.14	0.02	1.00	0.12	0.18	0.14	0.02	1.00
15	1.28	0.25	0.78	0.44	1.00	--	--	--	--	--
16	1.92	0.18	0.73	0.53	1.00	--	--	--	--	--
17	0.13	0.20	0.14	0.02	1.00	--	--	--	--	--
18	0.05	0.28	0.14	0.02	1.00	--	--	--	--	--
19	2.26	0.27	0.14	0.15	2.06	--	--	--	--	--
20	3.00	0.22	0.69	0.76	1.40	--	--	--	--	--
21	2.43	0.19	0.16	0.05	4.00	--	--	--	--	--
22	0.08	0.13	0.14	0.02	1.00	--	--	--	--	--
23	3.00	0.25	0.24	0.37	1.42	0.79	0.25	0.14	0.02	2.37
24	0.07	0.17	0.14	0.02	1.00	1.94	0.18	0.14	0.09	1.00
25	0.27	0.12	0.14	0.02	1.00	0.05	0.27	0.14	1.00	4.00
26	0.05	0.18	0.14	0.02	1.00	--	--	--	--	--
27	3.00	0.23	13.0	0.75	4.00	3.00	0.27	1.26	0.26	4.00
28	2.53	0.15	0.27	0.06	4.00	3.00	0.24	13.0	0.66	4.00
29	3.00	0.18	0.80	0.30	3.79	3.00	0.25	13.0	0.60	4.00
30	3.00	0.22	0.14	0.05	3.89	0.33	0.13	0.14	0.02	1.00
31	0.07	0.18	0.14	0.02	1.00	0.28	0.20	0.14	0.02	1.00
32	0.24	0.19	0.14	0.02	1.00	0.12	0.20	0.14	0.02	1.00
33	0.17	0.13	0.14	0.02	1.00	--	--	--	--	--
34	0.12	0.20	0.14	0.02	1.00	--	--	--	--	--
35	0.07	0.28	0.14	0.02	1.00	--	--	--	--	--

in Table 3 and the relay operating times are given in Table 4. Consider the same faults F6 and F14 here. UDDOR-TCV established different relay pairs compared to DOCR for the fault F6. The corresponding relay pair number was 18 with $R7_{rev}$ and $R8_{rev}$ in the reverse direction that operated as the primary and the backup relays. Whereas for F14, the primary relay was R15 which is DOCR-TCV due to the unidirectional flow of current in this branch with R14rev operating in the reverse direction as a backup relay. The operating times of the primary and the backup relays in both pairs were 0.250s and 0.450s with a CTI value of 0.2. It means the relays were adequately coordinated and no mal-functioning was observed.

The overall objective set is to minimize the total operating time of relays with zero constraint violations.The protection coordination problem was also solved with Dual setting DOCR(DS-DOCR) and non-standard DS-DOCR to show the supremacy of the proposed UDDOR-TCV. Table 4 is furnished with relay operating times for each pair of primary-backup relays for all the approaches simulated with

TABLE 4. Primary-Backup relay operating times all relay pairs for IEEE-33 bus system with all five protection schemes.

Pair No.	DOCR with single setting				DOCR with dual setting for forward and reverse directions					
	DOCR[28]		DOCR-TCV[24]		Dual setting DOCR[29]		Non-standard Dual setting DOCR[18]		Proposed UDDOR-TCV	
	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}	TOP_{PR}	TOP_{BR}
1	1.389	--	0.288	--	1.204	--	1.336	--	0.238	--
2	0.431	0.631	0.100	0.326	0.604	0.804	0.415	0.615	0.234	0.434
3	1.300	1.500	0.332	0.532	0.604	1.233	0.415	1.127	0.234	0.445
4	0.574	0.774	0.126	0.326	1.100	1.300	1.000	1.200	0.250	0.478
5	0.574	1.297	0.126	0.326	0.694	0.629	0.542	0.742	0.100	0.300
6	1.229	1.429	0.338	0.538	1.100	1.300	0.997	1.197	0.219	0.419
7	1.229	1.449	0.338	0.557	1.026	1.226	0.920	1.120	0.249	0.449
8	0.734	0.934	0.258	0.458	1.026	1.226	0.920	1.120	0.249	0.456
9	1.114	1.314	0.302	0.502	0.600	0.800	0.713	0.913	0.222	0.422
10	0.872	1.072	0.343	0.543	0.910	1.110	0.797	0.997	0.128	0.328
11	1.127	1.327	0.422	0.622	0.763	1.112	0.874	1.102	0.250	1.265
12	0.916	1.116	0.249	0.449	0.763	0.963	0.874	1.101	0.250	0.450
13	0.916	1.194	0.249	0.449	0.870	1.070	0.882	1.082	0.250	0.450
14	1.077	1.277	0.401	0.675	0.812	1.012	0.701	0.901	0.214	0.414
15	1.077	1.277	0.401	0.804	0.780	0.980	0.705	0.905	0.100	0.300
16	1.070	1.027	0.359	0.559	0.719	0.985	0.802	1.002	0.189	0.687
17	0.970	1.170	0.375	0.575	0.719	0.919	0.802	1.002	0.189	0.389
18	0.953	1.153	0.410	0.610	0.961	0.649	0.856	1.056	0.250	0.450
19	0.942	1.142	0.487	0.687	0.602	0.802	0.699	0.899	0.147	0.347
20	1.024	1.224	0.353	0.553	0.611	0.811	0.993	1.193	0.250	0.450
21	0.896	1.096	0.527	0.727	0.936	0.713	0.850	1.050	0.230	0.430
22	0.992	1.192	0.258	0.458	0.705	0.905	0.893	1.093	0.166	0.366
23	0.717	0.917	0.369	0.569	0.860	1.060	0.783	0.983	0.250	0.450
24	1.162	1.362	0.395	0.595	0.774	0.974	0.758	0.958	0.104	0.304
25	0.547	0.747	0.236	0.436	0.678	0.878	0.600	0.800	0.230	0.291
26	1.300	1.500	0.443	0.643	0.952	1.152	0.937	1.137	0.243	0.443
27	0.443	0.643	0.231	0.431	0.504	0.704	0.419	0.619	0.119	0.319
28	1.070	1.270	0.118	0.318	1.100	1.300	1.000	1.200	0.250	0.450
29	0.772	--	0.230	--	0.382	0.582	0.284	0.484	0.194	0.394
30	0.282	0.482	0.100	0.294	0.933	1.133	0.861	1.061	0.166	0.366
31	0.471	0.260	0.260	0.460	0.688	--	0.811	--	0.243	--
32	0.392	0.592	0.166	0.366	0.208	0.408	0.100	0.300	0.100	0.300
33	0.320	0.520	0.170	0.370	0.511	0.711	0.452	0.652	0.250	0.450
34	0.152	0.352	0.100	0.299	0.434	0.634	0.361	0.561	0.201	0.401
35	0.477	1.494	0.119	0.432	0.367	0.567	0.271	0.471	0.249	0.449
36	0.477	0.677	0.119	0.319	0.206	0.406	0.100	0.300	0.100	0.300
37	0.487	0.687	0.278	0.478	0.454	1.295	0.246	1.195	0.100	0.300
38	0.331	0.531	0.143	0.343	0.454	0.654	0.246	0.446	0.100	0.300
39	0.174	0.374	0.100	0.303	0.463	0.663	0.436	0.636	0.250	0.450
40	0.724	1.452	0.156	0.563	0.302	0.502	0.269	0.469	0.121	0.321
41	0.724	0.924	0.156	0.633	0.142	0.342	0.100	0.300	0.100	0.300
42	0.958	1.158	0.159	0.359	0.367	1.250	0.253	1.143	0.154	0.472
43	0.663	--	0.227	--	0.367	0.567	0.253	0.453	0.154	0.354
44	0.684	0.884	0.138	0.338	0.996	1.196	0.917	1.117	0.250	0.450
45	0.219	0.419	0.100	0.280	0.693	--	0.876	--	0.101	--
46	0.937	1.137	0.311	0.511	0.235	0.435	0.100	0.300	0.100	0.300
47	0.937	1.188	0.311	0.557	0.100	0.300	0.100	0.300	0.100	0.300
48	1.159	1.359	0.385	0.585	0.678	0.878	0.589	0.890	0.169	0.369
49	0.783	0.983	0.210	0.410	0.678	0.878	0.589	0.789	0.169	0.369
50	1.300	1.500	0.464	0.664	0.951	1.151	0.878	1.078	0.220	0.420
51	0.715	0.915	0.262	0.462	0.514	0.714	0.421	0.621	0.100	0.300
52	1.241	1.441	0.215	0.415	1.100	1.300	1.000	1.200	0.250	0.450
53	0.595	0.795	0.190	0.390	0.495	0.607	0.435	0.635	0.210	0.410
54	1.091	1.291	0.085	0.285	1.067	1.267	0.985	1.185	0.233	0.433
55	2.861	--	0.257	--	0.352	0.552	0.285	0.485	0.209	0.409
56	0.422	0.622	0.093	0.293	0.943	1.143	0.881	1.081	0.170	0.370
57	0.594	0.794	0.224	0.424	0.168	--	0.140	--	0.121	--
58	0.295	0.647	0.100	0.302	0.173	0.373	0.100	0.300	0.100	0.300
59	0.128	0.328	0.109	0.303	0.471	0.671	0.432	0.632	0.114	0.314
60					0.313	0.513	0.270	0.470	0.130	0.330
61					0.147	0.347	0.100	0.300	0.100	0.300
Total	102.851 sec		40.477 sec		87.978 sec		83.593 sec		34.97 sec	

TABLE 5. Overall operation time of relays and percentage reduction for different fault scenarios for case-1 of IEEE-33 bus system.

	DOCR	DOCR-TCV	DS-DOCR	nst. DS-DOCR	Proposed
			LG Fault		
Total operating time(sec)	123.99	50.84	105.14	99.86	43.12
% reduction in relay time	--	59.00	15.20	19.46	65.22
			LL Fault		
Total operating time(sec)	117.31	48.10	100.88	91.52	40.93
% reduction in relay time	--	59.00	14.00	21.98	65.11
			LLG Fault		
Total operating time(sec)	109.74	44.44	93.43	90.57	37.42
% reduction in relay time	--	59.50	14.86	17.47	65.90
			LLL Fault		
Total operating time(sec)	102.90	40.45	87.98	83.59	34.97
% reduction in relay time	--	60.69	14.50	18.76	66.02

the same test system, which also provides a fair comparison of the proposed approach with others.

The total relay operating time with a DS-DOCR and a non-standard DS-DOCR was 87.978s and 83.593s, which are 14.46% and 18.72% less than the base case. Whereas, with the proposed UDDOR-TC the total operating time was reduced to 34.097s, which is 66.848% less than the base case and even 60.645% less than DOCR-TCV. The highest reduction in operating time was achieved with the proposed UDDOR-TCV with all constraints were satisfied, and which ensures the fastest fault clearance for sustainable electrification. Moreover, the total number of relays installed for the proposed UDDOR-TCV was 35, which is also 32.692% less in numbers than installed for a DOCR and a DOCR-TCV protection scheme. Hence the proposed scheme provides an economical solution. This reduction in relay number was achieved with numerical programming of 22 relays [R2-R14, R23-R25 and R27-R32] out of 35 relays with the proposed UDDOR-TCV characteristics and the remaining 13 relays were programmed with DOCR-TCV as the current flow was unidirectional through these relays.

Further, bolted single line to ground (LG) fault, line-line(LL) fault, and double line to ground fault (LLG) are simulated at the midpoint of each line to verify the efficiency of proposed UDDOR-TCV protection scheme against these faults. The total operation time in each fault case and percentage reduction in total time of the state of art schemes and proposed scheme are reflected in Table 5. It is seen that the proposed scheme provides the least operation time of relays with zero mis-coordination in each fault cases than others, which shows the superiority and efficiency of the proposed scheme over other schemes.

G. PERFORMANCE EVALUATION WITH PV INTEGRATION

The impact of an inverter-based RES such as PV units is investigated in this section. The performance of the proposed relay characteristics was evaluated in terms of percentage reduction in the overall relay operating time and the elimination of mis-coordination. Three PV units were integrated with the IEEE-33 bus system. Similar to case-1, the locations and capacities of PV units were determined optimally. The PV unit's capacities were 805kVA, 1090kVA, and 1010kVA at the bus numbers 14, 24, and 30 respectively.

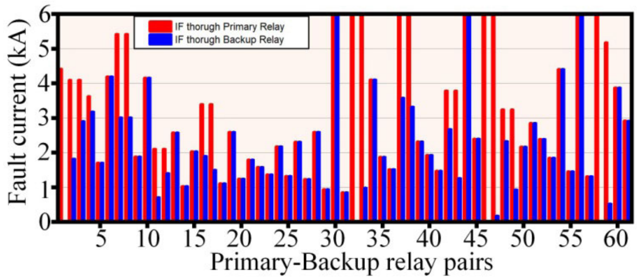

FIGURE 8. Fault currents through the primary and the backup relay pairs of IEEE-33 bus system protecting with UDDOR-TCV and hosting SCIG-WTGs and PV-units.

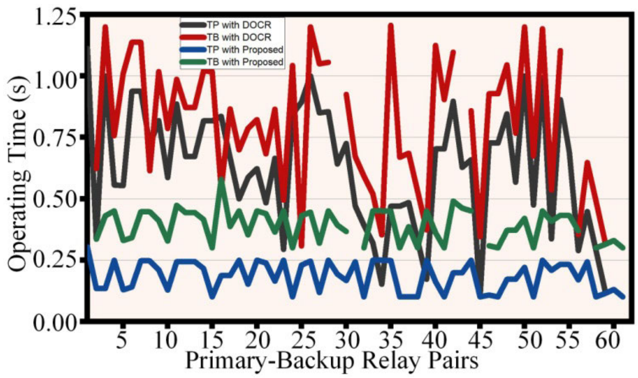

FIGURE 9. Operating times of primary-backup relays for DOCR and UD-DOCR for case-2 of IEEE-33 bus system.

The optimal locations were similar to SCIG-WTGs for three RES-DGs scenario, whereas these were different for one and two RES-DGs in [27]. The minimum voltage achieved with optimal integration of three PV units was 0.9788 p.u. at bus 18 and the total loss was reduced to 71.640kW. The SCIG-WTGs were also included in this case along with PV units and the impact of PV units was studied.

The same bolted three-phase faults F1 to F32 were applied in this case. The fault currents flew through the primary and the backup relays for the UDDOR-TCV scheme are reflected in Fig. 8. Fig. 9 represents the operating times of the primary-backup relays for DOCR and the proposed UDDOR-TCV. For brevity, the CTI between primary-backup relays obtained for DOCR, DOCR-TCV, DS-DOCR, nst-DS-DOCR, and the proposed UDDOR-TCV is shown in Fig. 10. It can be seen that there is no violation of CTI constraint with the proposed scheme, whereas there are five violations of CTI constraints with DOCR. The total operation time of relays for the base case was 105.851s. The percentage reduction in operating time achieved with DS-DOCR, nst.DS-DOCR, DOCR-TCV and UDDOR-TCV is 15.12%, 21.40%, 62.84%, and 68.26% respectively. Hence, the highest reduction in operation time was achieved with the proposed UDDOR-TCV relay characteristics.

The optimal values of UDDOR-TCV relay settings are given in Table 6. Comparing the Table 3 entities with Table 6 reveals that the relay settings are similar to the relay

TABLE 6. Optimal settings for TDS, Ip, A, B, and K for both in the forward and the reverse directions operation of UDDOR-TCV for IEEE-33 bus system for case-2.

Relay No	Forward characteristics settings					Reverse characteristics settings				
	TDS_{fw}	Ip_{fw}	A_{fw}	B_{fw}	K_{fw}	TDS_{rev}	Ip_{rev}	A_{rev}	B_{rev}	K_{rev}
1	0.31	0.28	0.14	0.02	1.00	--	--	--	--	--
2	2.10	0.27	0.14	0.06	2.64	3.00	0.27	0.33	0.05	4.00
3	0.47	0.22	0.14	0.03	1.19	3.00	0.16	0.14	0.02	4.00
4	2.59	0.19	0.14	0.04	3.90	3.00	0.19	4.49	0.34	4.00
5	3.00	0.18	1.29	0.29	4.00	3.00	0.18	13.0	0.56	4.00
6	3.00	0.25	0.90	0.31	3.44	2.92	0.25	12.2	1.00	4.00
7	2.22	0.23	0.15	0.04	4.00	3.00	0.23	13.0	0.87	4.00
8	3.00	0.17	1.26	0.39	3.61	3.00	0.17	13.0	0.68	4.00
9	3.00	0.24	8.10	1.00	4.00	3.00	0.24	0.58	0.09	4.00
10	3.00	0.23	13.0	0.87	4.00	2.57	0.23	1.21	0.20	4.00
11	2.71	0.15	13.0	1.00	4.00	1.85	0.15	0.32	0.05	2.90
12	2.49	0.18	6.99	1.00	4.00	3.00	0.18	12.9	0.50	4.00
13	0.06	0.16	0.14	0.02	1.00	0.26	0.16	0.14	0.02	1.00
14	0.22	0.18	0.14	0.02	1.00	0.12	0.18	0.14	0.02	1.00
15	1.77	0.25	1.35	0.65	1.00	--	--	--	--	--
16	0.53	0.18	0.16	0.06	1.05	--	--	--	--	--
17	0.12	0.21	0.14	0.02	1.00	--	--	--	--	--
18	0.05	0.28	0.14	0.02	1.00	--	--	--	--	--
19	2.58	0.27	0.68	0.58	1.49	--	--	--	--	--
20	3.00	0.22	0.72	0.45	4.00	--	--	--	--	--
21	1.61	0.19	0.38	0.18	2.41	--	--	--	--	--
22	0.07	0.13	0.14	0.02	1.00	--	--	--	--	--
23	0.18	0.19	0.14	0.02	1.00	0.70	0.25	0.63	0.02	4.00
24	0.08	0.17	0.14	0.02	1.00	0.63	0.18	0.14	0.03	1.01
25	0.27	0.12	0.14	0.02	1.00	0.05	0.27	0.14	1.00	4.00
26	0.05	0.18	0.14	0.02	1.00	--	--	--	--	--
27	3.00	0.23	13.0	0.74	4.00	3.00	0.27	0.85	0.19	4.00
28	3.00	0.15	0.14	0.04	4.00	3.00	0.24	13.0	0.66	4.00
29	2.97	0.18	2.29	0.53	4.00	3.00	0.25	13.0	0.60	4.00
30	2.96	0.22	0.14	0.12	2.49	0.33	0.13	0.14	0.02	1.00
31	0.07	0.18	0.14	0.02	1.00	0.28	0.20	0.14	0.02	1.00
32	0.24	0.19	0.14	0.02	1.00	0.12	0.20	0.14	0.02	1.00
33	0.17	0.13	0.14	0.02	1.00	--	--	--	--	--
34	0.12	0.20	0.14	0.02	1.00	--	--	--	--	--
35	0.07	0.28	0.14	0.02	1.00	--	--	--	--	--

settings obtained for case-1 with SCIG-WTGs regardless of a change in the fault current due to the PV units integration. This is due to the low fault current contribution of PV in comparison to SCIG-WTGs. Few relays (R2fw, R2rev, R3rev, R16fw and R23fw) had a significant change in TDS values, whereas the Ip, A, B, and K parameters had almost the same values as in case-1. This shows that the relay settings of the proposed scheme do not need to be modified for a minor change in the system. However, a central protection unit (CPU) can be installed to update the relay settings adaptively for significant changes in the system such as an outage of lines or SCIGs.

The proposed scheme is also evaluated with LG, LL, and LLG faults for this case and the results are presented in Table 7. It is obvious from results that the proposed scheme performs well during different fault cases and provide the minimum operation time of relays.

H. LOCAL-40 BUS SYSTEM

In this section, a local-40 bus radial distribution network of Gujranwala electric power company (GEPCO) Pakistan is used to evaluate the proposed protection scheme. The voltage of the system was 11kV and the total connected load had

TABLE 7. Overall operation time of relays and percentage reduction for different fault scenarios for case-2 of IEEE-33 bus system.

	DOCR	DOCR-TCV	DS-DOCR	nst. DS-DOCR	**Prop osed**
			LG Fault		
Total operating time(sec)	128.40	49.43	107.15	99.90	42.37
% reduction in relay time		61.50	16.55	22.20	67.00
			LL Fault		
Total operating time(sec)	121.08	46.94	98.03	95.65	39.17
% reduction in relay time		61.23	19.04	21.00	67.65
			LLG Fault		
Total operating time(sec)	115.24	43.75	98.09	90.19	37.88
% reduction in relay time		62.04	14.88	21.74	67.13
			LLL Fault		
Total operating time(sec)	105.85	39.33	89.85	83.20	33.60
% reduction in relay time		62.84	15.12	21.40	68.26

14.740MVA. There were 40 buses and 39 line segments. The complete line and load data is available in [30].

Integration of two RES-DGs i.e, two SCIG-WTG for the case-1 and two PV-units for the second case, are considered here. The optimal sizes for SCIG-WTGs were 5227kVA and 3565kVA at locations 17 and 30 respectively. Whereas for PV-units, the locations were the same but sizes were 3880kVA and 2864kVA. Fig. 11(a) and Fig. 11(b) represent the Local-40 bus system equipped with conventional DOCR in blue color and UDDOR-TCV in green color. The total

IEEE Access

TABLE 8. Overall results and fair comparison of all protection schemes for the Local-40 bus system.

	DOCR	DOCR-TCV	DS-DOCR	nst.DS-DOCR	Proposed
			Case-1		
Overall relay operation time in seconds	141.54	65.36	109.829	105.2815	**43.918**
% reduction in relay time	--	53.83	22.41	25.622	**68.973**
% reduction in relay number	--	0	39.7	39.7	**39.7**
CTI violations	8	0	0	0	**0**
			Case-2		
Overall relay operation time in seconds	131.02	67.628	109.796	105.207	**43.952**
% reduction in relay time	--	48.528	16.247	19.76	**66.563**
% reduction in relay number	--	0	39.7	39.7	**39.7**
CTI violations	6	0	0	0	**0**

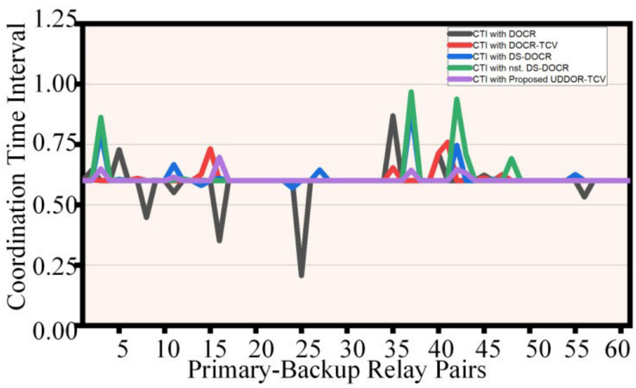

FIGURE 10. CTI between primary-backup relay pairs of for all relay pairs with all protection schemes for second case of IEEE-33 bus system.

primary-backup relay pairs for both systems were 68. However, each pair's primary- backup relay was different due to the forward and the reverse operation of dual setting DOCR.

The bolted three-phase fault was applied at the mid-point of each line. There were total of 39 faults represented as F1-F39. The operating times of the primary-backup relay pairs of DOCR and UDDOR-TCV are shown in Fig. 12(a) for case one and in Fig. 12(c) for case two. For brevity, the CTIs for all protection schemes as in the IEEE-33 bus system are reflected in Fig. 12(b) and Fig. (d) for case one and case two. It can be seen that there are violations of CTI in both cases with DOCR, whereas there are no violations with the proposed UDDOR-TCV. Also, the relay operating time with proposed UDDOR-TCV are much less than DOCR. The total operation time, percentage reduction in the time, the total CTI violations and the percentage reduction in the installed relay with all protection schemes are provided in Table 8 for both cases. It can be seen that superior results were achieved with the proposed UDDOR-TCV compared to the other protection schemes.

As mentioned earlier, no communication structure is required to send a block signal to the second backup relay because the proposed UDDOR-TCV can act as primary/backup in both the forward and the reverse directions. To validate this statement, consider a fault F-10 downstream of both RES-DGs and F-22, which was downstream of RES-DG-1 and the upstream of RES-DG-2. For F-10,

TABLE 9. Primary-backup-1 and backup-2 relay operating times in seconds for the two specific faults to show the performance of the proposed scheme without any communication infrastructure.

Fault	Case-1			Case-2		
	P (T_P)	B1(T_{B1})	B2(T_{B2})	P (T_P)	B1(T_{B1})	B2(T_{B2})
F-10	$R10_{fw}$ (0.25s)	$R9_{fw}$ (0.45s)	$R8_{fw}$ (0.72s)	$R10_{fw}$ (0.25s)	$R9_{fw}$ (0.45s)	$R8_{fw}$ (0.88s)
	$R11_{rev}$ (0.25s)	$R12_{rev}$ (0.45s)	$R13_{rev}$ (1.12s)	$R11_{rev}$ (0.25s)	$R12_{rev}$ (0.45s)	$R13_{rev}$ (1.63s)
F-22	$R23_{fw}$ (0.25s)	$R22_{fw}$ (0.45s)	$R21_{fw}$ (0.81s)	$R23_{fw}$ (0.25s)	$R22_{fw}$ (0.45s)	$R21_{fw}$ (0.83s)
	$R24_{rev}$ (0.25s)	$R25_{rev}$ (0.45s)	$R26_{rev}$ (1.27s)	$R24_{rev}$ (0.25s)	$R25_{rev}$ (0.45s)	$R26_{rev}$ (1.47s)

the primary downstream relay was R10fw with R9fw as the first backup relay and R8fw as the second backup relay. Whereas, on the upstream side R11rev operated as the primary relay with R12rev and R13rev as the first and the second backup relay. Similarly, the primary-backup relay pairs for F-22 and all the primary-backup relay pairs' operating times for both cases are reflected in Table 9. It can be seen that the first and the second backup relays operated after CTI without any violation. Hence, the proposed scheme provides a communication-less and cost-effective solution for the radial distribution networks hosting multiple RES-DGs and for fast fault clearance without any discoordination.

I. IEEE-8 BUS SYSTEM

The proposed protection scheme with UDDOR-TCV was mainly designed for radial distribution networks. However, performance of UDDOR-TCV has also been evaluated on IEEE-8 bus meshed distribution network to show the efficiency of proposed scheme in terms of reduction in overall relay operating time. The standard IEEE-8 bus system is a meshed distribution system with multiple sources [31]. It consists of 8 buses and 7 line segments. There are total 14 directional overcurrent relays (DOCR). The number of relays for UDDOR-TCV are also 14. These relays comprise 20 primary-backup relay pairs for both DOCR and UDDOR-TCV given in Table 10. However, each pair constitutes different primary-backup relay for DOCR and UDDOR-TCV. With UDDOR-TCV all relays in forward direction operate as primary relay and as backup relay in reverse direction. These relays are blocked through a communication signal to operate as backup relays in forward direction. Further, Bolted LG, LL, LLG and LLL faults are evaluated at the midpoint of

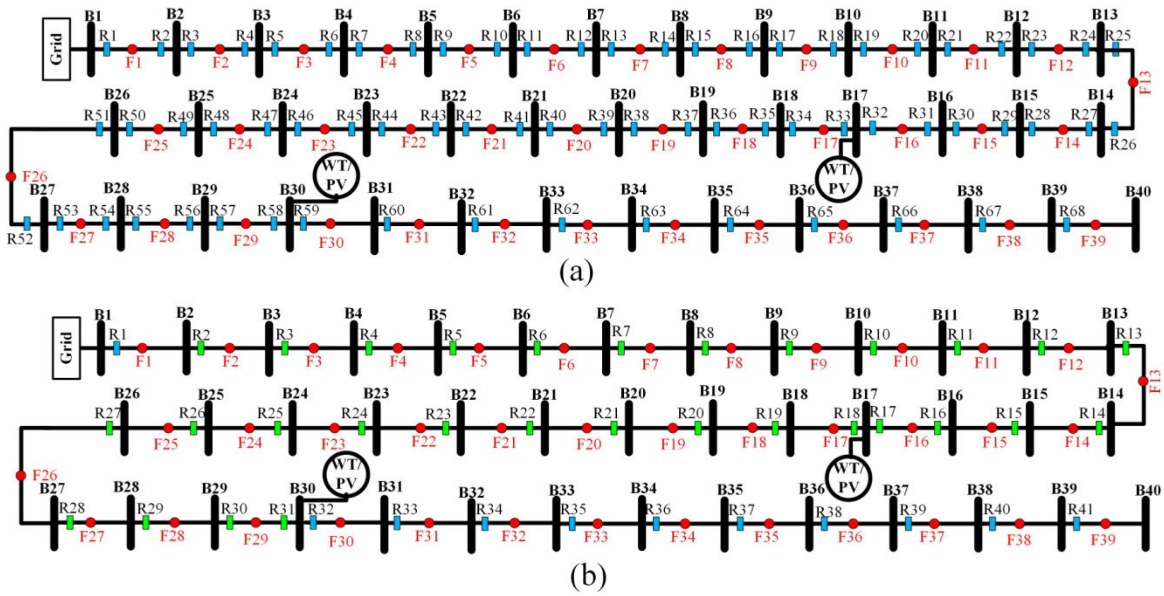

FIGURE 11. Local-40 bus radial distribution network hosting SCIG-WTGs and PV-units protected with (a) DOCR blue in color (b) UDDOR-TCV green in color.

TABLE 10. Primary backup relay pairs for all faults with DOCR and UDDOR-TCV for IEEE-8 bus meshed distribution network.

Pair No		P/B relay pairs with DOCR		P/B relay pairs with UDDOR-TCV		Pair No		P/B relay pairs with DOCR		P/B relay pairs with UDDOR-TCV	
	Fault	PR	BR	PR	BR		Fault	PR	BR	PR	BR
1	F1	1	6	1_{fw}	13_{rev}	11	F5	5	4	5_{fw}	11_{rev}
2		8	7	8_{fw}	2_{rev}	12		12	13	12_{fw}	6_{rev}
3		8	9	8_{fw}	14_{rev}	13		12	14	12_{fw}	7_{rev}
4	F2	2	1	2_{fw}	8_{rev}	14	F6	6	5	6_{fw}	7_{rev}
5		2	7	2_{fw}	14_{rev}	15		6	14	6_{fw}	12_{rev}
6		9	10	9_{fw}	3_{rev}	16		13	8	13_{fw}	1_{rev}
7	F3	3	2	3_{fw}	9_{rev}	17	F7	7	5	7_{fw}	6_{rev}
8		10	11	10_{fw}	4_{rev}	18		7	13	7_{fw}	12_{rev}
9	F4	4	3	4_{fw}	10_{rev}	19		14	1	14_{fw}	2_{rev}
10		11	12	11_{fw}	5_{rev}	20		14	9	14_{fw}	8_{rev}

TABLE 11. Optimal settings of relay parameters for DOCR, DOCR-TCV and proposed UDDOR-TCV for LG, LL, LLG, LLL faults simulated on the midpoint of each line on IEEE-8 bus meshed distribution network modified with WTG-Farms integration.

Relay No	Conventional DOCR		DOCR-TCV		Proposed UDDOR-TCV (LG)									
					Forward characteristics settings					Reverse characteristics settings				
	TDS	Ip	TDS	Ip	TDS_{fw}	Ip_{fw}	A_{fw}	B_{fw}	K_{fw}	TDS_{rev}	Ip_{rev}	A_{rev}	B_{rev}	K_{rev}
For LG-Fault														
1	0.15	0.11	0.24	0.16	0.07	0.11	0.14	0.02	1.00	0.25	0.13	0.14	0.02	1.00
2	0.32	0.25	0.66	0.25	0.09	0.18	0.14	0.02	1.00	0.66	0.16	0.14	0.02	4.00
3	0.24	0.19	0.47	0.19	0.09	0.14	0.14	0.02	1.00	0.21	0.12	0.14	0.02	1.00
4	0.14	0.27	0.23	0.27	0.06	0.20	0.15	0.02	1.00	0.26	0.13	0.14	0.02	1.00
5	0.11	0.14	0.15	0.19	0.06	0.14	0.14	0.02	1.00	0.31	0.09	0.14	0.02	1.00
6	0.22	0.17	0.41	0.17	3.00	0.17	2.81	1.00	1.00	0.15	0.15	0.14	0.02	1.00
7	0.05	0.17	0.14	0.16	0.09	0.16	0.14	0.02	1.00	0.27	0.13	0.15	0.02	4.00
8	0.19	0.16	0.73	0.12	0.12	0.12	0.14	0.02	1.00	0.05	0.14	0.14	0.03	1.00
9	0.16	0.13	0.26	0.18	0.07	0.13	0.14	0.02	1.00	0.24	0.18	0.14	0.02	1.00
10	0.26	0.12	0.52	0.12	0.09	0.09	0.14	0.02	1.00	0.26	0.09	0.14	0.02	1.00
11	0.32	0.20	0.64	0.20	0.09	0.15	0.15	0.02	1.00	0.17	0.15	0.14	0.02	1.00
12	0.44	0.18	0.75	0.18	0.10	0.13	0.14	0.02	1.00	0.18	0.13	0.15	0.02	1.00
13	0.09	0.19	0.21	0.19	0.08	0.14	0.14	0.02	1.00	0.20	0.14	0.14	0.02	1.00
14	0.11	0.18	0.13	0.25	0.08	0.18	0.14	0.02	1.00	0.10	0.18	0.14	0.02	4.00

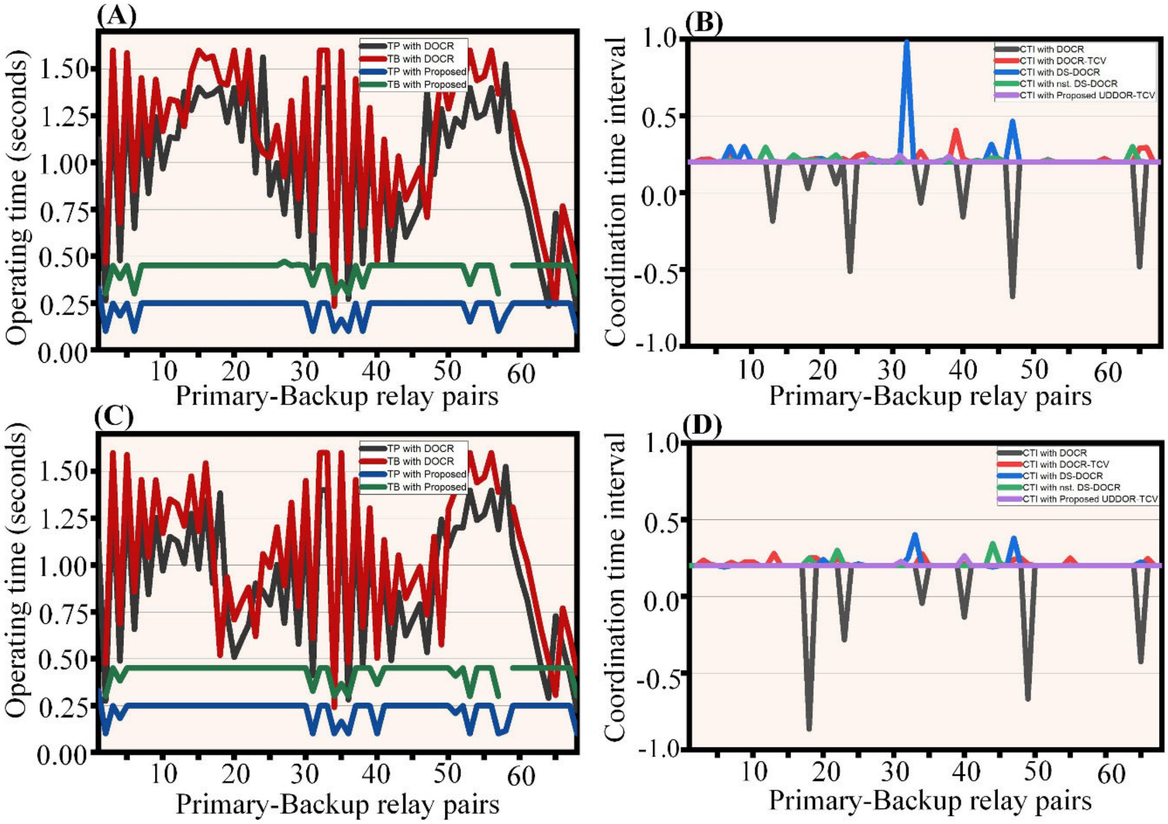

FIGURE 12. Primary-backup relays operating time for all the pairs of Local-40 bus system with DOCR, UDDOR-TCV, and CTI between the primary-backup relays with all protection schemes in (A), (B) for the case one and (C), (D) for the case two.

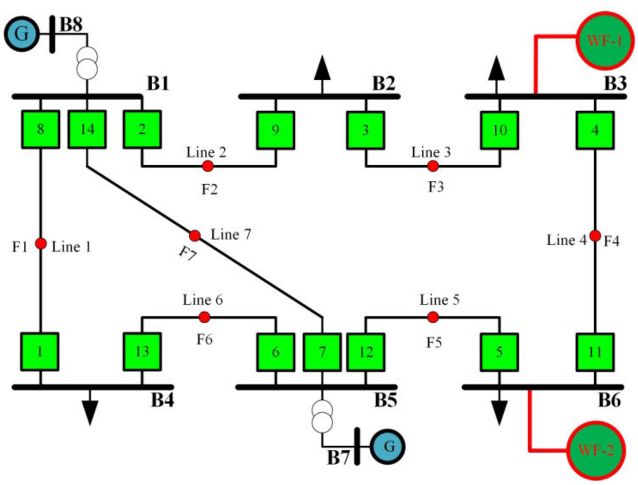

FIGURE 13. One-line diagram of IEEE-8 bus meshed distributed network.

each line. The standard IEEE-8 bus system is modified by integrating two wind farms at bus-3 and bus-6. The number of machines are 20 in each WF and details of WTGs in the wind farms are given in the Appendix (A.1). One-line diagram of the IEEE-8 bus system is given in Fig. 13.

The LG, LL, LLG and LLL faults are applied at the mid-point of each line and the faults currents passing through primary and backup relays are reflected in Fig. 14.

There is so much variation in the fault current level for each fault. The constrained relay coordination problem is solved with the fault currents obtained with LG, LL, LLG and LLL faults. The minimum and maximum limits of variables in the optimization model are kept same as in the case of radial distribution networks. For comparison of results with the stat of the art, the results obtained with conventional DOCR were considered as base case in all types of fault cases.

For brevity, the relay settings for conventional DOCR, DOCR-TCV are provided in Table 11 along with UDDORC-TCV. For LG fault, the total operation time of relays with DOCR was 39.368 sec, whereas with DOCR-TCV, it was 28.081 sec, which is 28.67% less than base case. For the same fault, the total relay operation time achieved with DS-DOCR and UDDOR-TCV were 11.288sec and 9.725 sec. which are 71.32% and 75.29% less than base case. Therefore, for LG fault the highest reduction in operation time was achieved with proposed UDDOR-TCV. Similarly, the LL, LLG and LLL faults are simulated at the midpoint of each line. The total relay operation times with conventional DOCR, DOCR-TCV, DS-DOCR and proposed UDDOR-TCV are reflected in Table 12 along with the percentage reduction in total relay operation time and the number of mis-coordinations. It can be seen that for each fault type case, the highest reduction in relay operation time is achieved with the proposed scheme.

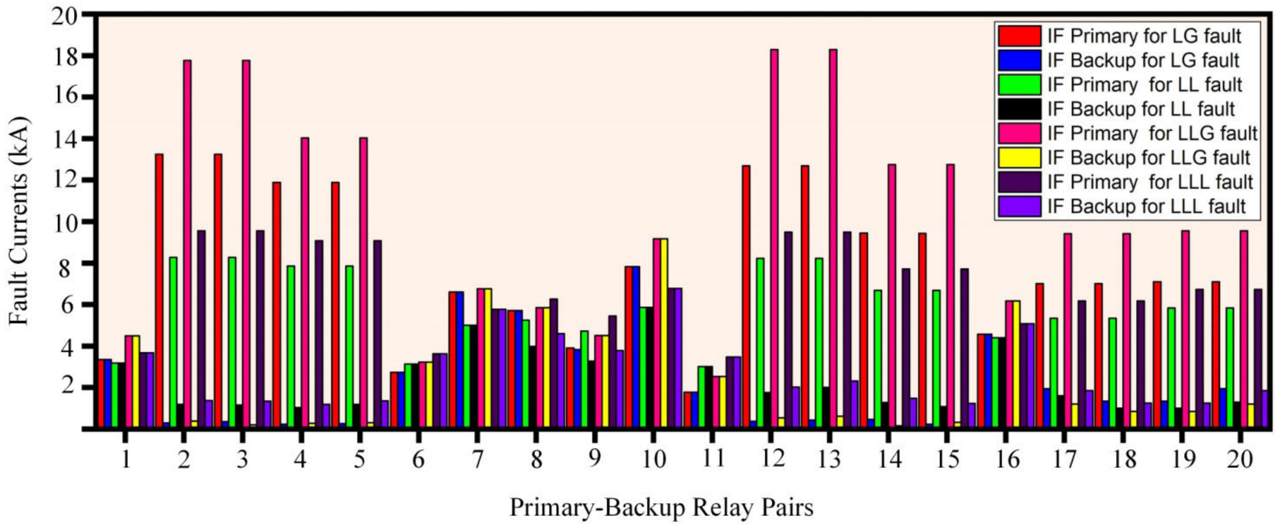

FIGURE 14. Fault currents through the primary and the backup relay pairs of IEEE-8 bus system hosting SCIG-WTG for LG, LL, LLG and LLL faults.

TABLE 12. Overall results and a fair comparison of all protection schemes for the IEEE-8 bus system.

	DOCR	DOCR -TCV	DS-DOCR	Proposed
		LG Fault		
Total relay operating time(sec)	39.36	28.08	11.28	**9.72**
% reduction in relay time	--	28.67	71.32	**75.29**
Number of mis-coordination	7	4	0	**0**
		LL Fault		
Total relay operating time(sec)	40.29	23.93	12.23	**8.66**
% reduction in relay time	--	40.60	69.64	**78.50**
Number of mis-coordination	2	0	0	**0**
		LLG Fault		
Total relay operating time(sec)	39.27	28.28	10.24	**9.7328**
% reduction in relay time	--	27.98	73.92	**75.21**
Number of mis-coordination	6	4	0	**0**
		LLL Fault		
Total relay operating time(sec)	37.75	22.09	11.77	**8.24**
% reduction in relay time	--	41.48	68.82	**78.17**
Number of mis-coordination	1	0	0	**0**

The operation time of each primary and backup relay with DOCR, DOCR-TCV and UDDOR-TCV for all relay pair is shown in Fig. 15(A), (C), (E), (G) and the coordination time interval between primary and backup relay is shown in Fig. 15(B), (D), (F), (H) for LG, LL, LLG and LLL faults respectively. It is seen that for each pair, the operation time of primary and backup relay with UDDOR-TCV is less than others. It shows the superiority of the proposed UDDOR-TCV over other schemes. The same relay optimal settings perform well irrespective of change in fault current level due to different faults.

III. CONCLUSION

This paper proposes a novel protection scheme using user-defined dual setting direction overcurrent relays with time current-voltage hybrid characteristics. The proposed scheme is evaluated with two standard radial distribution networks: the IEEE-33 bus system and the local-40 bus system. Both the systems were equipped with SCIG-WTGs and PV-units. The protection coordination problem was formulated in a non-linear programming fashion. Five protection schemes named DOCR, DOCR-TCV, DS-DOCR, nst-DS-DOCR, and the proposed UDDOR-TCV are evaluated on both test systems with similar parameters and a fair comparison shows that the proposed protection scheme provides better results compared to other protection schemes. For the first case, the total relay operating time achieved for 33 and 40 bus systems with UDDOR-TCV is 34.097s and 43.9184s, whereas it is 33.597s and 43.952 for the second case. The overall relay operating time with DOCR-TCV has a small difference from UDDOR-TCV. However, the number of relays used for the proposed scheme with UDDDOR-TCV has almost reduced up to 50 percent compared to the DOCR-TCV scheme. This makes the proposed scheme a cost-effective solution for a radial distribution network hosting RES-DGs without communication infrastructure. The scheme is also evaluated on IEEE-8 bus meshed DN and shows the highest reduction in relay operating times than other schemes. The authors will explore the application of the proposed UDDOR-TCV and its coordination with fuses and re-closers and its applicability in meshed distribution networks without communication infrastructure.

TABLE 13. WTGs parameters used in this paper.

Parameters	WTG
Nominal Power of each machine	3 MW
Generating voltage	0.690 kV
Frequency	50 Hz
Rated wind speed	13 m/s
L_s	0.0397 p.u
L_r	0.0397 p.u
L_m	1.354 p.u
$H_{(s)}$	0.95

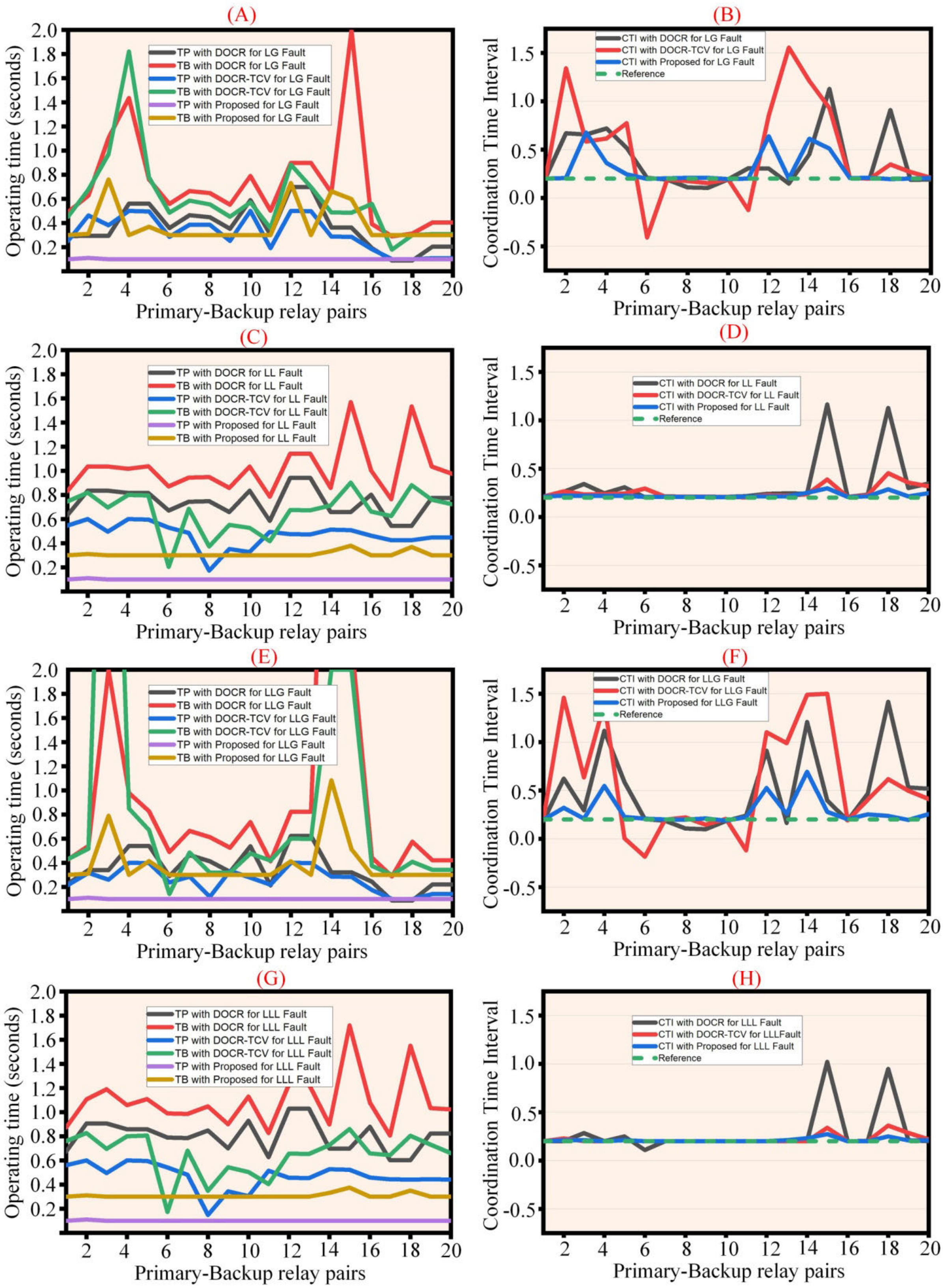

FIGURE 15. Primary-backup relays operating time and CTI for all the pairs of IEEE-8 bus system with state of the art and proposed scheme for (A), (B) LG fault, (C)(D) LL fault, (E), (F) LLG fault (G), (H) LLL fault respectively.

TABLE 14. PV panel parameters used in this paper.

Parameters	PV Pannel
Nominal Power of each pannel	110.3 Watt
V_{mp}	17.18V
V_{OC}	21.69V
Irradiance	1000W/m^2
T_a	30
T_c	5
MPP	0.11kW
Manufacturer	Photowatt
Model Name	Pw6-110

APPENDIX

ACKNOWLEDGMENT

The authors are thankful to the Department of Electrical Engineering, Southeast University and Prof. Lucheng Hong for the support given in conducting the research.

REFERENCES

[1] A. Yazdaninejadi, A. Hamidi, S. Golshannavaz, F. Aminifar, and S. Teimourzadeh, ''Impact of inverter-based DERs integration on protection, control, operation, and planning of electrical distribution grids,'' *Electr. J.*, vol. 32, no. 6, pp. 43–56, Jul. 2019.

[2] T. Soleymani Aghdam, H. Kazemi Karegar, and H. H. Zeineldin, ''Optimal coordination of double-inverse overcurrent relays for stable operation of DGs,'' *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 183–192, Jan. 2019.

[3] N. Nimpitiwan, S. Member, G. T. Heydt, and R. Ayyanar, ''Machine and inverter based distributed generators,'' *Power*, vol. 22, no. 1, pp. 634–641, 2007.

[4] A. Darabi, M. Bagheri, and G. B. Gharehpetian, ''Highly accurate directional overcurrent coordination via combination of Rosen's gradient projection–complex method with GA-PSO algorithm,'' *IEEE Syst. J.*, vol. 14, no. 1, pp. 1171–1182, Mar. 2020.

[5] A. Shabani and K. Mazlumi, ''Evaluation of a communication-assisted overcurrent protection scheme for photovoltaic-based DC microgrid,'' *IEEE Trans. Smart Grid*, vol. 11, no. 1, pp. 429–439, Jan. 2020.

[6] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E.-D.-A. El-Zahab, ''Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays,'' *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 115–123, Jan. 2015.

[7] J. Gholinezhad, K. Mazlumi, and P. Farhang, ''Overcurrent relay coordination using MINLP technique,'' in *Proc. 19th Iranian Conf. Elect. Eng.*, vol. 2, 2011, pp. 6–11.

[8] A. J. Urdaneta, L. G. Pérez, J. F. Gómez, B. Feijoo, and M. González, ''Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays,'' *Int. J. Electr. Power Energy Syst.*, vol. 23, no. 8, pp. 819–825, Nov. 2001.

[9] P. P. Bedekar and S. R. Bhide, ''Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach,'' *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 109–119, Jan. 2011.

[10] A. Yazdaninejadi, D. Nazarpour, and S. Golshannavaz, ''Dual-setting directional over-current relays: An optimal coordination in multiple source meshed distribution networks,'' *Int. J. Electr. Power Energy Syst.*, vol. 86, pp. 163–176, Mar. 2017.

[11] S. Xie, X. Wang, C. Qu, X. Wang, and J. Guo, ''Impacts of different wind speed simulation methods on conditional reliability indices,'' *Int. Trans. Electr. Energy Syst.*, vol. 20, pp. 1–6, Nov. 2013.

[12] A. S. Noghabi, J. Sadeh, and H. R. Mashhadi, ''Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA,'' *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 1857–1863, Oct. 2009.

[13] S. Tirumala Pallerlamudi Srinivas and K. Shanti Swarup, ''Optimal protection coordination of nonstandard overcurrent relays using hybrid QCQP method,'' *Electr. Power Compon. Syst.*, vol. 48, nos. 12–13, pp. 1327–1338, Aug. 2020.

[14] G. J. Meyer, T. Lorz, R. Wehner, J. Jaeger, M. Dauer, and R. Krebs, ''Hybrid fuzzy evaluation algorithm for power system protection security assessment,'' *Electr. Power Syst. Res.*, vol. 189, Dec. 2020, Art. no. 106555.

[15] M. T. Yang and A. Liu, ''Applying hybrid PSO to optimize directional overcurrent relay coordination in variable network topologies,'' *J. Appl. Math.*, vol. 150, no. 5, pp. 1568–1655, 2013.

[16] ARGUS2. *Numerical Directional Overcurrent Protection Relay*. Accessed: Dec. 17, 220. [Online]. Available: http://www.easunreyrolle.com/product.php

[17] (GRD100). *Protection and Control System*. Accessed: Dec. 17, 2020. [Online]. Available: http://www.toshibatds.com/tandd/products/pcsystems/en/grd100.htm

[18] A. Yazdaninejadi, M. S. Naderi, G. B. Gharehpetian, and V. Talavat, ''Protection coordination of directional overcurrent relays: New time current characteristic and objective function,'' *IET Gener., Transmiss. Distrib.*, vol. 12, no. 1, pp. 190–199, Jan. 2018.

[19] T. S. Aghdam, H. K. Karegar, and A. Abbasi, ''Discussion on 'optimal protection coordination for meshed distribution systems with DG using dual setting relays,''' *IEEE Trans. Smart Grid*, vol. 7, no. 3, p. 1756, May 2016.

[20] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, ''Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays,'' *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 143–151, Jan. 2018.

[21] H. Beder, B. Mohandes, M. S. El Moursi, E. A. Badran, and M. M. El Saadawi, ''A new communication-free dual setting protection coordination of microgrid,'' *IEEE Trans. Power Del.*, early access, Dec. 8, 2020, doi: 10.1109/TPWRD.2020.3041753.

[22] A. M. Nakhaee, E. Gadari, and A. Khorsandi, ''Simultaneous application of communiction-assisted dual setting DORs and hybrid cuckoo-linear algorithm in optimizing FCL-oriented protection schmes of microgrids,'' in *Proc. IPAPS*, 2020, pp. 30–31.

[23] K. Chheng, A. Priyadi, M. Pujiantara, and V. R. Mahindara, ''The coordination of dual setting DOCR for ring system using adaptive modified firefly algorithm,'' *Proc. Int. Semin. Intell. Technol. Its Appl. Hum. Reliab. Intell. Syst.*, 2020, pp. 44–50.

[24] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, ''Optimal coordination of directional overcurrent relays using a new time–current–voltage characteristic,'' *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 537–544, Apr. 2015.

[25] *Numerical Directional Overcurrent Protection Relay*, ARGUS2, Siemens. [Online]. Available: http://www.easunreyrolle.com/product.php?id=67

[26] M. E. Baran and F. F. Wu, ''Network reconfiguration in distribution systems for loss reduction and load balancing,'' *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[27] M. Rizwan, L. Hong, W. Muhammad, S. W. Azeem, and Y. Li, ''Hybrid harris hawks optimizer for integration of renewable energy sources considering stochastic behavior of energy sources,'' *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 2, pp. 1–27, Feb. 2021.

[28] M. Rizwan, L. Hong, M. Waseem, S. Ahmad, M. Sharaf, and M. Shafiq, ''A robust adaptive overcurrent relay coordination scheme for wind-farm-integrated power systems based on forecasting the wind dynamics for smart energy systems,'' *Appl. Sci.*, vol. 10, no. 18, pp. 1–16, 2020.

[29] E. E. H. H. Zeineldin, M. hebatallah Sharaf, and K. Doaa Ibrqahim, ''Optimal protection coordination for meshed distribution systems with DG using dual setting relays,'' *IEEE Trans. Smart Grid*, vol. 7, no. 3, p. 1756, 2016.

[30] S. W. M. Rizwan, L. Hong, and M. Waseem, ''Sustainable protection coordination in presence of distributed generation with distributed network,'' *Int. Trans. Electr. Energ Syst.* vol. 15, no. 26, pp. 15–31, 2019.

[31] R. M. Chabanloo, H. A. Abyaneh, S. S. H. Kamangar, and F. Razavi, ''Optimal combined overcurrent and distance relays coordination incorporating intelligent overcurrent relays characteristic selection,'' *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1381–1391, Jul. 2011.

LUCHENG HONG (Member, IEEE) was born in Nantong, China, in 1985. He received the B.S. degree in electrical engineering from the School of Electrical Engineering, Southeast University, Nanjing, China, in 2007, and the Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2013. He is currently a Lecturer with the School of Electrical Engineering, Southeast University. His research interests include modeling and control of flexible ac transmission systems and distributed power system stability and power quality.

MIAN RIZWAN was born in Pakistan, in 1992. He received the B.S. and master's degrees in electrical engineering from the University of Gujrat, Pakistan. He is currently pursuing the Ph.D. degree with the School of Electrical Engineering, Southeast University, Nanjing, China. His research interests include power inverters, protection coordination schemes, and power quality.

MUHAMMAD WASIF received the B.Sc. degree in electrical engineering from Riphah International University, Pakistan, in 2006, and the M.Sc. degree in mechatronics and the Ph.D. degree in robotics from King's College London, U.K., in 2008 and 2016, respectively. He is currently working as an Assistant Professor with the Department of Electrical Engineering, University of Gujrat, Pakistan. His research interests include robotics, intelligent control, active vision, machine vision, and machine learning.

SHAFIQ AHMAD received the Ph.D. degree from RMIT University, Melbourne, VIC, Australia. He is currently working as an Associate Professor with the Industrial Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia. He has more than two decades working experience both in industry and academia in Australia, Europe, and Asia. He has published a research book and several research papers in international journals and refereed conferences. His research interests include smart manufacturing, the IIOT and data analytics, multivariate statistical quality control, process monitoring and performance analysis, operations research models, and bibliometric network analysis. He is also a certified practitioner in Six Sigma business improvement model.

MAZEN ZAINDIN received the Ph.D. degree in electronics engineering from the Gdańsk University of Technology, Gdańsk, Poland, in 1995. He is currently an Assistant Professor with the Department of Statistics and Operations Research, Science College, King Saud University, Riyadh, Saudi Arabia. He is also leading a team for professional accreditation program. He has published number of research articles in previous years. His research interests include reliability, and statistical theory and practices.

MUHAMMAD FIRDAUSI received the B.Eng. degree from the University of Brawijaya, Indonesia. He is currently pursuing the master's degree with the Industrial Engineering Department, College of Engineering, King Saud University Riyadh, Saudi Arabia. He has experience working at a complex aircraft manufacturer company and FMCG company. He has completed several courses related to machine learning and python programming. His research interests include machine learning, the IIOT, data science, process monitoring, fault detection, scheduling, and bibliometric network analysis.