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Adaptive directional overcurrent relaying scheme for meshed distribution networks

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Abstract: Distribution networks are evolving into active meshed networks with bidirectional power flow as the penetration of distributed generation (DG) sources is increasing. This necessitates the use of directional relaying schemes in these emerging active distribution networks. However, conventional directional overcurrent (OC) protection will not be adequate to protect these networks against the stochastic nature of renewable DGs and the changing network architectures. Hence, this study proposes an adaptive directional OC relay algorithm that determines optimal protection settings according to varying fault currents and paths induced by the DGs in active meshed distribution networks. The proposed algorithm consists of a two-phase approach that deduces: (i) optimal floating current settings through a fuzzy decision-making module, and (ii) optimal floating time settings through an optimisation algorithm. Extensive case studies are implemented on the modified power distribution networks of IEEE 14-bus and IEEE 30-bus by varying the type, location, and size of DGs. The results validate the ability of the proposed protection scheme to capture the uncertainties of the DGs and determine optimal protection settings, while ensuring minimal operating time.

1 Introduction

Most of the existing urban and metropolitan distribution networks are meshed in structure to maintain power quality and provide uninterrupted power supply. With growing penetration of distributed generation (DG) sources in the future smart grids, even the existing passive radial distribution networks will evolve into active looped and meshed structures [1, 2]. Using traditional protection schemes such as fuses, reclosers, and overcurrent (OC) relays for these active distribution networks will lead to major protection issues such as nuisance tripping, blinding of protection, loss of fuse–recloser coordination, and unsynchronised reclosing [3, 4]. Hence, directional relaying schemes are being increasingly employed for the protection of meshed distribution networks such as in Singapore (https://www.dropbox.com/s/fkf49uf2ztnrln6/Singapore%20Distribution%20Network.pdf?dl=0). An appropriate directional protection scheme for an active meshed distribution network would enhance DG penetration, improve the system reliability, and minimise the system losses.

Directional overcurrent relays (DOCRs) have emerged as a viable and economic alternative for the protection of these active meshed distribution systems compared to differential and distance protection relays. Conventional DOCRs have two types of protection settings, namely pick-up current settings (I_{set}) and time-multiplier settings (TMS) that are determined using analytical methods or optimisation techniques for effective coordination between primary and backup relays. Several solution techniques are proposed in the literature to solve the coordination problem by minimising the operating time of DOCRs following a set of coordination constraints. Initially, the DOCR coordination was considered as a mixed integer non-linear problem where the current settings are integer variables and time settings are continuous. The problem was later simplified using linear programming techniques to find optimal time settings considering the values of current settings to be known [5–7]. The application of interior point algorithm to solve the linear programming problem, and the advantages of using pre-solution techniques were proposed in [8]. Considering the non-linear and complex nature of DOCR coordination, various optimisation algorithms (OA) such as genetic algorithm (GA), particle swarm optimisation, and differential evolution algorithms were proposed in [9–11], where the protection settings were considered as continuous variables.

The introduction of DGs in distribution networks complicates the problem as it tends to alter the short-circuit currents and disturb the sensitivity and coordination of DOCRs as detailed by the authors in [12]. Hence, this necessitates consideration of the heuristics of DGs while solving the DOCR coordination problem. Some of the recent research efforts have investigated the impacts of DGs, while solving the DOCR coordination problem. In [13, 14], the authors suggested fault current limiters (FCLs) to curtail the fault currents injected by DGs and maintain DOCR coordination. Optimal placement of FCLs and DOCRs were proposed in [15–17] to solve the protection coordination problem of distribution systems embedded with DGs. Authors in [18] introduced a new time–current–voltage tripping characteristic to minimise the overall DOCR operating time in meshed distribution networks with DGs. Four groups of relay settings were recommended in [19] considering user-defined relay characteristics to avoid the mis-coordination problem. While solving the DOCR coordination problem in meshed networks, the authors in [13–19] assumed that the DG capacity is known. However, this assumption would require a change in the relay settings for every additional DG installation. To avoid this situation, the authors in [20] proposed a fixed set of optimal protection settings that are valid for all future DG capacities. During optimisation, the authors assumed constant current settings and varied only the time settings for a desired interval of DG capacities. However, using constant current settings and varying only the time settings for various DG penetration levels might not be feasible with intermittent-type DGs such as solar, wind etc. that induces fluctuating fault current levels. The authors in [21] proposed an adaptive OC scheme to improve relay sensitivity based on changes in the network configuration. In [22], the authors have proposed a novel constraint reduction-based relay coordination method for radial as well as meshed distribution systems.

In the above-mentioned works [13–18, 21, 22], only synchronous-based DGs (SDGs) were considered, considering their huge impact on short-circuit levels compared to inverter-based

DGs (IDGs). However, fault current levels seen by the relays also vary depending on the type of DGs connected to the network. The contribution of fault current by IDGs cannot be neglected when considering different micro-grid modes of operation as mentioned in [23–26]. Similarly, the internal protection of IDGs against large current levels cannot react to fault currents that are lower than their settings. Hence, there arises a need to also consider the dynamic operation of DGs, irrespective of their types, while solving DOCR coordination.

In our previous work [27], we determined floating current settings in real time according to the status of DGs and changes in network scenario for a radial distribution system. The goal was to avoid the use of pre-calculated relay setting groups and consider the impacts of all types of DGs in the network. However, the time settings were defined in a 'downstream to upstream' manner to minimise the overall relay operating time. The proposed approach in [27] is applicable only for radial systems and is not feasible for meshed networks that require detection of bidirectional fault currents and efficient relay coordination. Hence, a complete protection strategy would require adaptive protection settings determined by evaluating the present network condition (with variation in power provided by DGs) to ensure minimal overall relay operating time.

This paper proposes an adaptive directional overcurrent relay (ADOCR) as an alternative to conventional DOCR for the protection of meshed distribution systems. The proposed ADOCR consists of a hybrid optimisation framework that captures the uncertainties of DGs irrespective of their type, capacity, and location. Specifically, the paper proposes development of a numerical relay with a two-phase approach to determine the optimal relay settings as follows. (i) *Optimal current settings*: an adaptive fuzzy current setting module (ACSM) that determines optimal current settings based on the relationship between varying DG output power and the respective terminal voltage of the feeder, and (ii) *optimal time settings*: the floating time settings are determined optimally to ensure a minimum overall relay operating time using an OA. The proposed protection approach is tested on the modified power distribution networks of IEEE 14-bus and IEEE 30-bus systems by simulating various DG scenarios. The results obtained using the proposed ADOCR are benchmarked with the conventional DOCR approach as well as protection algorithms available in the literature.

The rest of the paper is organised as follows: Section 2 discusses the characteristics and development of conventional DOCR. Section 3 describes the mechanism of the proposed adaptive numerical relay protection scheme. Section 4 presents various case studies (CS) and discusses the performance of proposed ADOCR scheme against conventional DOCR scheme. Section 5 discusses the benchmarking of ADOCR with protection algorithms available in the literature and Section 6 gives the conclusion.

2 Conventional approach of DOCR

In this section, modelling and characteristics of the designed DOCR are discussed in this section. It is noted that the conventional DOCR (modelled here) is used to benchmark the results with the proposed ADOCR technique.

Current and voltage signals detected by the current transformer (CT) and potential transformer (PT) are used to detect the fault point and calculate the fault current ratio. For accurate and fast signal estimation in the numerical relay, recursive discrete Fourier transform (RDFT) algorithm [28] is used here. Fundamental phasors estimated through the RDFT algorithm are processed further according to the relay characteristics.

The aim of DOCR coordination problem is to determine the I_{set} and TMS of each primary and backup relay for minimising the overall relay operating time. The I_{set} values are determined after conducting short-circuit analysis, and the relays are coordinated in pairs ensuring the critical current. Time settings are determined by coordinating the DOCRs around the loop according to their clockwise and anticlockwise direction. At the time of fault, when the measured value of the current exceeds the preset value of I_{set}, the relay operates based on the inverse-definite minimum time characteristics. Mathematically, it is defined as:

$$t_{ij} = \frac{A \times \text{TMS}_i}{(\text{FR})^B - 1} \tag{1}$$

$$\text{FR} = \frac{I_{\text{sc}_{ij}}}{I_{\text{set}_i}} \tag{2}$$

where operating time (t_{ij}) of the relay is an inverse function of the fault current, i the relay identifier, and j the fault location identifier, TMS the time multiplier setting, and FR the fault current ratio of the relay fault current I_{sc} and pickup current setting I_{set} of the relay. A and B are constants that define the relay characteristics. The objective function (OF) is to reduce the overall relay operating time (sum of primary and backup relay operating time), and is given as:

$$\text{OF} = \min T = \sum_{i=1}^{N} \sum_{j=1}^{Q} \left(\sum t_{ij}^{\text{b}} + t_{ij}^{\text{p}} \right) \tag{3}$$

The coordination time constraints on primary and backup relay can be represented as follows:

$$\left(t_{ij}^{\text{b}} - t_{ij}^{\text{p}} \right) \ge \text{CTI}, \quad \forall i, j \tag{4}$$

where t^{p} and t^{b} are the operating time of the primary and backup relays, N is the number of fault locations, and Q the total number of relays. The coordination time interval (CTI), which is the minimum time of operation between the primary relay and backup relay, is considered to be 0.3. Limits on the current and time settings are given as:

$$\text{TMS}_i^{\min} \le \text{TMS}_i \le \text{TMS}_i^{\max}, \quad \forall i \tag{5}$$

$$I_{\text{set}_i}^{\min} \le I_{\text{set}_i} \le I_{\text{set}_i}^{\max}, \quad \forall i \tag{6}$$

$$0 \le t_{ij}^{\text{p}} t_{ij}^{\text{b}} \le t_{ij}^{\max}, \quad \forall i, j \tag{7}$$

where $\text{TMS}^{\min}$ and $\text{TMS}^{\max}$ are the minimum and maximum limits of time multiplier setting, respectively, while $I_{\text{set}}^{\min}$ and $I_{\text{set}}^{\max}$ are the minimum and maximum limits of pickup current settings. A simple directional unit is included in overcurrent relay (OCR) and the current and voltage signals measured by CTs and PTs are used for direction detection. Whenever the current is higher than I_{set}, a trip signal is issued. However, the trip signal is activated only when the directional unit detects that the current is in forward direction.

Conventional DOCR coordination problem in (3) is formulated as a non-linear optimisation problem and solved using the function *fmincon* in Matlab optimisation Toolbox that solves continuous functions and first derivatives.

3 Proposed ADOCR and protection coordination scheme

In conventional relay coordination approach, protection settings, i.e. I_{set} and TMS, are determined after short-circuit analysis of the test system, and maintained constant thereafter. However, with the integration of stochastic-natured DGs in the distribution systems, fixed values of I_{set} may not be appropriate for accurate fault detection. Thus, an ADOCR that determines floating protection settings to solve the coordination problem is proposed in this paper. The relay coordination problem is decoupled into two subproblems to determine the adaptive current settings and optimal time settings, as shown in Fig. 1. Furthermore, a hybrid coordination strategy is introduced for robust coordination and increased computational efficiency to determine the feasible solution in minimum time. A brief description of the two subproblems and the hybrid strategy of the proposed ADOCR scheme is presented next.

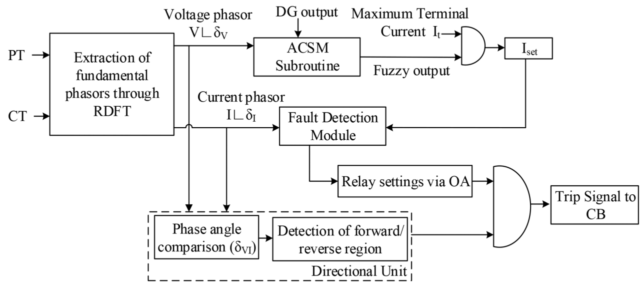

Fig. 1 *Framework showing sequence of the proposed hybrid approach*

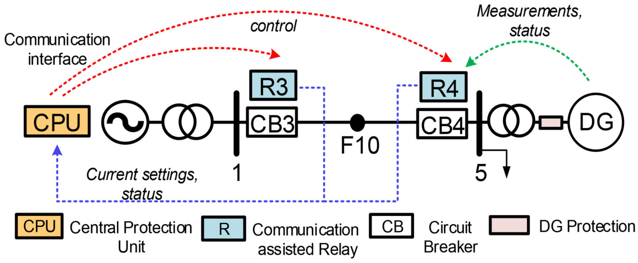

Fig. 2 *Centralised adaptive relay control system*

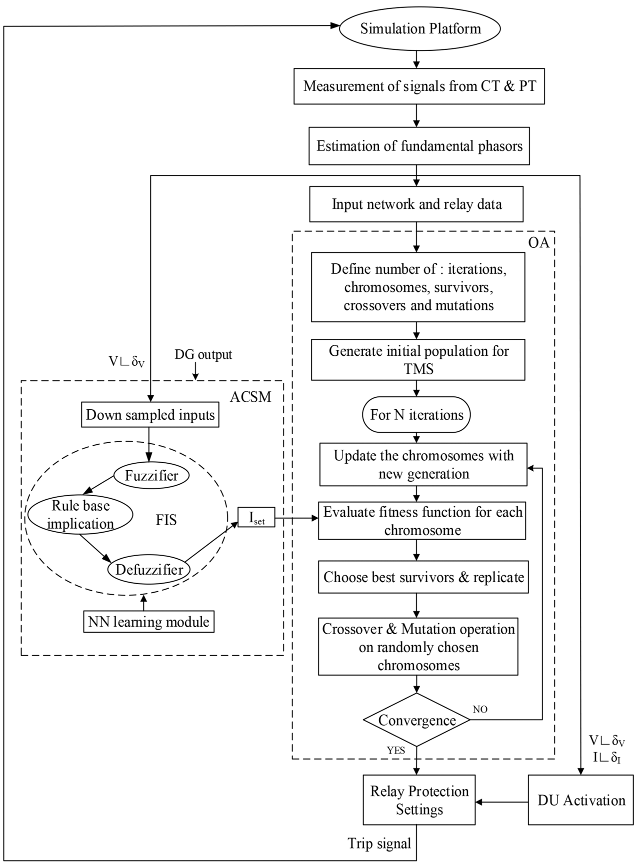

Fig. 3 *Detailed flowchart of the proposed ADOCR protection scheme*

In the *first subproblem*, voltage signals measured through PT are tracked and quantised for digital processing through the RDFT algorithm. The extracted voltage phasor and the output power from DG are given as inputs to adaptive current setting module (ACSM), which consists of a fuzzy inference system to determine the $I_{\rm set}$ variables. In the *second subproblem*, $I_{\rm set}$ values obtained from the first subproblem are used to solve the relay coordination problem by using an OA and optimal TMS values are determined. Once the protection settings are determined, a trip signal is issued according to the input from the directional unit, where the direction is determined by phase angle comparison of the estimated current and voltage signals. Thus, the $I_{\rm set}$ values are tuned locally by the ACSM based on DG status, and the OA determines the TMS values. It is worth mentioning that the coordination between the relays (primary and back-up) is managed by the central protection unit, according to the prevailing grid configuration, as shown in Fig. 2. The proposed adaptive relay determines the online protection settings where the TMS values are calculated offline, and updated regularly based on changes in the grid configuration. A comprehensive flowchart of the proposed ADOCR scheme is shown in Fig. 3. For better understanding, a detailed description of the hybrid ADOCR strategy that determines adaptive current and time settings is presented below.

3.1 Adaptive current settings

As part of the first subproblem, the ACSM receives the voltage phasor and uncertain output power from the DG as inputs (see Fig. 3) and determines the adaptive current settings ($I_{\rm set}$) for the proposed ADOCR using the fuzzy inference system. It is noted that fuzzy logic is incorporated in the proposed protection scheme to predict optimal $I_{\rm set}$ values considering its well-defined ability to handle stochastic data [29]. The fuzzy membership functions of the inputs [$\mu_{\rm in1}(x)$, $\mu_{\rm in2}(x)$] and output [$\mu_{\rm out}(x)$], used in the ACSM, are as shown in Fig. 4. Each membership function corresponds to six different variables, namely, very-small (VS), small (S), small–medium (SM), medium (M), large (L), and very-large (VL). The selection of fuzzy membership functions is explained vividly in [27]. The input–output relationship among the fuzzy inputs are mapped with the help of a defined rule base of 36 rules. These rules are framed based on the theory that $I_{\rm set}$ decreases gradually with the decrease in DG power for the respective terminal voltage. It is noted that an unsupervised neural network (NN) (a neural network is a self-adaptive computational tool that is capable of capturing non-linear and complex characteristics with a high degree of accuracy) based learning algorithm is used here to tune the rule base by adjusting weights of neuron connections. Next, the output from the fuzzy modules go through the process of aggregation and defuzzification to obtain crisp values which are further multiplied with load current to obtain the $I_{\rm set}$ values.

3.2 Optimal time settings

In the second subproblem, floating $I_{\rm set}$ values obtained via ACSM are given as inputs to the OA for evaluating the objective function (3), which is to minimise the overall operating time of the relays. GA is a powerful tool that attains a global optimum by searching a set of feasible and non-feasible solutions [9], hence, is used in this work to find the optimal TMS values. It is noted that in conventional OA, the decision variables, namely, $I_{\rm set}$ and TMS, are considered as a single genotype for 'n' OC relays, as shown in Fig. 5*a*, thereby, increasing the overall tripping time due to computational delay. However, in the proposed ADOCR algorithm, the decision variables are decomposed into two subproblems and are solved separately. Hence, each genotype in the population represents only the TMS variables as shown in Fig. 5*b* thus, requires lesser computational time.

Initial population of TMS variables are selected on a random basis following the constraint (5). Based on the fixed values of $I_{\rm set}$ extracted from ACSM, the objective function is evaluated for finding optimal TMS variables. Individuals in a population are selected for reproduction based on the rank they obtain. Probability of an individual being selected is given as:

$$\wp_z = \frac{Z_s - z + 1}{\sum_{z=1}^{Z_s} z} \tag{8}$$

where z is the individual, and Z_s the number of individuals selected in the population as parents to indulge in reproduction. Mutation and crossover operations are applied for creating new solutions, and the process is terminated after maximum number of iterations is reached. Constraint violations are handled using a penalty function (PF) that adds a penalty factor to the objective function for

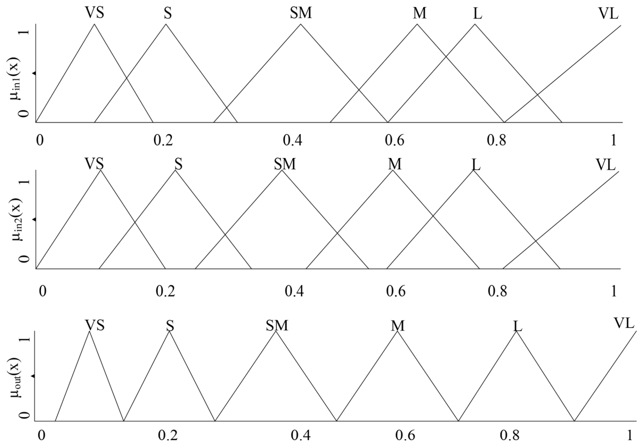

Fig. 4 *Fuzzy membership functions in ACSM subroutine*

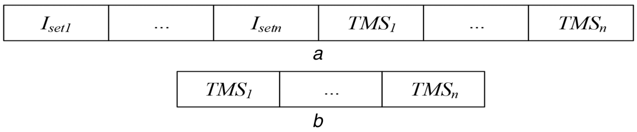

Fig. 5 *Structure of the genotype for*
(a) Conventional OA, ***(b)*** Proposed ADOCR

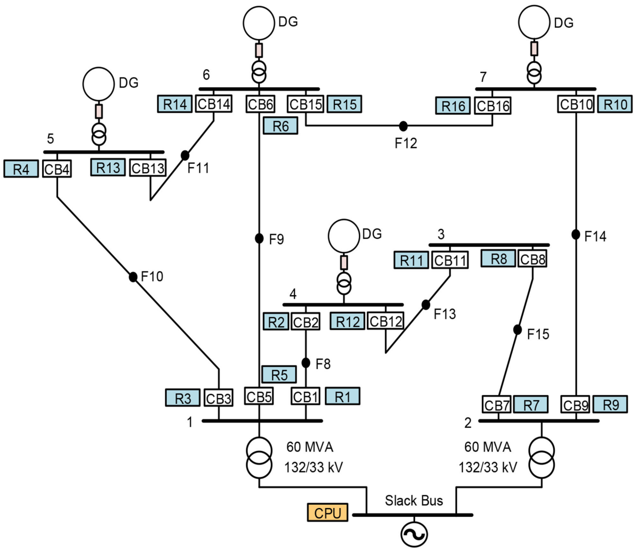

Fig. 6 *Modified power distribution network of IEEE 14-bus system*

penalising the infeasible solutions. It is noted that the value of the penalty factor is determined by trial and error. The PF is given as:

$$\mathrm{PF} - \beta \leq 0 \tag{9}$$

where β is a tolerance value. The constraints of the relay coordination problem are given in the form of PFs as

$$\mathrm{PF}_1 = W_1 \sum (-\Delta t) \tag{10}$$

$$\mathrm{PF}_2 = W_2 \sum (\mathrm{TMS}_i - \mathrm{TMS}_i^{\max}) \tag{11}$$

$$\mathrm{PF}_3 = W_3 \sum (\mathrm{TMS}_i^{\min} - \mathrm{TMS}_i) \tag{12}$$

where Δt represents the grading margin, W_1 is the weighting control parameter for miscoordination penalty, W_2 the weighting control parameter for upper bound penalty, and W_3 the weighting control parameter for lower bound penalty. With the inclusion of these PFs, the objective function in (3) is modified as:

$$\mathrm{OF} = \mathrm{OF} + \max(0, \mathrm{PF}_k) \tag{13}$$

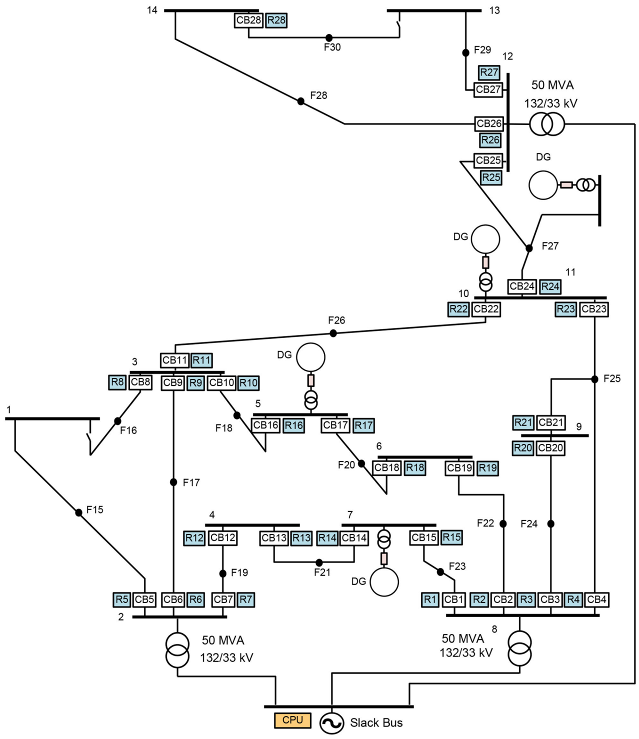

Fig. 7 *Modified power distribution network of IEEE 30-bus system*

$$\mathrm{PF}_k = \begin{cases} \sum_{k=1}^{3} -J_k & \text{if } (J_k < 0) \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

where PF_k is the kth PF and J_k the kth constraint function used. Only in the case of an existing constraint violation, the PF is added to the objective function. The I_{set} values are decided locally depending on the status of DGs and terminal voltage, whereas the TMS settings are calculated offline by OA and stored for online calculation of protection settings. To summarise, I_{set} values determined by ACSM in the first subproblem are called numerous times by the OA in the second subproblem to determine optimal protection settings. In this work, the OA is executed every 30 min to update the TMS according to any change in the distribution system.

4 Results and discussion

4.1 Test systems and simulation set-up

The proposed ADOCR protection mechanism is tested on the modified power distribution networks of IEEE 14-bus and IEEE 30-bus systems [30]. The IEEE 14-bus test distribution system shown in Fig. 6 is fed by two utility transformers of ratings 60 MVA, 132 kV/33 kV. The distribution system is equipped with 16 protection relays denoted as R1–R16 besides the fault nodes F8–F15. The IEEE 30-bus test system shown in Fig. 7 is fed through three utility transformers of ratings 50 MVA, 132 kV/33 kV that are connected at buses 2, 8, and 12. The distribution system is equipped with 28 relays denoted as R1–R28 besides the fault nodes F15–F30.

Both the distribution networks are modified by adding different types of DG units namely, type-1 DG (2 MVA Diesel generator) and type-2 DG (250 kW PV generation system). All DGs are connected to the distribution systems through a 0.48/33 kV, step-up transformer. For each case study, predefined series of phase-to-phase faults with fault resistances between 0 and 10 Ω and phase-to-ground faults with fault resistances between 0 and 100 Ω were simulated at 0.5 s.

Table 1 Relay settings for various CS simulated on IEEE 14-bus system

Relay	DOCR (for all cases)		Optimal TMS for ADOCR (s)		
	I_{set}, p.u.	TMS, s	CS I	CS II	CS III
R1	0.8846	0.05	0.1322	0.1262	0.1230
R2	0.3916	0.05	0.2631	0.1438	0.1391
R3	0.4832	0.05	0.5263	0.1033	0.1025
R4	0.0331	0.1431	0.4816	0.1821	0.1720
R5	0.7211	0.05	0.3724	0.1468	0.1263
R6	0.0792	0.1320	0.4011	0.0980	0.0890
R7	1.0311	0.05	0.1534	0.1371	0.1081
R8	0.3284	0.1320	0.3238	0.1201	0.1171
R9	0.6875	0.05	0.2147	0.1161	0.1054
R10	0.2961	0.05	0.1564	0.1454	0.1324
R11	0.7051	0.05	0.1287	0.1321	0.1156
R12	0.5371	0.05	0.0558	0.1174	0.1041
R13	0.2541	0.05	0.5697	0.2041	0.2647
R14	0.3651	0.05	0.5383	0.0824	0.0614
R15	0.5210	0.05	0.3231	0.1563	0.1357
R16	0.3130	0.05	0.1650	0.1127	0.1014

Table 2 Percentage reduction in overall relay operation time of ADOCRs with respect to conventional DOCRs for various DG scenarios

Network type	DG location	DG type	DG capacity, MVA	% Reduction in operation time
IEEE 14-bus system	—	—	—	68.23
	5, 7	SDG	4	69.54
	4, 5, 6, 7	SDG	8	70.41
	4	IDG	2	70.30
	5, 6, 7	SDG	6	70.30
IEEE 30-bus system	—	—	—	46.77
	5, 7	SDG	4	47.67
	5, 7, 10, 11	SDG	8	48.58
	5	IDG	2	44.39
	7, 10, 11	SDG	6	44.39

4.2 CS definition

To demonstrate the efficiency of the proposed protection coordination strategy, extensive CS are conducted considering various fault conditions and DG scenarios (type, location, and size). However, due to space constraint, four CS (CS I–CS IV) are presented in this paper. In CS I, relay coordination is conducted on both the test systems neglecting the presence of DGs. CS II discusses the changes required in the protection coordination with various penetration levels of SDGs. Protection coordination considering uncertainties in DGs with various penetration levels of both SDGs and IDGs is analysed in CS III. The impact of a sudden change in fault current levels due to the loss or disconnection of a DG in the network is elucidated in CS IV. It is noted that the proposed restoration strategy is implemented on MATLAB R2015B platform. Moreover, in all the CS, the performance of the proposed ADOCR is benchmarked with the conventional DOCR modelled in Section 2.

4.2.1 CS I protection coordination without DGs: In CS I, bolted ‘abc–g’ midpoint faults are simulated at each fault location in both IEEE 14-bus and IEEE 30-bus networks without the inclusion of DGs. However, due to space constraints, only the results obtained for IEEE 14-bus network are discussed in details for this case study. Table 1 demonstrates the optimal protection settings determined using the proposed ADOCRs when compared with protection settings determined using the conventional DOCRs for all the 16 relays present in the IEEE 14-bus network. For CS I, when I_{set} and TMS values are compared for the proposed ADOCR and DOCR protection scheme, it is observed that I_{set} values are almost same for both the schemes, due to the lack of DG input in ADOCRs. However, when the TMS values of ADOCRs are compared to the DOCRs, a reduction of 68.23% in the overall relay operation time is observed (as shown in Table 2).

Similar results are observed for IEEE 30-bus, where the I_{set} values are observed to be same while a 46.77% reduction in the overall relay operating time of the proposed ADOCR protection scheme is observed when compared with the DOCRs as shown in Table 2. Thus, this case study highlights that even in the absence of DG input, ADOCR achieves minimal overall relay operation time and faster convergence rate attributed to its reduced genotype length.

4.2.2 CS II protection coordination with penetration of SDGs: In this case study, the efficacy of the proposed ADOCRs to perform in the presence of SDGs is tested by equipping both the 14-bus and 30-bus test systems with type-I DGs. For the IEEE 14-bus test system, constant type-I DGs with 2 MVA capacity each are connected at buses 5 and 7, and a bolted ‘abc–g’ midpoint faults are simulated. Initially, protection settings of the DOCRs determined in CS I, shown in Table 1, are used for this case study. However, five instances of miscoordination between the primary and backup relay are observed with a CTI <0.3 s as shown in Table 3. This is mainly because of the increase in fault current seen by DOCRs due to the presence of SDGs which requires higher I_{set} values when compared with the scenario without DGs. Hence, a new set of protection settings that satisfies the constraints with the inclusion of SDGs (4 MVA total capacity) are proposed for DOCRs, as shown in Table 4. With the revised DOCR settings, it is observed that the operating times of primary and backup relays listed in Table 5 satisfied the CTI constraint of maintaining a minimum interval of 0.3 s. However, when the capacity of SDGs is increased further to 8 MVA (by connecting SDGs at buses 4, 5, 6, and 7), three instances of miscoordination are observed which necessitated another new set of protection settings. Hence, with every new DG addition or change in DG capacity, conventional DOCR requires a change in protection settings.

Now, all the DOCRs are replaced with the proposed ADOCR in the IEEE 14-bus network and the results for one of the relays are demonstrated in Fig. 8. For the situation when no SDG is considered in the system, the I_{set} value of ADOCR4 (at fault location F10) is observed to be 0.0331 p.u. at 0.5 s for bolted 'abc–g' fault, as shown in Fig. 8*a*. However, when SDGs of 2 MVA capacity each are connected at buses 5 and 7, the I_{set} value is increased from 0.0331 to 0.0714 p.u., as shown in Fig. 8*b*. Similarly, when the total capacity of SDGs is increased further to 8 MVA by connecting SDGs at buses 4, 5, 6, and 7, the I_{set} value increases further to 0.1213 p.u., as shown in Fig. 8*c*. Thus, it is observed that, the ACSM in ADOCR4 is able to adapt to the change in the DG input and modify the I_{set} values accordingly.

Table 3 DOCR operating times for case II simulated on IEEE 14-bus system

Fault location	Operating time of the relays, s (p, primary; b, backup)			CTI
	p	b1	b2	
F10	R3: 1.21	R2: 1.43	R6: 7.39	0.22
	R4: 1.42	R14: 1.80	—	
F13	R11: 1.59	R7: 1.68	—	0.09
	R12: 1.95	R1: 2.04	—	0.09
F14	R9: 1.86	R8: 2.05	—	0.19
	R10: 1.52	R15: 1.95	—	
F15	R7: 1.63	R10: 1.85	—	0.22
	R8: 2.09	R12: 2.87	—	

The optimal TMS values determined by ADOCRs for CS II with SDGs at buses 5 and 7 in IEEE 14-bus system can be observed from Table 1. When the operating times of ADOCR and DOCR shown in Table 5 are compared, it is observed that for an 'abc–g' fault at F10, the primary relays ADOCR3 and ADOCR4 operate at 0.79 and 1.02 s, whereas DOCR3 and DOCR4 operate at 1.47 and 1.88 s, respectively. Thus, the optimal protection settings determined by ADOCRs for faults (F8–F15) lead to a reduction of 69.54% for 4 MVA SDG penetration, and a reduction of 70.41% for 8 MVA SDG penetration in the overall relay operation time, as shown in Table 2.

Likewise, fault conditions are simulated at the aforementioned DG penetration levels (no DG, SDGs at buses 5 and 7, and SDGs at buses 5, 7, 10 and 11) for IEEE 30-bus network and the results are shown in Fig. 8. For an 'abc–g' fault with a fault resistance of 10 Ω at F20, I_{set} values of ADOCR17 determined are 0.334, 0.464, and 0.513 p.u., respectively, for various DG penetration levels, as shown in Fig. 8. The optimal TMS values determined by ADOCRs for CS II implemented on IEEE 30-bus network are presented in Table 6. It can be observed from Table 2 that the optimal protection settings of ADOCR for faults (F15–F30) lead to a reduction of 47.67% for 4 MVA SDG penetration, while 48.58% for 8 MVA SDG penetration in the overall relay operation time.

It is noted that in both test systems, the change in SDG capacity and location demands a change in the protection settings for attaining minimal overall relay operating time. The results demonstrate that the fault current variation due to various penetration levels of SDGs are well identified by the proposed ADOCR and thus, determine optimal protection settings.

4.2.3 CS III performance of the proposed ADOCR with penetration of both IDGs and SGDs: In this case study, to illustrate the impact of IDGs' inclusion in the test systems, both types of DGs, namely type-1 and type-2, are considered, and the

Table 4 Relay settings of conventional DOCR for IEEE 14-bus system

Relay	I_{set}, p.u	TMS, s	Relay	I_{set}, p.u	TMS, s
R1	0.889	0.050	R9	0.687	0.050
R2	0.425	0.075	R10	0.324	0.050
R3	0.483	0.050	R11	0.705	0.050
R4	0.113	0.184	R12	0.652	0.068
R5	0.721	0.050	R13	0.360	0.059
R6	0.085	0.287	R14	0.415	0.074
R7	1.031	0.050	R15	0.637	0.050
R8	0.328	0.256	R16	0.413	0.094

Table 5 Relay operating times for CS II simulated on IEEE 14-bus system

Fault location	Operating time of the relays, s (p, primary; b, backup)					
	Conventional DOCRs			Proposed ADOCRs		
	p	b1	b2	p	b1	b2
F8	R1: 1.92	R4: 4.21	R6: 3.04	R1: 0.68	R4: 1.04	R6: 1.21
	R2: 1.66	R11: 2.14	—	R2: 0.64	R11: 0.94	—
F9	R5: 1.64	R2: 2.17	R4: 3.31	R5: 0.96	R2: 1.26	R4: 1.59
	R6: 1.81	R13: 3.92	R16: 2.3	R6: 0.96	R13: 1.26	R16: 1.35
F10	R3: 1.47	R2: 2.64	R6: 8.04	R3: 0.79	R2: 1.21	R6: 2.5
	R4: 1.88	R14: 2.85	—	R4: 1.02	R14: 1.50	—
F11	R13: 1.51	R3: 2.04	—	R13: 0.96	R3: 1.31	—
	R14: 1.79	R5: 3.07	R16: 2.52	R14: 0.88	R5: 1.18	R16: 1.67
F12	R15: 1.74	R5: 2.81	R13: 3.41	R15: 0.97	R5: 1.34	R13: 1.74
	R16: 2.04	R9: 2.78	—	R16: 0.93	R9: 1.23	—
F13	R11: 1.74	R7: 2.37	—	R11: 0.72	R7: 1.02	—
	R12: 2.12	R1: 2.71	—	R12: 0.76	R1: 1.06	—
F14	R9: 2.08	R8: 3.62	—	R9: 0.74	R8: 1.24	—
	R10: 1.76	R15: 2.47	—	R10: 0.76	R15: 1.34	—
F15	R7: 1.74	R10: 2.59	—	R7:0.67	R10: 0.97	—
	R8: 2.19	R12: 2.57	—	R8: 0.64	R12: 0.94	—

results obtained for IEEE 30-bus system are shown in Table 7. A slight modification is done in CS II (8 MVA DG capacity) by replacing the SDG at bus 5 with a type-2 DG of same capacity in IEEE 30-bus distribution system. For an 'abc–g' fault at F20, with a fault resistance of 10 Ω, I_{set} value of ADOCR17 is decreased from 0.513 to 0.421 p.u. according to the fault current contributed by IDG and an appropriate trip signal is used at 0.64 s, as shown in Fig. 9. When I_{set} value of DOCR17 (0.532 p.u.) is stored and used

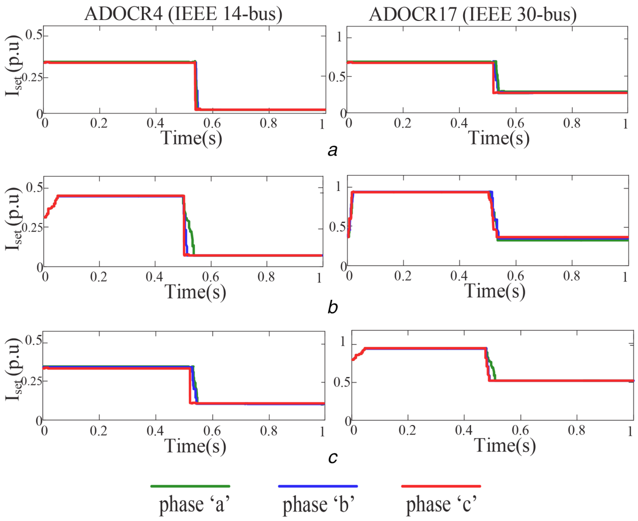

Fig. 8 *Floating I_{set} values of ADOCR for various DG penetration levels*
(a) Without DG, ***(b)*** With 4 MVA type 1 DGs, ***(c)*** With 8 MVA type 1 DGs

here, the trip time is observed to be 2.3 s, which is longer than its usual trip time, 1.54 s. The operating times of ADOCRs given in Table 2 show a reduction of 44.39% in the overall relay operating time compared to the conventional DOCRs. Hence, it is evident that the proposed ADOCR is able to accommodate the varying power of IDGs and determine optimal protection settings that ensure minimal relay operating time.

4.2.4 CS IV impact of sudden disconnection/loss of a DG: To demonstrate an unexpected disconnection or loss of a DG in the distribution system, IDG connected at bus 5 in CS III is disconnected at 0.3 s and an 'a–g' fault at F20 with a fault resistance of 5 Ω is simulated. Primary relay ADOCR17 senses the fault according to the voltage drop in the line modifies the I_{set} value to 0.357 p.u. and issues a trip signal at 0.63 s as shown in Fig. 10. However, with the pre-calculated I_{set} value of DOCR17 (0.532 p.u.), the relay fails to issue the trip signal, and results in 'blinding of protection' as shown in Fig. 10*c*. Thus, the proposed ADOCR determines floating protection settings by detecting the connection status of DG.

5 Benchmarking of overall relay operating time

To further validate our results, the proposed ADOCR method is benchmarked with protection algorithms proposed in [18, 19]. Specifically, the overall relay operating time which is the main objective function in the proposed adaptive relay has been compared as shown in Table 8.

Table 8 highlights the comparison of relay operating time between the proposed approach and [18] for two scenarios, namely with and without DGs for both IEEE 14-bus and 30-bus test

Table 6 Optimal time settings (s) of ADOCRs for various CS simulated in IEEE 30-bus system

Relay	CS I	CS II	CS III	Relay	CS I	CS II	CS III
R1	0.100	0.103	0.157	R15	0.334	0.320	0.237
R2	0.100	0.138	0.189	R16	0.251	0.156	0.158
R3	0.100	0.125	0.112	R17	0.100	0.221	0.145
R4	0.100	0.143	0.171	R18	0.100	0.115	0.151
R5	0.100	0.121	0.155	R19	0.380	0.215	0.173
R6	0.150	0.123	0.110	R20	0.290	0.174	0.208
R7	0.100	0.104	0.173	R21	0.473	0.272	0.137
R8	0.100	0.100	0.139	R22	0.281	0.142	0.175
R9	0.112	0.285	0.124	R23	0.490	0.251	0.187
R10	0.100	0.100	0.100	R24	0.100	0.134	0.110
R11	0.100	0.101	0.100	R25	0.280	0.141	0.153
R12	0.100	0.142	0.127	R26	0.100	0.127	0.130
R13	0.100	0.313	0.209	R27	0.100	0.101	0.165
R14	0.100	0.104	0.107	R28	0.100	0.102	0.181

Table 7 Primary and backup relay operating times for CS III simulated in IEEE 30-bus system

Fault location	Operating time of the relays, s (p, primary; b, backup) for ADOCR										
	p	b1	b2	b3	b4		p	b1	b2	b3	b4
F15	R5: 0.61	R9: 1.02	R12: 1.15	—	—	F23	R1: 0.69	R19: 1.09	R20: 1.19	R21: 1.02	R23: 1.21
F16	R8: 0.58	R6: 0.88	R16: 0.93	R22: 1.04	—		R15: 0.76	R13: 1.09	—	—	—
F17	R6: 0.55	R12: 0.89	—	—	—	F24	R3: 0.62	R15: 0.92	R19: 0.92	R21: 0.92	R23: 1.05
	R9: 0.64	R16: 0.99	R22: 0.99	—	—		R20: 0.87	R4: 1.17	R23: 1.25	—	—
F18	R10: 0.65	R6: 1.02	R22: 1.44	—	—	F25	R4: 0.68	R15: 0.98	R19: 1.07	R20: 0.98	—
	R16: 0.81	R18: 1.25	—	—	—		R21: 0.77	R3: 1.07	R25: 1.24	—	—
F19	R7: 0.64	R9: 1.04	—	—	—		R23: 0.97	R11: 1.27	—	—	—
	R12: 0.67	R14: 0.97	—	—	—	F26	R11: 0.64	R6: 1.15	R16: 1.08	—	—
F20	R17: 0.64	R10: 0.94	—	—	—		R22: 0.66	R4: 1.37	R21: 1.21	R25: 1.86	—
	R18: 0.74	R2: 1.24	—	—	—	F27	R24: 0.65	R4: 0.96	R11: 0.98	R21: 1.09	—
F21	R13: 0.73	R7: 1.04	—	—	—		R25: 0.58	—	—	—	—
	R14: 0.59	R1: 0.92	—	—	—	F28	R26: 0.64	R24: 0.94	—	—	—
F22	R2: 0.63	R15: 1.01	R20: 1.32	R21: 1.18	R23: 1.29	F29	R27: 0.59	R24: 0.91	—	—	—
	R19: 0.67	R17: 0.97	—	—	—	F30	R28: 0.62	R26: 0.92	—	—	—

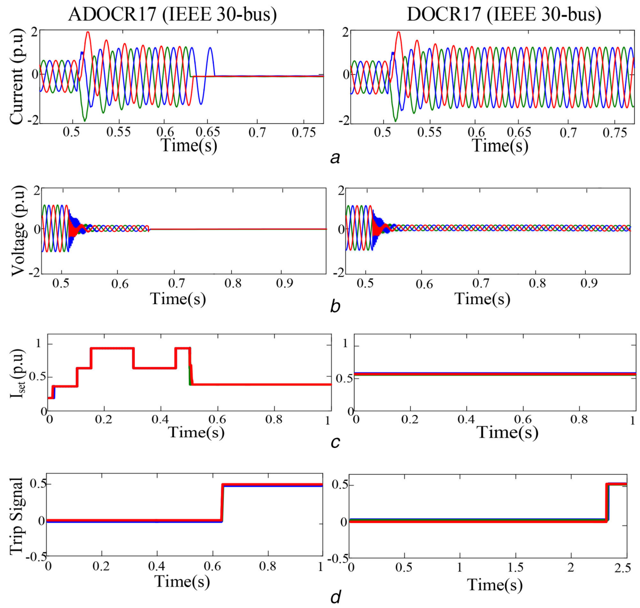

Fig. 9 *Behaviour of ADOCR17 and DOCR17 for CS III*
(a) Current signals, ***(b)*** Voltage signals, ***(c)*** Current settings, ***(d)*** Trip signal

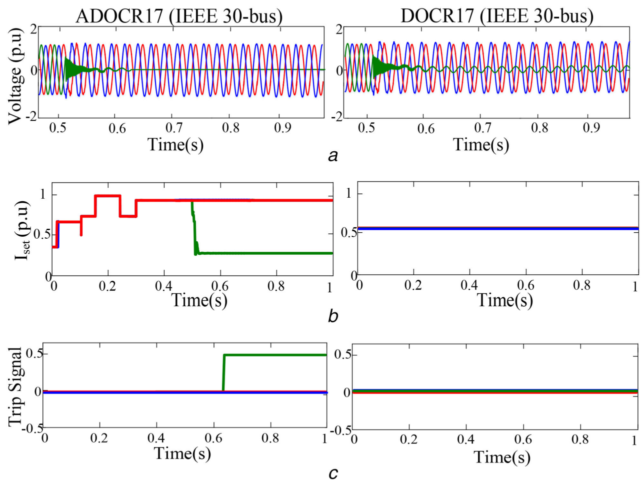

Fig. 10 *Comparison of ADOCR17 and DOCR17 for CS IV in IEEE 30-bus distribution system*
(a) Voltage signals, ***(b)*** Current settings, ***(c)*** Trip signal

systems. From Table 8, it can be seen that the operating times of ADOCRs show a reduction of >20% in the overall relay operating time compared to [19] for both the test systems and DG scenarios.

When results of the proposed approach are compared with [19], it is observed from Table 8 that the proposed ADOCR method performs on par with [19]. Specifically, in the case study with DGs (6 MVA capacity), the overall relay operating time observed in [19] is only 1% less compared to the proposed ADOCR algorithm. It is noted that, although the protection algorithm in [19] performs slightly better compared to our proposed ADOCR approach, the authors in [19] have proposed four different settings for each relay assuming that the DG capacity is already known. Using such predefined protection settings might not be feasible with intermittent-type DGs such as solar and wind, which induces fluctuating fault currents. Unlike the algorithm in [19], the proposed ADOCR determines online protection settings considering the dynamic operation of DGs, while solving the DOCR coordination. Hence, the proposed ADOCR algorithm is able to determine optimal floating protection settings while ensuring minimal overall relay operating time for highly meshed distribution networks under varying network conditions and DG scenarios.

Results from the CS and comparison with other protection algorithms indicate that the proposed ADOCR successfully handles

Table 8 Comparison of the overall relay operating time of ADOCRs with respect to other protection methods for various DG scenarios

Network type	DG location	DG capacity, MVA	Relay operation time, s	
			Algorithms in literature	Proposed ADOCR
IEEE 14-bus system	—	—	554.7 [18]	24.67
	3, 4, 5, 6, 7	10	542.8 [18]	22.98
IEEE 30-bus system	—	—	9033 [18]	35.02
	—	—	35.06 [19]	35.02
	3, 6, 10	6	34.56 [19]	34.85
	3, 4, 5, 7, 10, 11	12	9026 [18]	34.42

the uncertainties of DGs and determines optimal protection settings. Major advantages of the proposed adaptive relay scheme are summarised below:

i. Optimal protection settings are determined for various levels of DG penetration without any user interference.
ii. The proposed ADOCR determines optimal settings irrespective of the type, sizing, and location of DGs.
iii. In the case of any unexpected loss of a DG, protection settings are obtained by sensing the DG condition.
iv. The ADOCR scheme can be efficiently coordinated with other digital relays in the case of large-scale distribution systems with multiple DGs.

6 Conclusion

In this work, DOCR coordination problem is investigated for meshed distribution systems, considering the stochastic nature of DGs. Recognising that a predefined set of relay settings will not offer complete protection against the impacts of DGs and changing network scenarios, an adaptive relay is developed. A novel hybrid approach for obtaining adaptive relay settings and efficient relay coordination is proposed, considering the uncertainty of DGs. The proposed relay consists of a fuzzy-based current setting module that considers DG output while determining the current settings, and an OA for minimising the overall relay operating time. Several CS conducted on the IEEE distribution systems prove the efficacy of the proposed relay over conventional DOCRs and other protection algorithms in the literature. With optimal time settings, the proposed relay shows a reduction of almost 58% in the overall operating relay time. Furthermore, optimal relay settings are achieved irrespective of the type, location, and size of DGs for all possible fault conditions in the network.

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