A q component-based adaptive protection coordination optimisation using overcurrent relays in coordination with fuses for hybrid microgrid

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Abstract

In a hybrid microgrid, the overcurrent relays (OCRs) must sense the changes in the fault currents while the microgrid switches from the grid-connected to the islanded mode of operation. Further, for the different types of distributed generator (DG), such as photovoltaic (PV), wind turbines of types I, III, and IV, the variation in fault currents must also be detected by the relays. This leads to delay and inappropriate coordination in conventional protection schemes. To minimise the impact of inappropriate coordination in this study, an adaptive protection scheme with optimal settings is proposed for phase and earth faults detection. It also takes care of different nature of DGs, all feasible operating modes of hybrid microgrid with only quadrature (q) component of fault current while zero component is used to differentiate between earth and phase faults. Also, only q component-based proposed technique optimises the coordination time (CT) of fuses as a backup to primary and backup relays with newly proposed CT interval constraints. A differential evolutionary algorithm is proposed for determination of optimal settings for the directional OCRs.

1 INTRODUCTION

In conventional power system protection overcurrent relay (OCR) has an inverse relationship between the relay operation time (OT) and the short-circuit current at a given instant. A relay has time-dial settings (TDS) as a tuning parameter, the pickup current ($I_p$) and the minimum value of current above which the relay operates. For proper protection coordination optimisation (PCO), the objective function is considered for OT minimisation of relays with constraints as TDS, $I_p$ and coordination time interval (CTI). In the integration of distributed generators (DGs), this PCO problem has become more complex due to bidirectional feeding, blinding, and maloperation of relays. In addition, this problem becomes more complex when low inertia and low $X/R$ ratio DGs are integrated with the conventional power system, which has a high inertia and $X/R$ ratio. Low inertia means missing rotational (or small rotational) components due to which reactance component ($X$) decreases in wind (small induction generators as compared to synchronous generators), and in photovoltaic (PV) DGs no reactance is involved.

In PV DGs, very small reactance is present due to the transformer presence. With the decrease in reactive component, $X/R$ ratio decreases, which, in turn, governs the rate of rise of fault current and leads to the different behaviour of relays that were designed based on high $X/R$ ratio of conventional systems. All these have majorly affected the operation of directional OCRs. The problem has become of serious concern with the different modes such that islanded and grid-connected mode of operation of the microgrid power system are a serious concern in the issues related to the interconnection of low and high inertia-based power systems.

Very few literature have reported emphasising the type of DGs connected in microgrid operation. Rarely, a few literature reported considering only PV and wind DGs that can cater for the maximum load connected in a microgrid system. In the perspective of microgrid protection, optimal sizing of fault current limiters (FCLs) and subsequent settings for directional OCRs are proposed in [1]. In this study, the problem has been formulated as a constrained non-linear programming problem and is
solved using the genetic algorithm (GA) with the static penalty constraint-handling technique [2].

A scheme is proposed that is capable of properly operating in forward and reverse direction coordinating through a communication channel in [3]. Based on the cuckoo optimisation algorithm, an optimisation tool is developed with linear programming to get optimal coordination protection settings for relays [4]. For better power quality and proper protection coordination (PC) in presence of distributed energy resources (DERs), optimal sizing of solid-state unidirectional FCLs is proposed [5].

Harmonic current injection capability and the characteristic curve of overcurrent devices are modified for inverter-based DGs (IBDGs) [6, 7]. Superconducting FCLs are used to provide fault ride-through (FRT) capability with proper PC [8]. For all possible network topologies, the proper PC is designed with the optimal relay settings with N−1 contingency [9]. An optimal protection scheme based on a differential evolution algorithm considering different operating modes of microgrid along with different types of phase fault is proposed in [10].

A differential protection scheme is proposed for microgrid protection capable of operating in both grid-connected and islanded modes [11]. The adaptive modified firefly algorithm and fuzzy decision-making tool are proposed for optimal coordination settings in [12, 13]. Optimal sizing of the supercapacitors is done based on the two-level optimisation scheme along with optimising its controller parameters [14]. A new PC scheme is proposed for minimising power loss for wind DGs in [15]. In [16], a digital over- and under-frequency relay is proposed, which operates for over and under frequency in coordination with the digital proportional integral derivative (PID) controller. The change in impedance of network micro phasor measurement units sends a signal to update OCRs settings using a communication channel [17]. Virtual inertia is controlled depending on change in frequency during different modes by the optimal proportional integral (PI) controller using particle swarm optimization (PSO) to minimise the PC time interval [18]. A non-standard tripping characteristic curve with modified settings for the current multiplier finalised by GA is proposed in [19]. Definite time grading relay using negative sequence resistance for islanded IBDGs is proposed using voltage frequency control [20].

Also, it is to be noted that the available protection schemes that are used in ac systems are not feasible to be used in dc systems [21]. Also, a protection scheme is needed to be designed that is economical, feasible and reliable for different nature DGs (PV and wind types I, III and IV), whose efficacy is not hindered by nature of DGs, mode of operation, type of fault and type of system (ac or dc) and so forth. The main contribution of this study is that only q component (static component) of fault current as the main parameter for fault detection. A new concept of fuse constraints for fast fault removal is also validated in the proposed scheme where fuses provide backup to primary and backup relays. Here, hybrid microgrid term is used to represent different types of generation or different nature of DERs that are involved in feeding the load.

The organisation of the study is as follows. Section 2 presents the system details of the hybrid microgrid and mathematical model of an optimisation problem. The procedure of proposed optimum protection scheme using a differential evolutionary algorithm (DEA) is discussed in Section 3. Section 4 presents the implementation of the proposed protection scheme and the results. Finally, the study is concluded in Section 5.

2 | SYSTEM DETAILS AND MATHEMATICAL MODEL

The hybrid microgrid is used as a platform for the validation of the proposed adaptive protection scheme modelled in Matlab/Simulink environment. It is modelled as per the specifications given in ‘Conditions of Supply’ by the Punjab State Electricity Regulatory Commission [22]. The load of small Indian coastal village that was earlier fed by the utility is now connected to the hybrid microgrid. The wind speed and solar insolation are available abundantly in coastal India. The loads are mostly resistive and inductive as the domestic and agrarian load (three-phase motive load)) have power consumption level of 400 kW and the feeders are operated at 415 V. Interconnection of wind turbines (types I/III/IV), PV (hybrid system)-based DGs, load and utility resemble a hybrid microgrid. Integrated test system involving different nature DGs, available volt-amperes at point of common coupling (PCC) are checked as per the ‘Conditions of Supply’ mentioned in [22] to feed the rural village. Amperes range of distribution-side load is 1000 Amperes, voltage range 440–410 V, frequency range 49.5–50.25 Hz and THD 5% [23]. Base MVA is 1, base voltage on grid end is 11 kV and base voltage on PV and wind DG end is 440 V. The proposed hybrid microgrid is self-sufficient to feed the connected loads irrespective of the availability of utility grid. The locations of circuit breakers (CBs; 14 CBs marked as CB1 to CB14), current transformers (CTs; seven CTs marked as CT1 to CT7), equal numbers of fuses (F1–F14) placed near CBs and OCRs (R–shown as R1 to R14) as shown in Figures 1 and 2.

2.1 | System details of hybrid microgrid model

The schematic diagram of the proposed microgrid model is shown in Figure 1. It shows the layout of a three-phase ac microgrid system equipped with 1 MVA/440 V PV system, wind energy (WE-I, III and IV) system of 1 MVA/440 V. All are interconnected with utility grid of 1 MVA and 11 kV capacity through a step-down transformer of 1 MVA, 11 kV/440 V, 50 Hz PCC. The entire system has a resistive load of 800 kW and a reactive load of 300 kvar.
Different faults are simulated at the same location but with different DGs for same fault duration of 0.1 s. The PV generator is controlled based on inverter control using a double synchronous rotating frame (DSRF) for the more flexible FRT control. The inner-loop current control uses the regulators under a DSRF and the outer-loop voltage control regulates the dc-link voltage to realise maximum power point tracking that is used in [24]. The wind generators (type I) and doubly fed (types III and IV) are modelled with variable pitch in this study as per [25]. The type I wind generator is modelled as a squirrel cage induction generator. The converters of DFIGs (types III and IV) are modelled according to [26].

2.2 Mathematical model and problem formulation

In case of directional OCRs, inverse characteristics of the short-circuit current magnitude decide OT of the relay, and it is given as Equation (1) as per [1]:

\[
T = \frac{K1 \times TDS \left( \frac{I_f \times CTR}{I_p} \right)^{K2} - 1}{K1 \times TDS \left( \frac{I_f \times CTR}{I_p} \right)^{K2} - 1} \tag{1}
\]

where \( T \) is trip time, \( K1 \) and \( K2 \) are constants dependent on inverse-time characteristics of operation, \( TDS \) is time-dial setting, \( CTR \) is current transformer ratio, \( I_f \) is the current through the relay and \( I_p \) is pickup current. Normally, the standard inverse is set for relays used in-line protection with \( K1 \) as 0.014 and \( K2 \) as 0.02. So while deciding the optimal solution, the main parameters considered are \( TDS \) and \( I_p \). The objective function is to aim for minimum operating time of relay. It is represented as follows in Equation (2) [1]:

\[
\min T = \sum_{i=1}^{n} t_i \tag{2}
\]

where a total number of relays are \( n \) and operating time for a relay under consideration is \( t_i \). For proper optimisation, three constraints are necessary, which are TDS constraint, pickup current constraint and CTI. Minimum and maximum constraints for TDSs and pickup current of a relay are bound to lower and upper limits. The lower limit of pickup current tap setting \( (I_p - i) \) is set in such a manner for every relay that the threshold of the current resultant \( (CTR \times I_p) \) is more than rated load current (normally 1.25 p.u.) for the respective part to be protected. Third constraint CTI, which is the difference in a minimum OT gap of a primary and backup relay, is to be set as 120 ms. Third constraint is further supported by two newly defined fuse constraints for primary and backup fuses to back up the primary and backup relays if the relays fail to operate.

The change in the mode of operation of a hybrid microgrid is shown in Table 1 where status 1 means utility/DG is in operation and status 0 means utility/DG is not in operation. The different modes of operation are selected in hybrid microgrid by keeping buses 1, 3, and 4 in hybrid microgrid operation or out of operation as shown in Figure 2 and Table 1. Load flow studies are performed every time during a change in the hybrid microgrid mode of operation. In most of the literature, only two modes, such as grid-connected and islanded operation of the microgrid is considered. In this study, different modes of hybrid microgrid are considered that are grid-connected, islanded and hybrid mode (wind and PV DG working together). The PV and wind DGs together are not considered in most of the literature with proper consideration of low inertia and low reactance. The objective function is the sum of the OT, \( T \), of all the primary and backup relays in operation during an event of a fault. It is given with modification to relation [1] as per change in the mode of operation as shown in Equation (3):

\[
T_{total} = \text{Min} \sum_{m=1}^{n_b} \left( \sum_{k=1}^{n_b} \left( \sum_{j=1}^{n_b} \left( \sum_{i=1}^{n_b} t_{i,j,k} \right) \right) \right) \tag{3}
\]
where $T_{on,i}$ is the sum of operating times of all relays with $nb$ as the number of modes of operation that depend on the magnitude of q0 component of fault current available at given $nf$ fault locations with $nb$ as the number of buses of the system and $np$ as the number of primary relays at fault locations. $t_{i,j,k}$ is the time of operation of relay $R_{i,j}$ for fault occurrence at the bus number $k$, $R_{i,j}$ is the relay in-branch $ij$ near bus $i$. Similarly, $R_{i,j}$ is the relay at the generator bus $i$. $t_{i,j,k}$ is the time of operation of relay $R_{i,j}$ for fault occurrence at the bus number $k$. $I_{f(i,j,k)}$ is fault current between buses numbers $i$ and $j$ for fault at bus $k$. $I_{f(i,j,k)}$ is the pickup value of relay $R_{i,j}$, value of $I_{f(i,j,k)}$ and $I_{f(i,j,k)}$ is chosen in such a manner that overload current margin range is 15%–25%. $t_{i,j,k}$ is calculated as the inverse-time characteristic function with $K_1$ as 0.014 and $K_2$ as 0.02 and given by Equation (4):

$$ t_{i,j,k} = \frac{K_1 \times TDS}{(K_2)^2} - 1 \quad (4) $$

The constraints of the objective function are assigned for TDS and $I_p$ where $TDS_{min,i}$ and $TDS_{max,i}$ are minimum and maximum limits on TDSs, $I_{pmin,i}$ and $I_{pmax,i}$ are minimum and maximum limits for pickup current for $i$th relay. There are some relays ready for backup relay operation for each fault. So for proper coordination of backup relays, coordination constraint per fault is needed to be satisfied that is given as CTI, which is taken to be 0.120 s.

The constraints in limits that are set to minimise objective function are as follows [1]:

$$ TDS_{min,i} - TDS \leq TDS_{max,i} $$

$$ PSM_{pmin,i} \leq PSM_{pmax,i} $$

$$ I_{f(i,j,k)} = I_{p(i,j,k)} $$

In $i$, $I_{f(i,j,k)}$ and $I_{p(i,j,k)}$ $b$ represents the operation mode, it is either grid-connected or islanded or hybrid mode, $l$ is the location of the fault, $bkr$ means $(k)$ number of backup relays, and $pr$ means primary relay in operation. New CTI constraints are proposed for backup to primary relay and backup relay. Fuses as a backup are considered in the distribution system as, by any means, if relays fail to operate, fuses will blow depending on fault amperes. Fuses as a backup make tripping more effective guaranteed in distribution systems. Fuses are less expensive as compared to relay circuit breakers. CTI for primary backup fuses to back up the backup relay is taken to be 0.05 s. CTI for backup fuses to back up the backup relay is taken to be 0.10 s:

$$ t_{pfuse} - t_{relay} \geq 50 \text{ ms} $$

$$ t_{pbfuse} - t_{fuse} \geq 100 \text{ ms} $$

where $t_{pfuse}$ is operating time of the primary backup fuse, $t_{relay}$ is operating time of backup relay and $t_{fuse}$ is operating time of secondary backup fuse. Based on q0 components of fault current, the relations are modified and proposed as Equation (5) [21]:

$$ I_p = I_{relay}(q, 0) \quad (5) $$

Equation (1) is modified and proposed for $I_p$ and $I_f$ as follows:

$$ T = \frac{K_1 \times TDS}{(CTR \times I_p(0))^2} - 1 \quad (6) $$

The proposed modification is validated using a DEA in the next section below. CTR for grid side and wind DGs is 400, 300 for PV DGs, and 200 for all the load-side nodes. For the minimisation of many variables involved in the adaptive protection schemes, the transformation of ac three-phase current to dq0 current is done using Park’s transformation as per [21], which is mentioned by Equation (7):

$$ [I_{dq0}] = [K_2] \times [I_{q0,0}] \quad (7) $$

where $I_{d0q} = [I_d] \times [I_0]$; $I_{d0q}$ and $I_{q0,0}$ are respective dq0 and three-phase current matrices. $I_{q0,0}$ are instantaneous quantities as a function of time, represented in matrix form. $K_2$ represents the dq0 transformation matrix, where $\theta$ represents the angular displacement of the dq0 system.

The microgrids comprise DGs with low $X/R$, which directly affects the $I_q$ component as mentioned above. So the variation in the $I_q$ component is considered to detect fault, which justifies that this system works for any $X/R$ ratio [21]. As given in this study, only q0 components are sufficient to detect a fault and its location. To minimise the impact of dynamicity in the hybrid microgrid, an adaptive feature in the protection scheme is implemented based on the equations used in [21]. Furthermore, out of two components q and 0, only q0 component of fault current is used as follows in Equations (8) and (9):

$$ I_{relay} = (I_{qG} \times GridStatus) + \sum_{k=1}^{n} \left( k_i \times I_{DG}^{kG}(q) \times StatusDG^k \right) \quad (8) $$

**TABLE 1 Mode change during hybrid microgrid operation**

|          | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|----------|--------|--------|--------|--------|--------|--------|
| Utility  | 1      | 1      | 1      | 0      | 0      | 0      |
| Wind distributed generator (DG) | 1 | 0 | 1 | 1 | 0 | 1 |
| Photovoltaic (PV) DG | 1 | 1 | 0 | 1 | 1 | 0 |
Also,

\[ I_{(q)f}^{DG} = I_{qrated}^{DG} \times G \]  

(9)

Here, \( I_{relay} \) is relay current, \( I_{qG} \) is grid current during the fault, \( Grid_{Status} \) is 0 or 1 (depending on availability of grid), \( k_i \) represents the impact factor of \( i \)th DG on the fault current of the relay, \( I_{qf}^{DG} \) is the maximum fault current contribution of \( i \)th DG in terms of \( q \) components, \( Status_{DG}^{DG} \) is 0 or 1 (depending on availability of \( i \)th DG), \( I_{qrated}^{DG} \) is the corresponding maximum \( q \) component currents of \( i \)th DG and \( G \) is current coefficient whose value depends upon the nature of DG. Its impact factor depends on the impedance between the DGs and relays within a radial distribution. So change in \( I_n \) can be used to detect the fault, considering a minimum number of parameters as per [21]. The \( I_d \) and \( I_0 \) can be neglected, and effective protection could be redesigned according to change in relation given as Equations (10) and (11):

\[ I_n = f(I_q, I_0) \]  

(10)

\[ I_n = f(I_q) \]  

(11)

An adaptive PCO scheme based on Equation (11) can easily detect any fault at any location with any number and any type of DG. Q component-based adaptive PC is best in fault detection. But for differentiating among phase and earth faults, zero component of fault current is equally important as q component. The new constraints are defined for proper PC among relays and fuses, which helps in the understanding of slow relay operation of PV DG-side system in comparison to wind DG side.

3 | ALGORITHM

Figure 3 shows the flowchart of the proposed q component-based adaptive PCO scheme. In this study, PC problem is optimised based only on q component, and 0 component is for identification among phase and earth faults component of fault current in a hybrid microgrid. The hybrid microgrid has different types of wind generators as types I, III, IV, and PV DG connected with the utility grid. These proposed adaptive optimisation settings resolve all the issues arising because of the integration of different wind DGs (type I, III, and IV) with utility and PV DGs. For the optimisation of linear as well as a non-linear problem as shown in Equations (1) and (2), the best technique is the meta-heuristic hybrid DEA. It is also validated that q components of fault current are sufficient with the help of zero components. It helps in identifying earth faults that were not considered earlier in resolving PC problems. Figure 3 shows the flowchart of the proposed adaptive protection coordination for the hybrid microgrid.

DEA considering only q component (one variable) of fault current is proposed for getting optimal settings of plug setting multiplier (PSM), TDS, and optimum PC time for primary and backup relays. Storn and Price introduced the population-based stochastic algorithm in 1995 [27]. The given adaptive PC problem is non-linear as well as non-differentiable and DEA provides direct search approach. It is simple and fast in implementation with the ability of finding out global best available values [28]. DEA has four steps that are the initialisation of parameters, mutation, crossover, and selection with good convergence properties. The above-mentioned steps are repeated until the optimal global setting values are obtained. Iteration number and objective function stop updating only when best fit global settings are obtained. In this study, with the approach of obtaining optimal
solution meta-heuristic, DEA considering q components of fault current is found to be the best meta-heuristic algorithm.

The main emphasis of this study is on obtaining the best adaptive optimum PC settings with only q component of fault current in a hybrid microgrid with any number and any type of DGs that was not done earlier. A brief explanation of DEA can be found in [27, 28]. The flowchart in Figure 3 shows the q component-based DEA flow for obtaining the adaptive optimal set of PSM and TDS of relay settings for the hybrid microgrid. The flowchart shows setting up hybrid microgrid parameters such as DG and grid ratings, load impedances, and load locations. After that, load flow studies are performed to check the feasibility of proposed hybrid microgrid followed by different fault current calculations at every location for different modes of operation for a hybrid microgrid. The procedure of DEA-based optimisation process for the hybrid microgrid is as follows:

- Set utility grid and DG MVA ratings and system impedances depending on location and load.
- Check load flow for all the possible modes of operation for the hybrid microgrid.
- Calculate fault current q component at all fault locations for different fault during all possible modes of the hybrid microgrid.
- Input: Maximum (2.5) and minimum (0.5) limits of PSM with step size 0.05 and maximum (2.5) and minimum (0.5) of TDS with step size 0.01 with a discrimination time of 120 ms along with the different CTR at different buses is given as input. Also, the input parameters for the DEA are considered as generation number and population size. A maximum generation number of 1000 with a population size of 45 is set.
- Initialisation: PSM and TDS are initialised from lower bounds as shown in constraint equalities and are initialised for all the 14 relays in the proposed hybrid microgrid.
- Data recreation: Recreation of data is possible by mode of operation of the hybrid microgrid as shown in Table 1. Dynamic nature of hybrid microgrid modes of operation not only changes the fault current levels but also alters the primary and backup relay pairs to be activated for given fault locations. Phase and earth faults have different levels of fault current. So it is very much important to get primary-backup relay pairs for different short-circuit currents for each 4th phase and earth faults for every mode of operation in a hybrid microgrid.
- Fitness function calculation: The minimum values of objective function given in relation is calculated. For any constraint’s violation, the penalty is added from error values obtained. Obtained setting values must satisfy all the constraints.
- Update vector: As per the mutation strategy of DEA, the update vector is generated for PSM and TDS settings of every relay of each ith fault location.
- Stopping criteria: Termination of DEA happens for the minimum threshold value of penalty function (0 or 10\(^{-5}\)).

The input parameters for the DEA are considered as generation number and population size. A maximum generation number of 1000 with a population size of 45 is set. The number of variables as three with penalty weight of 40 is considered on constraint violation. Optimisation strategy ‘DE/best/2’ is used [29]. Crossover factor is initially set for 0.5 for fast convergence. For mutation, three distinct vectors are considered. The mutation rate is set at 3%.

### RESULTS AND DISCUSSION

The hybrid microgrid single line diagram is shown in Figure 2 in which 14 relays are installed as \(R_1-R_{14}\) and fuses \(F_1-F_{14}\) for proper protection and backup by an equal number of fuses. Table 1 shows all possible modes of operation for hybrid microgrid where status 1 shows utility, wind, and PV DGs, which are active in that mode of operation, whereas 0 means inactive. The phase and earth faults are simulated for proper hybrid microgrid PC. Proposed relay settings for PSM and TDS for different modes of operation are shown in Tables 2–7 to achieve adaptive optimum PC. Table 8 shows different types of fuses used to assist primary and backup relay for fast adaptive PC. Tables 9–20 show OT and coordination time (CT) of primary (P) and backup (B) relay with assistance from fuses in different modes of operation for three-phase and earth faults at different locations. Table 21 shows steady-state, minimum pickup current and fault current values of q component of fault current for different modes of hybrid microgrid operation for different faults at different locations. Out of the given set of relays, primary relays installed must operate first, and if primary fails, the backup relay must operate within a specified CTI as discussed in Section 2.2. In the proposed scheme, if in any case, primary

| Relays | PSM | TDS |
|--------|-----|-----|
| 1      | 2.25| 0.25|
| 2      | 2.25| 0.25|
| 3      | 1.75| 0.20|
| 4      | 1.75| 0.20|
| 5      | 1.75| 0.20|
| 6      | 1.75| 0.20|

| Relays | PSM | TDS |
|--------|-----|-----|
| 7      | 2.5 | 0.15|
| 8      | 2.5 | 0.15|
| 9      | 1.85| 0.12|
| 10     | 1.85| 0.12|
| 11     | 1.85| 0.12|
| 12     | 1.85| 0.12|

| Relays | PSM | TDS |
|--------|-----|-----|
| 7      | 2.5 | 0.15|
| 8      | 2.5 | 0.15|
| 9      | 1.85| 0.12|
| 10     | 1.85| 0.12|
| 11     | 1.85| 0.12|
| 12     | 1.85| 0.12|
TABLE 4  TDS and PSM for mode 3

| Relays | PSM | TDS |
|--------|-----|-----|
| 7      | 2.45| 0.12|
| 8      | 2.45| 0.12|
| 9      | 1.95| 0.18|
| 10     | 1.95| 0.18|
| 11     | 1.95| 0.18|
| 12     | 1.95| 0.18|
| 13     | 2.5 | 0.10|
| 14     | 2.5 | 0.10|

TABLE 5  TDS and PSM for mode 2

| Relays | PSM | TDS |
|--------|-----|-----|
| 1      | 2.15| 0.2 |
| 2      | 2.15| 0.2 |
| 3      | 1.9 | 0.18|
| 4      | 1.9 | 0.18|
| 5      | 1.9 | 0.18|
| 6      | 1.9 | 0.18|
| 13     | 2.5 | 0.14|
| 14     | 2.5 | 0.14|

and backup relaying fails, the fuses will coordinate with the given backup relay and blow after CTI of backup relay as per fuse constraints discussed in Section 2.2. Minimum CTI for backup relay is set as 120 ms, for primary fuse is 50 ms, and for backup fuse, it is 100 ms.

For the validation of the proposed adaptive PCO scheme, hybrid microgrid operation modes are discussed as optimal adaptive settings of PSM and TDS for different modes of operations with phase and earth faults. PSM decides the severity of fault by giving the magnitude of fault current over reference current value, and TDS decides delay given to relay operation. For only PV feeding the load buses while buses 1 and 4 are not in operation, mode 5 is set as shown in Figure 1. If only wind DGs feed the load buses, then buses 1 and 3 are not in operation, and the microgrid is operated in mode 6 as shown in Figure 1. When PV and Wind DGs feed the loads, only bus 1 is not in operation, and the system operates in mode 4. When the PV DG and grid feed the loads, only bus 4 is not in operation, and the microgrid is set in mode 2. When wind DG and grid feed the loads, only bus 3 is not in operation, and the microgrid can be set in mode 3 operation.

When PV DG, wind DG and grid feed the loads and all buses are in operation, the system is set in mode 1. Tables 2 and 3 show

TABLE 6  TDS and PSM for mode 4

| Relays | PSM | TDS |
|--------|-----|-----|
| 1      | 2.25| 0.2 |
| 2      | 2.25| 0.2 |
| 3      | 1.75| 0.15|
| 4      | 1.75| 0.15|
| 5      | 1.75| 0.15|
| 6      | 1.75| 0.15|
| 7      | 2.35| 0.1 |
| 8      | 2.35| 0.1 |
| 9      | 1.8 | 0.15|
| 10     | 1.8 | 0.15|
| 11     | 1.8 | 0.15|
| 12     | 1.8 | 0.15|

TABLE 7  TDS and PSM for mode 1

| Relays | PSM | TDS |
|--------|-----|-----|
| 1      | 2.3 | 0.15|
| 2      | 2.3 | 0.15|
| 3      | 1.7 | 0.2 |
| 4      | 1.7 | 0.2 |
| 5      | 1.7 | 0.2 |
| 6      | 1.7 | 0.2 |
| 7      | 2.45| 0.10|
| 8      | 2.45| 0.10|
| 9      | 1.85| 0.15|
| 10     | 1.85| 0.15|
| 11     | 1.85| 0.15|
| 12     | 1.85| 0.15|
| 13     | 2.5 | 0.05|
| 14     | 2.5 | 0.05|

TABLE 8  Fuses used as backup for backup relay in hybrid microgrid

| Node | Fuse type | Rating (MVA) |
|------|-----------|--------------|
| 1    | 50T       | 1 PV DG      |
| 2    | 50T       | 1 PV DG      |
| 3    | 15T       | 0.3 load     |
| 4    | 15T       | 0.3 load     |
| 5    | 15T       | 0.3 load     |
| 6    | 15T       | 0.3 load     |
| 7    | 50T       | 0.3 load     |
| 8    | 50T       | 0.3 load     |
| 9    | 25T       | 0.4 load     |
| 10   | 25T       | 0.4 load     |
| 11   | 25T       | 0.4 load     |
| 12   | 25T       | 0.4 load     |
| 13   | 50T       | 1.0 grid     |
| 14   | 50T       | 1.0 grid     |
The proposed adaptive PSM and TDS settings for phase and earth faults detected using q components of fault current for hybrid microgrid for mode 5 (PV DG feeding load in islanded mode) and mode 6 (wind DG feeding load in islanded mode). As islanded wind DG has more current share as compared to islanded PV DG, so the severity of fault will be more for wind DG in comparison to PV DG. Tables 2 and 3 show this fault severity by setting PSM higher for wind DG as compared to PV DG by the proposed adaptive PCO scheme. In a similar manner, depending on the severity of the fault, TDS is low for wind DG connection in comparison to PV DG connection.

Tables 4 and 5 show the proposed adaptive PSM and TDS settings for phase and earth faults detected using q components of fault current. For a hybrid microgrid in mode 3, wind DG and utility grid feeding load in wind-grid mode and mode 2 (PV DG and utility grid feeding load in PV-grid mode) are in operation as shown in Figure 1. As wind DG and utility grid (mode 3) have more current share as compared to PV DG and utility grid (mode 2), so the severity of fault will be more for mode 3 in comparison to mode 2. Tables 4 and 5 show this fault severity by setting PSM higher for wind DG and utility grid as compared to PV DG and utility grid.

### Table 9
Operation time (OT) and coordination time (CT) of primary (P) and backup (B) relay with fuses in mode 5 for the three-phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R6P    | 0.157 | 0               | 15T       | 0.392          |
| R3B    | 0.336 | 0.179           | 15T       | 0.501          |
| R1P    | 0.197 | 0               | 50T       | 0.413          |
| R2B    | 0.356 | 0.159           | 50T       | 0.533          |

### Table 10
OT and CT of primary (P) and backup (B) relay with fuses in mode 5 for earth fault s (LG-LLG)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R6P    | 0.197 | 0               | 15T       | 0.448          |
| R3B    | 0.393 | 0.196           | 15T       | 0.556          |
| R1P    | 0.208 | 0               | 50T       | 0.430          |
| R2B    | 0.367 | 0.159           | 50T       | 0.543          |

### Table 11
OT and CT of primary (P) and backup (B) relay with fuses in mode 6 for three-phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R12P   | 0.174 | 0               | 25T       | 0.441          |
| R9B    | 0.379 | 0.205           | 25T       | 0.553          |
| R8P    | 0.153 | 0               | 50T       | 0.382          |
| R7B    | 0.321 | 0.168           | 50T       | 0.494          |

### Table 12
OT and CT of primary (P) and backup (B) relay with fuses in mode 6 for earth faults (LG-LLG)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R12P   | 0.205 | 0               | 25T       | 0.463          |
| R9B    | 0.407 | 0.202           | 25T       | 0.525          |
| R8P    | 0.160 | 0               | 50T       | 0.378          |
| R7B    | 0.321 | 0.160           | 50T       | 0.438          |

### Table 13
OT and CT of primary (P) and backup (B) relay with fuses in mode 2 for three-phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R6P    | 0.171 | 0               | 15T       | 0.356          |
| R3B    | 0.299 | 0.128           | 15T       | 0.418          |
| R1P    | 0.164 | 0               | 50T       | 0.441          |
| R2B    | 0.383 | 0.159           | 50T       | 0.512          |
| R14P   | 0.157 | 0               | 50T       | 0.372          |
| R13B   | 0.314 | 0.157           | 50T       | 0.435          |

### Table 14
OT and CT of primary (P) and backup (B) relay with fuses in mode 2 for earth faults (LG-LLG)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R6P    | 0.143 | 0               | 15T       | 0.356          |
| R3B    | 0.295 | 0.152           | 15T       | 0.420          |
| R1P    | 0.167 | 0               | 50T       | 0.443          |
| R2B    | 0.386 | 0.159           | 50T       | 0.507          |
| R14P   | 0.145 | 0               | 50T       | 0.347          |
| R13B   | 0.290 | 0.145           | 50T       | 0.415          |

### Table 15
OT and CT of primary (P) and backup (B) relay with fuses in mode 3 for three-phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R12P   | 0.165 | 0               | 25T       | 0.352          |
| R9B    | 0.295 | 0.130           | 25T       | 0.421          |
| R8P    | 0.179 | 0               | 50T       | 0.359          |
| R7B    | 0.300 | 0.121           | 50T       | 0.421          |
| R14P   | 0.146 | 0               | 50T       | 0.348          |
| R13B   | 0.292 | 0.146           | 50T       | 0.411          |

### Table 16
OT and CT of primary (P) and backup (B) relay with fuses in mode 3 for earth faults (LG-LLG)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|----------------|
| R12P   | 0.157 | 0               | 25T       | 0.338          |
| R9B    | 0.281 | 0.124           | 25T       | 0.402          |
| R8P    | 0.167 | 0               | 50T       | 0.344          |
| R7B    | 0.288 | 0.122           | 50T       | 0.417          |
| R14P   | 0.150 | 0               | 50T       | 0.359          |
| R13B   | 0.300 | 0.150           | 50T       | 0.421          |
TABLE 17  OT and CT of primary (P) and backup (B) relay with fuses in mode 4 for three phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|---------------|
| R6P    | 0.140 | 0               | 15T       | 0.341         |
| R3B    | 0.284 | 0.144           | 15T       | 0.406         |
| R1P    | 0.194 | 0               | 50T       | 0.401         |
| R2B    | 0.353 | 0.159           | 50T       | 0.433         |
| R12P   | 0.167 | 0               | 25T       | 0.421         |
| R9B    | 0.291 | 0.124           | 25T       | 0.421         |
| R8P    | 0.162 | 0               | 50T       | 0.339         |
| R7B    | 0.282 | 0.121           | 50T       | 0.403         |

TABLE 18  OT and CT of primary (P) and backup (B) relay with fuses in mode 4 for earth faults (LG-LLG)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|---------------|
| R6P    | 0.142 | 0               | 15T       | 0.353         |
| R3B    | 0.293 | 0.151           | 15T       | 0.417         |
| R1P    | 0.197 | 0               | 50T       | 0.417         |
| R2B    | 0.356 | 0.159           | 50T       | 0.483         |
| R12P   | 0.173 | 0               | 25T       | 0.395         |
| R9B    | 0.300 | 0.128           | 25T       | 0.423         |
| R8P    | 0.142 | 0               | 50T       | 0.319         |
| R7B    | 0.263 | 0.121           | 50T       | 0.385         |

Fuses are used in the proposed hybrid microgrid that is present near relays and acting as backup protection for backup relays. Table 8 shows the fuses that are used in the proposed hybrid microgrid. Table 9 shows the OT and CT of primary relay 6 (R6P) and backup relay 3 (R3B) with backup fuses for three-phase faults (LLL) at node 3 during microgrid operation in mode 5 as shown in Figure 1. R6P has OT of 0.157 s with zero CT as it is a primary relay. R3B has OT of 0.197 s with 0.196 s delay for CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R6P operates only if R3B fails. The primary backup fuse must not blow till 0.336 s and operate with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to operate. The secondary backup fuse must not blow till 0.392 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.556 s. Table 9 shows three-phase faults at node 1 in mode 5 as shown in Figure 1. R6P has OT of 0.197 s with zero CT as it is a primary relay. R3B has OT of 0.393 s with 0.196 s delay for CT.

TABLE 19  OT and CT of primary (P) and backup (B) relay with fuses in mode 1 for the three-phase fault (LLL)

| Relays | OT(s) | CT of relays(s) | Fuse type | CT of fuses(s) |
|--------|-------|-----------------|-----------|---------------|
| R6P    | 0.147 | 0               | 15T       | 0.321         |
| R3B    | 0.267 | 0.121           | 15T       | 0.382         |
| R1P    | 0.159 | 0               | 50T       | 0.373         |
| R2B    | 0.318 | 0.159           | 50T       | 0.434         |
| R12P   | 0.142 | 0               | 25T       | 0.315         |
| R9B    | 0.262 | 0.121           | 25T       | 0.371         |
| R8P    | 0.141 | 0               | 50T       | 0.344         |
| R7B    | 0.288 | 0.147           | 50T       | 0.395         |
| R14P   | 0.154 | 0               | 50T       | 0.341         |
| R13B   | 0.283 | 0.129           | 50T       | 0.393         |

1) have more current share as compared to PV DG and wind DG (mode 4), so the severity of fault will be more for mode 1 in comparison to mode 4. Tables 6 and 7 show this fault severity by setting PSM higher for wind DG, PV DG and grid as compared to wind DG and PV DG together. In a similar manner, depending on the severity of the fault, TDS is low for wind DG, PV DG and grid connection in comparison to wind DG and PV DG connection.

Tables 6 and 7 show the proposed adaptive PSM and TDS settings for phase and earth faults found using q components of fault current for a hybrid microgrid in mode 4, as shown in Figure 1, PV and wind DGs feeding load in PV-wind hybrid mode and mode 1 PV, wind DGs and utility grid feeding load in hybrid-grid mode. As wind DG, PV DG and utility grid (mode 1) have more current share as compared to PV DG and wind DG (mode 4), so the severity of fault will be more for mode 1 in comparison to mode 4. Tables 6 and 7 show this fault severity by setting PSM higher for wind DG, PV DG and grid as compared to wind DG and PV DG together. In a similar manner, depending on the severity of the fault, TDS is low for wind DG, PV DG and grid connection in comparison to wind DG and PV DG connection.

Table 10 shows the OT and CT time of primary relay 6 (R6P) and backup relay 3 (R3B) with backup fuses for three-phase faults (LLL) at node 3 during microgrid operation in mode 5 as shown in Figure 1. R6P has OT of 0.157 s with zero CT as it is a primary relay. R3B has OT of 0.336 s with 0.179 s delay for CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R6P operates only if R3B fails. The primary backup fuse must not blow till 0.336 s and operate with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to operate. The secondary backup fuse must not blow till 0.392 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.556 s. Table 9 shows three-phase faults at node 1 in mode 5 as shown in Figure 1. In a similar manner, the OT and CT of primary relay 1 (R1P) and backup relay 2 (R2B) are obtained with backup fuses using the proposed only q component-based adaptive PCO scheme.

Table 10 shows the OT and CT time of primary relay 6 (R6P) and backup relay 3 (R3B) with backup fuses for earth faults (LG and LLG) during mode 5 at node 3 shown in Figure 1. Also, in Table 10, it is shown that during earth faults at node 1, in mode 5 as shown in Figure 1, the OT and CT of primary relay 1 (R1P) and backup relay 2 (R2B) are available with backup fuses as shown in Figure 1. R6P has OT of 0.197 s with zero CT as it is a primary relay. R3B has OT of 0.393 s with 0.196 s delay for CT.
### TABLE 21
Steady-state, minimum pickup current and fault current values in quadrature (q)-axis component of fault current for different modes of hybrid microgrid operation for faults at different locations

| Mode, faulted side | Steady state, $I_q$ (A) | $I_{min}^{pickup}$, $I_q$ (A) | $I_q$ for LL fault (A) | $I_q$ and $I_0$ for LLG fault (A) | $I_q$ for LLI fault (A) |
|--------------------|------------------------|-------------------------------|------------------------|----------------------------------|-------------------------|
| PVI, PV            | 600                    | 750                           | 770                    | 820, 40                          | 840                     |
| W1, W              | 780                    | 975                           | 3500                   | 3550, 130                        | 3700                    |
| PVG, PV            | 600                    | 750                           | 790                    | 860, 100                         | 900                     |
| PVG, G             | 30                     | 37.5                          | 130                    | 170, 50                          | 200                     |
| WG, W              | 780                    | 975                           | 2700                   | 4500, 150                        | 5000                    |
| WG, G              | 30                     | 37.5                          | 160                    | 220, 80                          | 235                     |
| WPV, PV            | 600                    | 750                           | 780                    | 800, 160                         | 820                     |
| WPV, W             | 780                    | 975                           | 2600                   | 4000, 200                        | 4800                    |
| WPVG, PV           | 600                    | 750                           | 880                    | 900, 300                         | 915                     |
| WPVG, W            | 780                    | 975                           | 7500                   | 7800, 350                        | 8300                    |
| WPVG, G            | 30                     | 37.5                          | 230                    | 280, 90                          | 340                     |
| Load1PVside        | 300                    | 375                           | 620-6000               | 710-6300, 50–200                  | 800-7700                |
| Load2PVside        | 300                    | 375                           | 620-6000               | 710-6300, 50–200                  | 800-7700                |
| Load1Wside         | 390                    | 487.5                         | 900-6500               | 930-7000, 50–300                  | 950-8000                |
| Load2Wside         | 390                    | 487.5                         | 900-6500               | 930-7000, 50–300                  | 950-8000                |

CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R6P operates only if R3B fails. The primary backup fuse must not blow until 0.448 s and operate with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to operate. The secondary backup fuse must not blow until 0.448 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.556 s. Three-phase and earth faults are not considered on node 4 in mode 5 as this will also obtain nearly the same values of OTs and CTs for same faults on node 3 (since the load and line parameters are same). Furthermore, there is no role of relays from R7 to R14, as in mode 5, these relays remain out of operation due to the PV DG islanded mode.

Table 11 shows the OT and CT of primary relay 12 (R12P) and backup relay 9 (R9B) at node 9 with three-phase fault and OT and CT of primary relay 8 in mode 6, OT and CT of primary relay 8 (R8P) and backup relay 7 (R7B) with backup fuses for earth faults at node 8 during mode 6 as shown in Figure 1. R12P has OT of 0.205 s with zero CT as it is a primary relay. R9B has OT of 0.407 s with 0.202 s delay for CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R12P must blow only if R9B fails. The primary backup fuse does not operate until 0.463 s and blows with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R9B. The secondary backup fuse that is present near R9B blows only if primary backup fuse fails to operate.

The secondary backup fuse must not blow until 0.463 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.525 s. Three-phase fault and earth fault are not considered on node 10 in mode 5, as this will also obtain nearly the same values of OTs and CTs as for the same faults on node 9 (load and line parameters are the same). Furthermore, there is no role of relays from R1 to R6, R13 and R14, as in mode 6, these relays remain out of operation due to the wind DG islanded mode. From Tables 9 to 12, CT for primary relays in operation is zero. Tables 9 to 12 show that OT and CT of primary and backup relays are different during three-phase fault and earth fault. The q component of fault current differs with a change in nature of DGs feeding the fault, mode of operation of hybrid microgrid and with the type of fault.

Adaptive settings for different relays must be varying in accordance with the obtained optimum relay settings during the...
islanded mode of operation for hybrid microgrid. As shown in Tables 9 to 12, primary and backup relays with backup fuses are working in minimum time with no constraint violation. Tables 13 and 14 show the OTs and CTs of primary and backup relays for LLL and LLG faults at nodes 3, 1, and 14 during mode 2 as shown in Figure 1 of hybrid microgrid operation. R6P has OT of 0.171 s with zero CT as it is a primary relay, R3B has OT of 0.299 s with 0.128 s delay for CT as it is a backup relay. The backup fuses do not operate until backup relays fail to operate. The primary backup fuse that is present near R6P operates only if R3B fails.

The primary backup fuse must not blow till 0.299 s and operates with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to blow. The secondary backup fuse must not blow till 0.356 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.418 s. In a similar manner, the OT and CT of primary relay 1 (R1P), backup relay 2 (R2B), primary relay 14 (R14P) and backup relay 13 (R13B) are obtained for earth faults with backup fuses using the proposed only q component-based adaptive PCO scheme. During mode 2, wind DG and loads of nodes 12 and 11 are disconnected, so no role of relays R7 to R12 exist.

Tables 15 and 16 show the OTs and CTs of primary and backup relays for LLL and LLG faults at nodes 9, 8, and 14 during mode 3 as shown in Figure 1 of hybrid microgrid operation. R12P has OT of 0.165 s with zero CT as it is a primary relay. R9B has OT of 0.295 s with 0.130 s delay for CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R12P operates only if R9B fails. The primary backup fuse must not blow till 0.295 s and operate with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R9B. The secondary backup fuse that is present near R9B operates only if primary backup fuse fails to blow. The secondary backup fuse must not blow till 0.352 s and operate with minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.406 s. In a similar manner, OT of adaptive overcurrent primary relay (R6P) and backup relay (R3B) islanded PV DG side is shown in Figure 4. In a similar manner, the OT and CT of primary relay 1 (R1P), backup relay 2 (R2B), primary relay 12 (R12P), backup relay 9 (R9B), primary relay 8 (R8P) and backup relay 7 (R7B) are obtained for earth faults with backup fuses using the proposed only q component-based adaptive PCO scheme. During mode 3, PV DG and Loads of node 6 and 5 are disconnected, so no role of relays R1 to R6 exist.

It is clear from Tables 13–16 that the OT and CT of primary and backup relays are different during three-phase and earth faults in different operation modes of the hybrid microgrid. Also, the q component of fault current is considered in the minimisation of the main objective function with Tables 13–16 clearly showing different adaptive settings for different modes and faults without any constraint violation. All the primary and backup relays are operating with optimum PC with proper backup given by fuses to backup relays.

Tables 17 and 18 show the OTs and CTs of primary and backup relays for LLL and LLG faults at nodes 3, 1, 8, and 9 during mode 4 as shown in Figure 1 of hybrid microgrid operation. R6P has OT of 0.140 s with zero CT as it is a primary relay. R3B has OT of 0.284 s with 0.144 s delay for CT as it is a backup relay. The backup fuses must not blow until the backup relay fails to operate. The primary backup fuse that is present near R6P blows only if R3B fails. The primary backup fuse does not operate till 0.284 s and operates with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to blow. The secondary backup fuse must not blow till 0.341 s and operate with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.406 s. In a similar manner, the OT and CT of primary relay 1 (R1P), backup relay 2 (R2B), primary relay 12 (R12P), backup relay 9 (R9B), primary relay 8 (R8P) and backup relay 7 (R7B) are obtained for earth faults with backup fuses using the proposed only q component-based adaptive PCO scheme. During mode 4, the utility grid with nodes 13 and 14 is disconnected, so no role of relays R13 to R14 exist.

OT of adaptive overcurrent primary relay (R6P) and backup relay (R3B) islanded PV DG side is shown in Figure 4. In a similar manner, OT of adaptive overcurrent primary relay (R12P) and backup relay (R9B) of islanded wind DG side is shown in Figure 5. Also, the OT of adaptive overcurrent primary relay (R6P) and backup relay (R3B) present at load1 end of PV DG side when wind DG and grid are connected are shown in Figure 6. The figure shows the adaptive nature of same relay R6P and R3B for grid-connected mode considering only q component of fault current. Figure 6 also shows that with an increase in fault current during the grid-connected mode, the operating time for primary and backup relays shifts downwards. So the

![Figure 4](Image)

**FIGURE 4** Primary and backup relay operating characteristics for islanded PV distributed generator (DG) microgrid
FIGURE 5  Primary and backup relay operating characteristics for islanded wind DG microgrid

FIGURE 6  Primary and backup relay operating characteristics for grid-connected PV and wind DG microgrid

OT of adaptive relays changes with the increase or decrease in fault current and with the change in the mode of operation.

Tables 19 and 20 show the OTs and CTs of primary and backup relays for LLL and LLG faults at nodes 3, 1, 8, 9, and 14 during mode 1 of hybrid microgrid operation. During mode 1 as shown in Figure 1, all the nodes are in action, so consecutively all the relays are in operation. In Table 19, R6P has OT of 0.147 s with zero CT as it is a primary relay. R3B has OT of 0.267 s with 0.121 s delay for CT as it is a backup relay. The backup fuses must not blow until backup relays fail to operate. The primary backup fuse that is present near R6P blows only if R3B fails.

The primary backup fuse does not operate till 0.267 s and operates with a minimum delay of 50 ms (as per primary fuse constraint) added to OT of R3B. The secondary backup fuse that is present near R3B operates only if primary backup fuse fails to blow. The secondary backup fuse must not blow till 0.321 s and operates with a minimum delay of 100 ms (as per secondary fuse constraint) added to OT of the primary fuse. CT for backup fuse is 0.382 s. In a similar manner, the OT and CT of primary relay 1 (R1P), backup relay 2 (R2B), primary relay 12 (R12P), backup relay 9 (R9B), primary relay 8 (R8P), backup relay 7 (R7B), primary relay 14 (R14P) and backup relay 13 (R13B) are obtained for earth faults with backup fuses faults at nodes 4 and 10 are not considered as they have the same load and line parameters as that of nodes 3 and 9. If faults are simulated at nodes 4 and 10, the optimum values obtained for OTs and CTs for relays R4-R5 and relays R10-R11 are going to be nearly the same as relays R6-R3 and relays R12-R9.

Table 21 shows steady-state and minimum pickup current values in terms of quadrature-axis component of fault current for different modes of hybrid microgrid operation. Quadrature-axis component share of fault current for PV DG, wind DG, grid and all loads during different modes of operation is also shown in Table 21. For different loads, range of quadrature-axis component of fault current during phase and earth faults for different modes of hybrid microgrid operation is also presented in Table 21. Also, Table 21 helps in understanding the side of the microgrid that will see the fast operation as compared to other parts of the hybrid microgrid. PV1 and WI shows that PV and wind DG are islanded, PVG and WG shows that PV and wind DG are connected to grid, WPV shows that wind and PV DG are operating together, WPVG means wind and PV are operating in grid connected mode. Also, relay and fuse operation on grid side is faster in comparison to wind DG and PV DG sides. Relays on PV DG side are slower as the rate of rise of quadrature-axis current on PV DG-side system is small as compared to wind DG and utility grid (G).

Error versus iteration plot shown in Figure 7 shows that maximum initial error obtained is 0.021, and when minimum error count is reached (0–10−5), iteration stops; in most of the cases, maximum iterations taken are 140. Furthermore, it is also being concluded that the relay and fuse operation on wind DG side is faster in comparison to PV DG side. Direct-axis current components are not considered to reduce the PC dependency on the greater number of variables. Q component of fault current alone provides satisfactory PC settings as concluded from the above results. The proposed methodology considers a smaller number of iterations and generation number as compared to [10]. Also, the q component-based PCO is fast in comparison with [10]. In comparison to [21, 30–33], the proposed scheme is equally effective with the proposed reduced number of variables. The efficiency and accuracy of the relay settings can be examined by observing the primary relay operational time and CTI during faulty conditions. It can be observed that all the primary relays are operating within 1.2 s under phase and earth faults.

Moreover, it reflects the range of CTI for all operational modes of the microgrid. In this study, the CTI range has been considered as 0.120 and 0.15 s (primary fuse CTI 50 ms and
backup fuse CTI 100 ms excluding CTI for backup relay) for relays and fuses, and it can observe that none of the relay operations is violating the CTI constraint. From the operation of primary and backup relays with backup fuses for respective faults in different modes with different DGs at different nodes, it can be observed that all the primary and backup are in coordination with the fuses. All relays and fuses can operate in a coordinated manner within minimum time subjected to all constraints. There is no need for earth fault relays or any of the additional circuitry to measure q0 components as they are already available in interfaced converters. The proposed scheme easily removes the significantly changing fault currents with any fault, any type of DG and location with a single variable for the dynamicity observed because of operating modes of the hybrid microgrid. So the presented adaptive protection scheme provides an efficient and cost-effective solution for protection schemes in ac-dc hybrid microgrids.

Table 22 shows the comparison among existing protection schemes with the proposed scheme. Comparison with existing protection techniques is done in terms of nature of generation (DG can be PV type, wind type, low X/R synchronous generator or any DG of small capacity). The feasibility and effectiveness of the proposed protection scheme have been compared with existing protection schemes for different modes of microgrid operation presented in Table 22. The minimum time of operation for primary relay during the three-phase faults is also considered in this comparison. The efficacy of the proposed protection scheme with reduced number of variables (only q component of fault current) in comparison to dq0 and three-phase (RYB) currents or voltages is also found to be high. The proposed technique is fast with time of operation for the primary relay as 0.145 s using only a single variable that is q component of fault current. It is also equally applicable for different nature of DGs that operate in a grid-connected or islanded mode.

### 5 | CONCLUSION

The design of feasible, reliable, and economical adaptive protection scheme for hybrid microgrids should be made simpler. In this study, a new approach of adaptive PCO based on only q component of fault current for a hybrid microgrid is proposed and validated for three-phase and earth faults. It works efficiently with minimum OT using backup fuses for different nature of DGs, operating modes of hybrid microgrid with the

### Table 22 | Comparison of existing protection technologies for microgrid protection

| Reference | Generation type | Mode of operation | Speed of operation (s) | Variables three-phase/dq0 |
|-----------|-----------------|-------------------|------------------------|--------------------------|
| [6] | PV | Islanded and grid-connected | 0.923 | 3 (RYB) |
| [7] | PV | Islanded and grid-connected | 0.372 | 3 (RYB) |
| [10] | DG | Islanded and grid-connected | 0.3 | 3 (RYB) |
| [11] | DG | Islanded and grid-connected | 0.170 | 3 (RYB) |
| [12] | DG | Islanded and grid-connected | 0.388 | 3 (RYB) |
| [17] | Wind | Islanded and grid-connected | 0.2 | 3 (RYB) |
| [19] | Wind | Islanded and grid-connected | 0.22 | 3 (RYB) |
| [20] | PV | Islanded | 0.112 | 3 (RYB) |
| [21] | Low X/R ratio DG | Islanded and grid-connected | 0.132 | 2 (q0) |
| [24] | PV | Islanded and grid-connected | 0.14 | 3 (RYB) |
| [25] | Wind | Islanded and grid-connected | 0.3 | 3 (RYB) |
| [30] | Wind-PV | Islanded and grid-connected | 0.14 | 2 (q0) |
| [31] | Wind-PV | Islanded | 0.1 | 2 (q0) |
| [32] | DG | Islanded and grid-connected | 0.225 | 3 (RYB) |
| Proposed Scheme | Wind-PV | Islanded and grid-connected | 0.145 | 1 (q) |
minimum number of fault detection variables. Newly defined fuse constraints for optimum PC among relays help in easy and quick removal of fault or isolation of fault, which also reduces CT delay. The proposed scheme reduces the dependability on earth fault relay as q component of fault current is detecting the changes corresponding to earth faults. The proposed adaptive PC is economical, feasible, and reliable under different conditions. The proposed approach is tested on hybrid microgrid feeding agrarian and domestic loads of rural India. In future work, this scheme is to be tested on hybrid microgrid with fuel cells, micro-turbines and diesel generators with low $X/R$ ratio.

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