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Protection scheme for reconfigurable radial distribution networks in presence of distributed generation

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ABSTRACT

In this paper, a new scheme of recloser-fuse coordination for reconfigurable radial distribution networks (RDNs) considering distributed generations (DGs) is introduced. Further, a new graph theory based approach has been developed to obtain all possible topologies in RDNs. Also, a new constraint reduction strategy has been introduced to eliminate a large number of constraints in the formulation because of the consideration of various topologies. To solve the formulated optimum recloser-fuse coordination problem, an analytical interior-point method has been adopted. The developed strategy has been applied to obtain the optimum recloser-fuse settings in the IEEE 33 and 69 bus reconfigurable RDNs in the presence of DGs. The obtained settings have been compared with conventional recloser-fuse settings thereby proving the effectiveness of the presented scheme.

1. Introduction

The most economic and efficient protection scheme of feeders in radial distribution networks (RDNs) is achieved by means of appropriate coordination of recloser and fuses [1]. The recloser is often placed near the substation and the fuses are placed at the laterals which are downstream of the recloser. The proper coordination among recloser and downstream fuses is one of the inherent requirement for secured operation of the network. The poor protection coordination may cause a sizeable number of consumers to suffer unnecessary outages in case of a fault. Mostly, the recloser has at least one fast mode and one slow mode of operation while the fuses have only one mode of operation. For a temporary fault in any feeder, the fuse concerned does not melt as the fast operation of the recloser allows the temporary fault to self-clear. Most of the temporary faults get cleared with fast mode operation of the recloser. On the other hand, for a permanent fault in any feeder, the fuse concerned must melt first so that the final delayed trip operation of the recloser is avoided. This strategy prevents the unnecessary interruption of the loads between the fuse and the recloser for permanent faults [2]. The recloser-fuse protection coordination scheme works effectively in RDNs where the flow of currents is unidirectional during normal and faulted conditions. However, with the integration of distributed generations (DGs) to different feeders in RDNs, the unidirectional flow of currents no longer exists during faults [3]. Also, reconfiguration ability of modern RDNs to achieve minimum loss, high reliability and better voltage profile, can change the direction of flow of currents in the feeders during an electrical fault [4]. Therefore, there is always possibility of miscoordination (violation of operating sequence) in the operation of recloser and fuses during faults in the presence of DGs and reconfiguration of the network.

For protection of RDNs, recloser-fuse coordination has been widely studied in the literature without DG [5–7]. In such systems, proper coordination can be guaranteed without any miscoordination as the flow of currents remains unidirectional even during the fault. However, the proper protection coordination using recloser and fuses in RDNs in the presence of DGs is a very difficult task and hard to gets without any miscoordination [8]. In [9], a scheme to disconnect DG during faults has been discussed to prevent cases of miscoordination. Also, an optimal strategy has been introduced in [10] to disconnect DGs during faults. Disconnecting DGs during fault to ensure proper coordination is not a good option because it may lead to instability issue as mentioned in the recent IEEE Standard [11]. To prevent miscoordination of recloser-fuse protection schemes, fault current limiters have been considered by minimising the impact of DG during faults [12]. Subsequently, adaptive variation of settings of recloser is presented to handle high penetration of DGs in RDNs in [13–15]. The major requirement for such protection schemes is communication enabled remotely controlled reclosers and circuit breakers [16]. Adaptive variation of settings of reclosers reduces the cases of miscoordination significantly as compared to those with

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Nomenclature

i	Network topology; $i \in \{1,2,\ldots,NC\}$.
j	Nodes of network; $j \in \{1,2,\ldots,m\}$.
k	Fuses present in network; $k \in \{1,2,\ldots,NF\}$.
NC	Number of configurations of the system.
NF	Number of fuses in the system.
NF_j	Number of fuses in fault path when fault is at j^{th} node.
TNR	Indicator of a radial topology.
TN	Total number of radial topologies.
M	Number of branches or feeder section.
m	Number of nodes.
N	Number of buses.
T	Number of tie-switches.
U	Total number feeder section and tie-switches.
$MFCTI$	Minimum fuse coordination time interval
$MRCTI$	Minimum recloser coordination time interval.
OF	Objective function.
OLF	Overloading factor.
PCS	Pickup current setting of recloser.
TDS	Time dial setting of recloser.
TDS_{fm}	TDS value for recloser fast mode of operation.
$TDS_{\max}$	Upper limit on time dial setting.
$TDS_{\min}$	Lower limit on time dial setting.
TDS_{sm}	TDS value for recloser slow mode of operation.
A, B, p	Characteristics parameters of recloser.
a	Fuse constant (slop parameter).
a_k	Fuse constant a for fuse k.
$a_{\max}$	Upper limit on fuse constant a.
$a_{\min}$	Lower limit on fuse constant a.
b	Fuse constant (intercept parameter).
b_k	Fuse constant b for fuse k.
$b_{\max}$	Upper limit on fuse constant b.
$b_{\min}$	Lower limit on fuse constant b.
I_{FF}	Magnitude of fault current through fuse.
I_{FR}	Magnitude of fault current through recloser.
I_{Lmax}	Magnitude of maximum load current.
I_{LmaxA}	$max(I_{Lmax,1}, I_{Lmax,2}, \cdots, I_{Lmax,NC})$; where $I_{Lmax,1}$ is the maximum load current through recloser in $1st$ configuration.
$I_{FF,ijk}$	Magnitude of current through fuse k when fault is at j^{th} node in i^{th} configuration.
$I_{FR,ij}$	Magnitude of current through recloser when fault is at j^{th} node in i^{th} configuration.
t_F	Operating time of fuse.
t_R	Operating time of recloser.
$t_{F,ijk}$	Operating time of fuse k when fault is at j^{th} node in i^{th} configuration.
$t_{R,fm,ij}$	Operating time of recloser in fast mode when fault is at j^{th} node in i^{th} configuration.
$t_{R,sm,ij}$	Operating time of recloser in slow mode when fault is at j^{th} node in i^{th} configuration.
$\mathbf{A}$	Row reduced incidence matrix.
$\mathbf{A}_{inc}$	Incidence matrix.
$\mathbf{B}$	Subset of matrix $\mathbf{A}$ of size $(N-1)\times M$.
$\mathbf{MT}$	Memory matrix of size $TN \times U$.

non-adaptive protection schemes [17]. It is clear from these studies that achieving appropriate coordination with a fixed characteristics of recloser and fuses is not possible under various operating conditions of DGs and therefore, recloser settings need to be modified adaptively. In these studies, the impact of network reconfiguration on the protection schemes has not been considered explicitly.

A novel optimisation based recloser and fuse protection scheme has been proposed in [18], which can address most of the above mentioned problems efficiently. However, the presented scheme is only applicable for fixed network topology and DG locations. The change in network topology adversely affects the recloser-fuse coordination and may compromise the system operation. In [19], feeder reconfiguration considering protective device (recloser and fuses) coordination has been discussed. In order to ensure that the protective devices remain properly coordinated during feeder reconfiguration, the locations of the fuses in the distribution system under study are determined by using a heuristic algorithm. A set of switchable regions within which switch operations are allowed for feeder reconfiguration has been identified. Once the locations of the switches and the switchable regions are determined, the feeders can be reconfigured during real-time distribution system operation with all protective devices properly coordinated by changing the open/closed status of the switches in the switchable regions. However, this study is limited to small or medium size reconfigurable RDNs. In [20], similar studies have been performed to obtain reconfiguration of RDNs without affecting recloser-fuse coordination. In this study, genetic algorithm has been used to obtain new configuration of the system (for achieving minimum active power loss and voltage deviation) while maintaining proper coordination among the protective devices. In both the above two studies, main focus was to obtain optimum configuration of the system without affecting recloser-fuse coordination adversely. Also, the impact of DG penetrations has not been considered in these works. In [21], a new protection scheme involving recloser and fuses has been discussed by utilizing smart hardware sensors, redundant communication infrastructure, standard communication protocols and flexible multi-functional software algorithms. The proposed approach has also considered change in network topologies as well as varying DG penetration level. However, because of the presence of several hardware and software elements, this scheme is complex and costly.

To address the above mentioned issues, this paper presents a new optimisation based coordination scheme of reclosers and fuses for reconfigurable RDNs in the presence of DGs. A new graph theory based approach has been developed to obtain all possible configurations of any radial network. Also, an efficient constraint reduction strategy has been introduced to reduce the number of effective constraints in the formulated optimization problem. The developed formulation has been solved using an interior point method (IPM) based algorithm. The proposed scheme has been validated on the IEEE 33 and 69-bus reconfigurable RDNs under three different scenarios: i) the system has no DG, ii) the system has a single DG and iii) the system has multiple DGs. Also, the results of the proposed optimum recloser-fuse settings have been compared with those of conventional recloser-fuse settings. The presented protection scheme can be used in distribution automation system to ensure secure and efficient operation of the distribution networks.

The remainder of this paper is as follows. Conventional recloser-fuse coordination approach and the issues of miscoordination is briefly discussed in Section 2. The proposed formulation of recloser-fuse coordination is discussed in Section 3. The procedure to obtain all possible configurations is explained in Section 4. The proposed constraint reduction strategy is described in Section 5. The procedure for solving the formulated problem is described in Section 6 while results and discussion are given under the section "case studies" (Section 7). Finally, the conclusions are presented in Section 8.

2. Conventional recloser-fuse coordination and miscoordination issues

The conventional recloser-fuse coordination schemes work adequately in RDNs [22]. It has been observed that the flow of current is unidirectional in such systems. During both normal operating conditions, the direction of flow of the current is from the sub-station to the load points and during the faulted conditions, the flow of current is also from the sub-station to the fault point. The unidirectional flow of currents allow the conventional recloser-fuse coordination scheme to provide proper protection to RDNs. Mathematically, the operating time of recloser is modelled to follow extremely inverse time current characteristics (TCC) curve whereas the operating time of fuse is modelled to follow log-log TCC curve [22].

The operating time of a recloser is expressed as following [22];

$$t_R = TDS \times \left[\frac{A}{(I_{FR}/PCS)^p - 1} + B\right] \quad (1)$$

where PCS is defined as following;

$$PCS = OLF \times I_{Lmax} \quad (2)$$

It is to be noted that a recloser has at least one fast and one slow operating characteristic. Commonly, these two TCC curves of the reclosers are obtained by using two different values of TDS parameter of the recloser.

The TCC curve of a fuse is expressed as a straight line on log-log graph as follows [22];

$$log(t_F) = a \times \log(I_{FF}) + b \quad (3)$$

The operating time of a fuse can be obtained using Eq. (3) as follows;

$$t_F = exp(a \times \log(I_{FF}) + b) \quad (4)$$

For obtaining proper coordination using reclosers and fuses, recloser-fuse, fuse-recloser, fuse-fuse and recloser-recloser coordination need to be achieved through their TCC curves for all possible fault types and locations.

2.1. Convention scheme for recloser and fuse coordination

The philosophy of conventional recloser-fuse coordination scheme is based on fuse-save approach. In this protection philosophy, characteristics of all downstream fuses are kept within the fast and slow operating modes of the recloser placed at the substation. For this, recloser settings (TDS and PCS) are fixed based on the maximum load and fault currents. Subsequently, using time-grading approach, the operating times of downstream fuses are calculated [22]. After that, fuse constants (*a* and *b* parameters) of all the fuses are obtained with the known values of the maximum value of fault currents and the operating times of the fuses. This scheme can be described using the following steps.

1. Fix *PCS* parameter of the recloser.
2. Select TDS values of fast and slow mode of recloser.
3. Calculate operating times of fuses placed in various feeders.
4. Calculate fuse constants (*a* and *b*).

More details for obtaining recloser and fuse parameters are discussed in [22,23].

2.2. Miscoordination issues with convention recloser and fuse coordination scheme

The conventional recloser-fuse coordination works well as long as the flow of current remains unidirectional. However, the integration of DGs and reconfiguration of feeders in RDNs disturb the unidirectional flow of currents during faults. Thus, several cases of miscoordination are observed with recloser-fuse coordination.

2.2.1. Miscoordination because of the presence of DGs

The presence of a DG in any feeder of RDN completely alters the flow of currents through fuses during faults. Additionally, the magnitude of fault current passing through the recloser placed at the sub-station also gets changed. In some cases, the fault currents flowing through fuses become more than that flowing through the recloser, while in some other cases, the direction of the flow of current through some fuses gets reversed due to the presence of DG in the fault path [5,13,14,17,22]. Under these circumstances, it is difficult to provide appropriate protection using the convention recloser-fuse coordination scheme [13,15]. Additionally, the presence of multiple DGs into the network makes the coordination of reclosers and fuses very complex. Also, synchronous machine based DGs contribute more to the fault and are more prone to cause miscoordination.

2.2.2. Miscoordination because of the change in topology

In order to obtain minimum active power loss, better voltage profile and reliable operation, reconfiguration of distribution system is carried out regularly. However, it is quite difficult to maintain the protection coordination in reconfigurable networks as the directions of current through the feeder sections change with the change in configuration.

In order to obtain proper coordination in the presence of DGs in reconfigurable RDNs, a new optimum coordination approach of recloser and fuses is developed in the next section. Additionally, synchronous generator based DGs have been considered as these are likely to cause more miscoordination because of the higher values of fault currents contributed by them.

3. Proposed scheme for recloser and fuse coordination

With the conventional recloser-fuse coordination scheme the operating times of all downstream fuses must be within the operating times of the fast and slow mode operation of the recloser for any permanent fault within their protection zone. Additionally, a proper sequence of operation among various protective devices present in the fault path must be maintained. For this, a recloser in its fast mode of operation must disconnect power supply to the fault and not allow the nearest fuse in fault path to self-blow (it is called fuse-save strategy). After a few cycles, the recloser reconnects the network to restore power supply. By this strategy, most of the temporary faults get cleared. For a permanent fault, the nearest fuse to the fault location in the faulted path must blow to limit the fault within the faulted zone. However, if the nearest fuse fails to clear the fault then the next upstream fuse must operate. If all the fuses fail to isolate the fault then the recloser in its slow mode disconnects the power supply to the entire network. Subsequently, additional operation is required to restore the power supply. The recloser-fuse coordination problem can be formulated as an optimization problem where objective function (OF) is minimization of the sum of operating times of reclosers and fuses while maintaining the proper operating sequences of the reclosers and fuses for all possible operating sequences as discussed in [18].

In this paper, all possible network topologies are considered in the problem formulation. Therefore, the proposed recloser-fuse protection coordination scheme considering multiple network topologies need to be reformulated. The objective function (OF) of this optimization problem is minimization of the sum of operating times of the recloser (in their fast and slow modes of operations) and the fuses under all network configurations. The constraints of this formulation must ensure that the correct operating sequence of recloser and fuses with a minimum time gap between them is maintained in all feasible configurations of the system. This optimization problem can be expressed as follows;

$$OF = \min \sum_{i=1}^{NC} \sum_{j=1}^{m} \left(t_{R,fm,ij} + t_{R,sm,ij} + \sum_{k=1}^{NF_j} t_{F,ijk} \right) \quad (5)$$

Subject to

$$t_{F,ijk} - t_{R,fm,ij} > MRCTI/2 \quad (6)$$

$$t_{F,ij(k+1)} - t_{F,ijk} > MFCTI \quad (7)$$

$$t_{R,sm,ij} - t_{F,ijk} > MRCTI/2 \quad (8)$$

$$t_{R,sm,ij} - t_{R,fm,ij} > MRCTI \quad (9)$$

$$TDS_{min} \leq TDS_{fm} \leq TDS_{max} \quad (10)$$

$$TDS_{min} \leq TDS_{sm} \leq TDS_{max} \quad (11)$$

$$a_{min} \leq a_k \leq a_{max} \quad (12)$$

$$b_{min} \leq b_k \leq b_{max} \quad (13)$$

where

$$t_{R,fm,ij} = TDS_{fm} \times \left[\frac{A}{(I_{FR,ij}/PCS)^p - 1} + B \right] \quad (14)$$

$$t_{R,sm,ij} = TDS_{sm} \times \left[\frac{A}{(I_{FR,ij}/PCS)^p - 1} + B \right] \quad (15)$$

In eqns. (14) and (15), the PCS can be calculated as follows;

$$PCS = OLF \times I_{LmaxA} \quad (16)$$

where $I_{LmaxA} = max(I_{Lmax,1}, I_{Lmax,2}, \cdots, I_{Lmax,NC})$.

The operating times of fuses used in Eq. (5) are defined as follows;

$$t_{F,ijk} = exp\left(a_k \times \log(I_{FF,ijk}) + b_k\right) \quad (17)$$

The final solution gives the optimum values of TDSs (TDS_{fm} and TDS_{sm}) for the recloser and fuse constants a and b for the fuses (a_k and b_k for $k = 1, 2, \ldots, NF$). To determine all possible radial configurations of a distribution system, the procedure described in the next section has been adopted.

4. Determination of all possible radial configurations of a distribution system

Consider a distribution system which has N buses, M feeder sections and T tie-switches. It is to be noted that all the branches are considered to be equipped with sectionalising switches. As the original network is radial, $M = N - 1$. Let U represents the total number of the branches which is the sum of all feeder sections and all tie-switches i.e., $U = M + T$. For determining the total number of configurations of a radial network, initially the incidence matrix of the network is formed [24,25]. Each row of this matrix represents the corresponding node of the graph while each column corresponds to a branch. When a graph has N nodes and U branches, the incidence matrix $[\mathbf{A}_{inc}]$ is a $N \times U$ rectangular matrix whose elements ($a_{i,j}$) are defined as

1. If branch j is incident at node i and is oriented away from the node, $a_{i,j} = 1$.
2. If branch j is incident at node i and is oriented towards node i, $a_{i,j} = -1$.
3. If branch j is not incident at node i, $a_{i,j} = 0$.

Once the incident matrix $\mathbf{A}_{inc}$ of size $N \times U$ is formed using the above procedure, one row is removed to form reduced incident matrix $\mathbf{A}$ of size $(N-1) \times U$. It is to be noted that selection of the row to be removed does not have any effect on further analysis [24]. In this study, the last row has been considered to be removed. The total number of all the possible radial configurations TN is defined as [24];

$$TN = det(\mathbf{AA}^t) \quad (18)$$

In Eq. (18), matrix $\mathbf{A}$ represents the row reduced incidence matrix of size $(N-1) \times U$, t represents transpose operator on the matrix $\mathbf{A}$ and the function $det(\mathbf{X})$ gives determinant of matrix $\mathbf{X}$.

To select a radial configuration from a distribution network of N buses, M feeder sections and T tie-lines, the following procedure is used. Any M columns from the row reduced incidence matrix $\mathbf{A}$ are selected to form another matrix $\mathbf{B}$ of size $(N-1) \times M$. To determine whether matrix $\mathbf{B}$ represents a radial configuration or not, a quantity TNR is calculated as below [24];

$$TNR = det(\mathbf{BB}^t) \quad (19)$$

In Eq. (19), if $TNR = \pm 1$ then matrix $\mathbf{B}$ represents a radial network. Now, to select all the possible configurations of the radial network under study, the following procedure has been adopted. Initially, a matrix **MT** of size $TN \times U$ is initialized with zeros. After that, a binary string **R** of length U with M '1's and T '0's is generated randomly. A binary value '1' denotes that the branch corresponding to this bit position is present in the circuit (i.e. the switch on this feeder is 'ON'). On the other hand, a binary value '0' denotes that the branch corresponding to this bit position is not present in the circuit (i.e. the switch on this feeder is 'OFF'). This binary string is used to form matrix **B** for testing the radiality of the network represented by the string using Eq. (19). If the generated string qualifies the radiality test then its uniqueness is checked with each row of matrix **MT**. If the string does not exist as any row in matrix **MT** then it is included in the matrix in place of a zero row. This three step process (i.e., generation of a binary string, testing of radiality of the network represented by the string and determination of uniqueness of the string) continues till all the zero rows of matrix **MT** get replaced by the generated strings. Finally, matrix **MT** gives the set of binary strings which represents all the possible radial configurations. Fig. 1 gives a detailed flowchart of the procedure to select all possible radial configurations of a given distribution system.

It is to be noted that the proposed approach is generalized, easily programmable and applicable to any network of any size. This approach

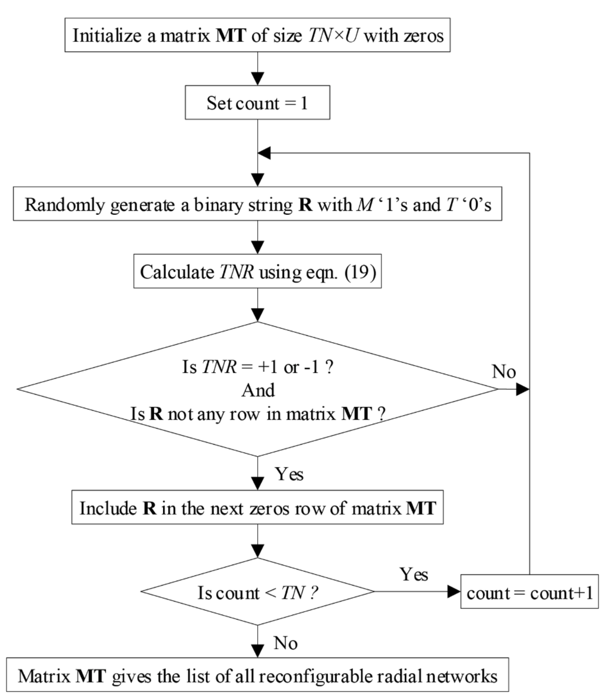

Fig. 1. Flowchart for selection of all the possible radial configurations.

is also quite fast as it is not necessary to check all “ON-OFF” combinations of the network switches. This flowchart has been implemented by developing a software program in MATLAB environment [26] in this work.

5. Constraint reduction strategy in reconfigurable radial networks

The constraint reduction strategy can easily be understood through an example. Fig. 2 shows an example of a typical 4-bus RDN. This system is protected by a recloser at substation and two fuses downstream of the recloser. Fig. 3 shows typical TCC plots of the recloser and two fuses. It is to be noted that, it is essential to maintain proper protection coordination among recloser and fuses at the maximum and minimum operating fault currents. Once the coordination is maintained for these critical fault currents, then for the other fault currents within this range (i.e. between minimum and maximum fault current) proper coordination would be maintained. Further, a minimum gap between the characteristics of recloser slow mode of operation and the nearest fuse curve needs to be maintained.

Now, if the network shown in Fig. 2 is a part of a reconfigurable RDN, then it is possible that the protective devices (R, F1 and F2) can have many sets of values of currents due to faults on any other section and variation in the configuration. However, only two of them (maximum and minimum fault currents) for each protective device of the sequence are important for the purpose of protection coordination. If the coordination is maintained for these two values of fault currents then for the other values of fault currents coordination would be maintained (Fig. 3). So, if there are three protective devices in an operating sequence then there are only six critical values of fault currents for which the protection co-ordination should be maintained. It will guarantee a proper coordination for any value of fault current of that sequence. Also, it is possible that the critical values of fault currents may be the same for the three protective devices in this sequence. Thus, the minimum and maximum number of critical values of fault currents in this example (of only one operating sequence) is two and six, respectively. Thus, each operating sequence can have a minimum of two critical values of fault currents and the maximum number of critical values of fault current is two times the number of protective devices present in that sequence.

6. Solution procedure

The optimum recloser and fuse coordination problem formulated in Section 3 is a non-linear and twice continuously differentiable problem. This property allows IPM to be applied for solving this problem [26]. The proposed optimum recloser-fuse coordination problem is of this kind and thus IPM is very suitable to solve it.

To solve the proposed optimum coordination problem of recloser and fuses, the following approach has been adopted. Initially, reconfiguration analysis as discussed in Section 4 is performed to obtain all feasible network topologies (i.e., for which the load flow analysis is converged within ±10% of bus voltage limits). Subsequently, load flow and short circuit analysis have been performed to calculate the maximum load currents and various fault currents passing through protective devices (recloser and fuses) under all the feasible network topologies. In this study, backward-forward sweep method (BFSM) for steady state load flow analysis and bus impedance matrix (Zbus) based short circuit analysis approach have been adopted [5,27]. The maximum and minimum fault currents passing through various protective devices have been calculated by applying near-end bolted three phase fault and far-end node line-to-line fault, respectively. Subsequently, the maximum and minimum fault currents passing through the protective devices corresponding to all possible operating sequences have been selected by applying constraint reduction strategy as discussed in Section 5 and thereafter, PCS of the recloser is calculated using Eq. (2). Finally, the formulated problem is solved using IPM and optimum settings of the parameters are obtained. The overall procedure can be described by the following steps:

1. Perform reconfiguration analysis and select feasible network topologies.
2. Perform steady-state load flow and short-circuit current calculation for all feasible network topologies.
3. Select the fault currents to be cleared by the recloser and the fuses under possible operating sequences.
4. Set PCS of recloser using Eq. (16).
5. Solve the problem formulated in Section 3 using IPM.
6. Record the optimum values of TDS_{fm}, TDS_{sm}, and (a_k and b_k) $\forall k$.

A detailed flowchart of the adopted procedure to obtain the optimum settings is shown in Fig. 4.

The following points have been considered while solving the proposed optimum recloser and fuses coordination problem [2], [28]:

- Recloser operation: *2 fast + 2 slow*
- Fuse TCCs: *within 2nd fast and 1st slow modes of recloser operation*
- TDSs to be optimized: *2nd fast and 1st slow mode TDS of recloser*
- TDS to be fixed: *1st fast and 2nd slow mode TDS of recloser*
- Recloser TCC parameters: $A = 28.2, B = 0.1217, p = 2$ [22]
- Recloser TDS: $TDS \in [0.5,\ 10]$ [22,29]
- Fuse TCC parameters: $a \in [-2.4,\ -1.2], b \in [2,\ 20]$ [14]
- Coordination time intervals: $MFCTI = 0.2$, $MRCTI = 0.5$ [22,28].

It is to be noted that for any particular network condition (given by the number of DGs connected in the system), all the fuses are considered to have the same slope (i.e., fuse constant a is same for fuses). This philosophy has been adopted following the guideline given in [22]. In this paper, all simulation studies have been performed in MATLAB environment [26].

7. Case studies

The proposed optimum recloser-fuse coordination scheme has been tested on the IEEE 33 and 69-bus reconfigurable RDNs. In both test systems, the following three different scenarios have been considered:

1. No DG
2. Single DG
3. Multiple DGs

The obtained optimum protection coordination of recloser and fuses under each of the above cases for both these systems are discussed subsequently in this subsection.

7.1. Results on the IEEE 33-bus system

Fig. 5 shows the IEEE 33-bus system having 32 branches and 5 tie-switches (a total of 37 line) and supplied by a substation with 100 MVA short-circuit capacity [30]. The different locations of DGs considered for this system are also shown with connection switches. This system requires one recloser and six fuses as shown in the figure. Placing

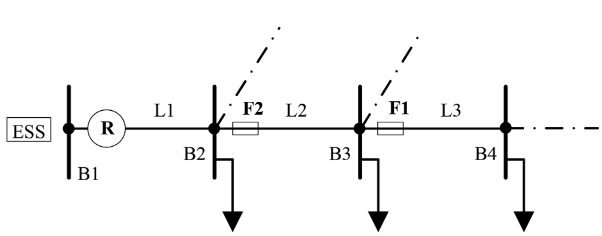

Fig. 2. Example of a typical 4-bus radial system.

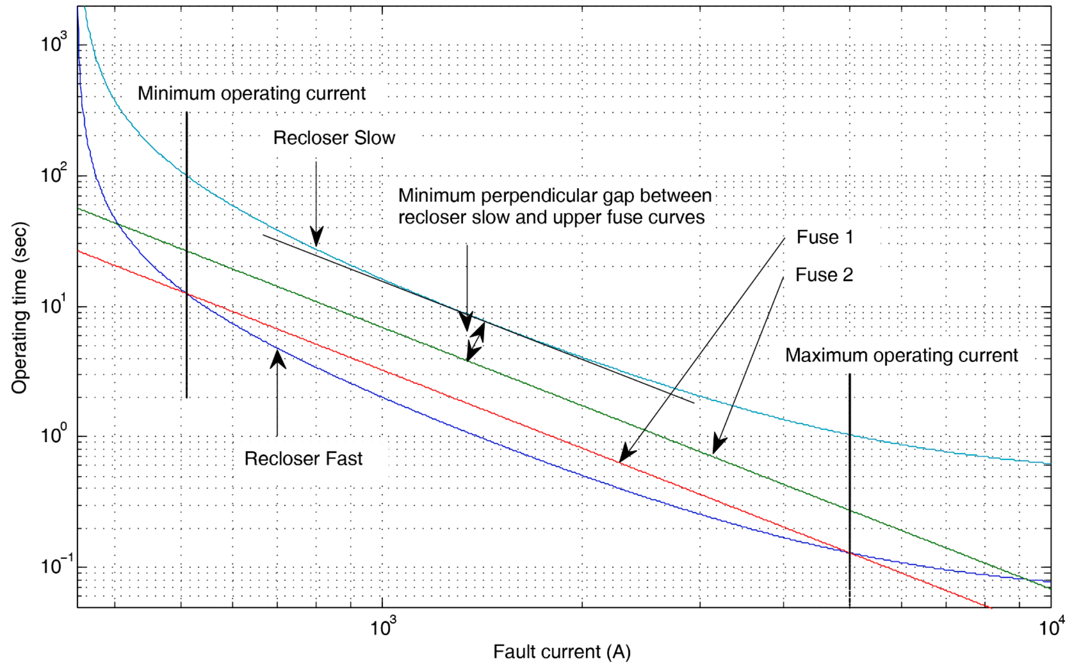

Fig. 3. Typical TCC plots of recloser and fuses in the 4-bus system.

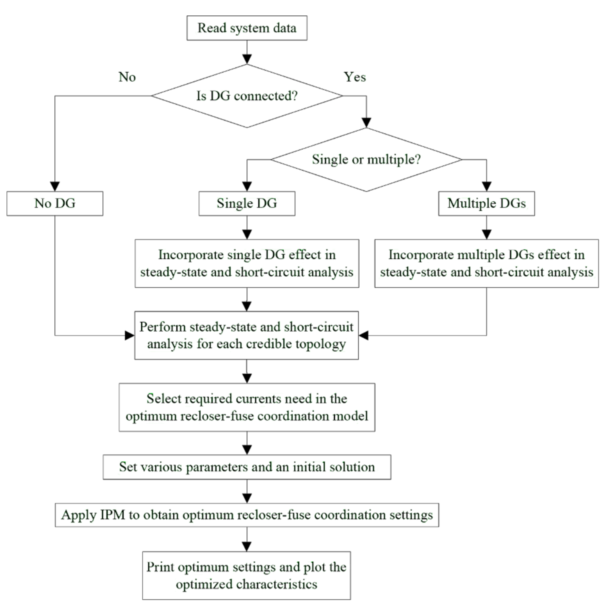

Fig. 4. Flowchart of the overall proposed approach.

fuse at each branching point rather than at each lateral provides additional selectivity for a fault in the main feeder. However, extra care must be taken in order to select the characteristic coefficients of the main feeder fuses.

The possible operating sequences of various protective devices are given in Table 1. The total number of operating sequences with the six fuses and fast and slow modes of operation of the recloser is seven only for a fault anywhere in the system under any configuration.

It is to be noted that only one of the operating sequences is responsible to operate for a particular fault anywhere in the system under any network topology. As an example, for a fault at node 30 under the base case configuration (all switches are open), the correct operating sequence of the protective devices is given in serial no. 6 in Table 1. Here, the recloser in their fast mode (R_{FM}) will operate first followed by

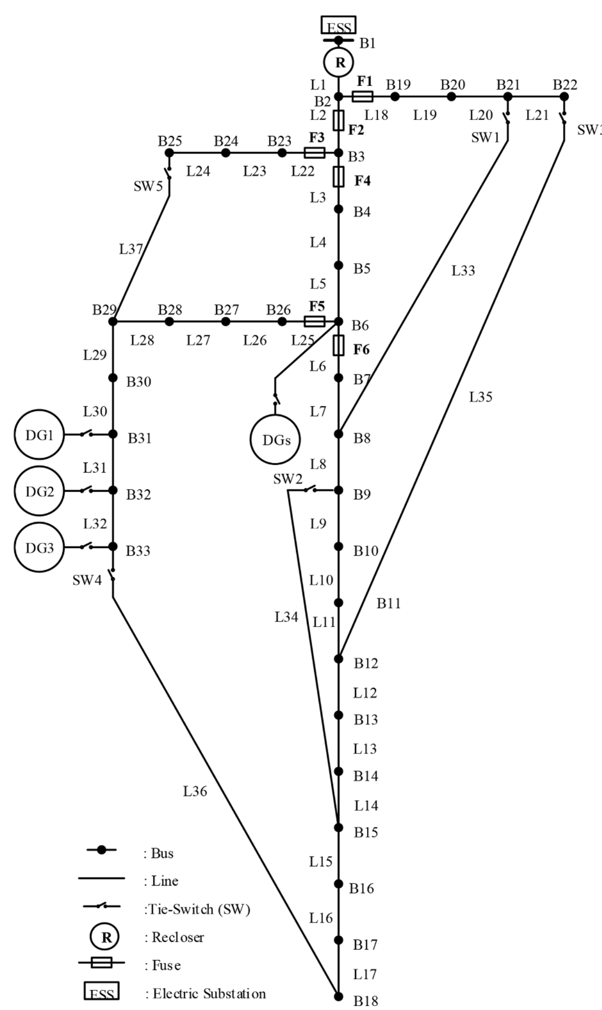

Fig. 5. IEEE 33-bus reconfigurable RDN.

Table 1
Operating Sequences in the IEEE 33-bus System.

Sl. No.	Correct operating sequences	No. of operating devices
1	$R_{FM} - R_{SM}$	1
2	$R_{FM} - F1 - R_{SM}$	2
3	$R_{FM} - F2 - R_{SM}$	2
4	$R_{FM} - F3 - F2 - R_{SM}$	3
5	$R_{FM} - F4 - F2 - R_{SM}$	3
6	$R_{FM} - F5 - F4 - F2 - R_{SM}$	4
7	$R_{FM} - F6 - F4 - F2 - R_{SM}$	4

fuse 5, fuse 4, fuse 2, and finally, if all devices fail, the recloser in its slow mode of operation (R_{SM}) will provide overall backup for the entire network. It is also observed from Table 1 that the sum of total number of operating devices in the seven protective devices (one recloser and six fuses) is 19.

7.1.1. Selection of feasible configurations

In the IEEE 33-bus system there are a total of 50,751 possible radial network configurations (obtained using the concepts discussed in Section 4). Out of 50,751 possible radial network configurations, feasible power flow solutions are obtained (i.e., all bus voltages are within 0.9 p.u. and 1.1 p.u.) for only 14,727 configurations. Further, to prevent reverse power flow through all the fuses, branches 1 to 5 are kept connected. This results in a further reduction of 5339 configurations. Thus, the total number of credible radial network configurations is 9388 only.

From Table 1, it is to be noted that originally there are only seven primary-backup operating sequences and thus only one sequence will be responsible to operate for fault at any node. However, it is possible that the values of fault current passing through the protective devices of the same operating sequence may be different for fault at different nodes. For example, the operating sequence 7 is responsible to operate for fault in any branch from node 7 to 18. Therefore, there are a total of 11 cases of operation with different values of fault currents (as there are 11 fault points) for this operating sequence. As a result, corresponding to a fault on each node of a feasible radial network, there are 32 cases of operation with different values of fault currents in the seven original operating sequences of the protective devices given in Table 1. Hence, there are a total of 9388 $\times$ 32 cases of operation in the seven operating sequences for coordination of recloser with downstream fuses (as there are 9388 feasible configurations) in all the possible configurations.

7.1.2. Constraint reduction strategy

The total number of cases of operation in the IEEE 33-bus system is 9388 $\times$ 32 which is quite large to be solved efficiently by any commercial solver. The constraint reduction strategy discussed in Section 5 can be applied to reduce it further so that the problem can be solved efficiently.

In the IEEE 33-bus system, there are 7 operating sequences involving a total of 19 operating devices in these sequences (third column of Table 1). Thus, the total number of critical values of fault currents in a given network configuration in this system is 38 (2 $\times$ 19). It is to be noted that the maximum possible number of the critical values is 38 as each protective device of a sequence has 2 critical values of fault currents whereas, the minimum possible number of the critical values of fault currents is 14 (2 $\times$ 7) as each sequence can have only 2 critical values (which are same for all protective devices participating in that operating sequence).

In view of the above observations, although the total number of cases of operation is equal to 9388 $\times$ 32 in all the feasible configurations, the effective number of cases of operations is between 14 to 38 depending on the network operating conditions.

7.1.3. Results without DG

In this case, only substation is supplying all the loads through bus 1. The optimum values of TDSs for recloser and ('a' and 'b') constants for all the fuses considering all feasible radial configurations are given in Table 2. The TCC plots of recloser and fuses corresponding to the optimum coordination results are shown in Fig. 6.

From Table 2, it is noted that the optimum values of TDSs for the fast and slow modes of recloser operation for the network without DG are 0.5 and 3.4268, respectively. Further, from Table 2, it is observed that fuse constant a is - 1.6614 for all the fuses. Also, fuse constant b for F4 is higher than that for F5 and F6, while for F2 fuse constant b is higher than that for F3 and F4 confirming the correct coordination sequences 1–7 as mentioned in Table 1.

From Fig. 6, it is clear that the TCC curves of the fuses lie within those of the fast and slow modes of the recloser. Additionally, the operating sequences of the fuses are also maintained as mentioned in Table 1 while maintaining MFCTI among the fuses. Here, it is to be noted that the $log - log$ plot has been used to show the operating times of protective devices for wide-range of fault current values. This ensure that the obtained settings are coordinating properly as the desired operating sequence are maintained.

The optimum DG locations and injections in the IEEE 33-bus system have been widely studied in the literature [31–33] for two cases. These cases are: i) DG at single location [31,32] and ii) DGs at multiple locations [33]. The optimum location of the DG in the first case is at bus 6 with an optimum injection of 2.48 MW at unity power factor [32] whereas, the optimum locations of the DGs in the second case are at buses 31, 32 and 33 with respective injections of 0.5586 MW, 0.5258 MW and 0.5840 MW at unity power factor [33]. The following have been considered while calculating the fault current in the presence of DGs. In single DG case, the short-circuit capacity of the DG is assumed as 25 MVA whereas in the case of multiple DGs, the short circuit capacity of each DG has been assumed as 10 MVA.

7.1.4. Results in the presence of a single DG

The optimum values of TDSs, a and b considering all feasible radial configurations with a single DG are given in Table 3. The resulting TCC plots of recloser and fuses corresponding to the optimum coordination results are shown in Fig. 7.

From Table 3, it is observed that the optimum values of TDSs for the fast and slow modes of recloser operation for the network for this case are 0.5 and 4.9913, respectively. Further, the fuse constant a is - 2.1906 for all the fuses. From this table, it can be noted that fuse constant b for F4 is higher than that for F5 and F6, while for F2, the constant b is higher than that for F3 and F4 confirming the correct operating sequences 1–7 mentioned in Table 1. Thus, the obtained results can provide proper coordination among the protective devices for any fault in the network under all feasible configurations in the presence of a single DG.

Similar to the previous case, from Fig. 7, it can be observed that the TCC curves of fuses lie within the TCC plots of the fast and slow modes of the recloser. Additionally, the operating sequences of the fuses are also maintained as mentioned in Table 1. Thus, the obtained recloser settings and fuse constants can provide protection in all feasible radial configurations in the presence of a single DG.

7.1.5. Results in the presence of multiple DGs

The optimum values of TDSs, a and b in this case are given in Table 4. The resulting TCC plots of recloser and fuses corresponding to the obtained optimum coordination results are shown in Fig. 8.

From Table 4, it is observed that the optimum values of TDSs for the fast and slow modes of recloser operation for the network considering the presence of multiple DGs are 0.5 and 3.7889, respectively. Further, from Table 4, it can be observed that fuse constant a is - 1.9483 for all the fuses. Also, fuse constant b for F4 is higher than that for F5 and F6, while for F2, fuse constant b is higher than that for F3 and F4 confirming the correct operating sequences 1–7 mentioned in Table 1.

Table 2
Optimum Coordination Results without DG in the IEEE 33-bus System.

Recloser settings			Fuse settings						
Modes	PCS (A)	TDS	Constants	F1	F2	F3	F4	F5	F6
Fast	275	0.5000	*a*	- 1.6614	- 1.6614	- 1.6614	- 1.6614	- 1.6614	- 1.6614
Slow	275	3.4268	*b*	12.8043	12.7127	12.4436	12.5127	12.2441	12.3127

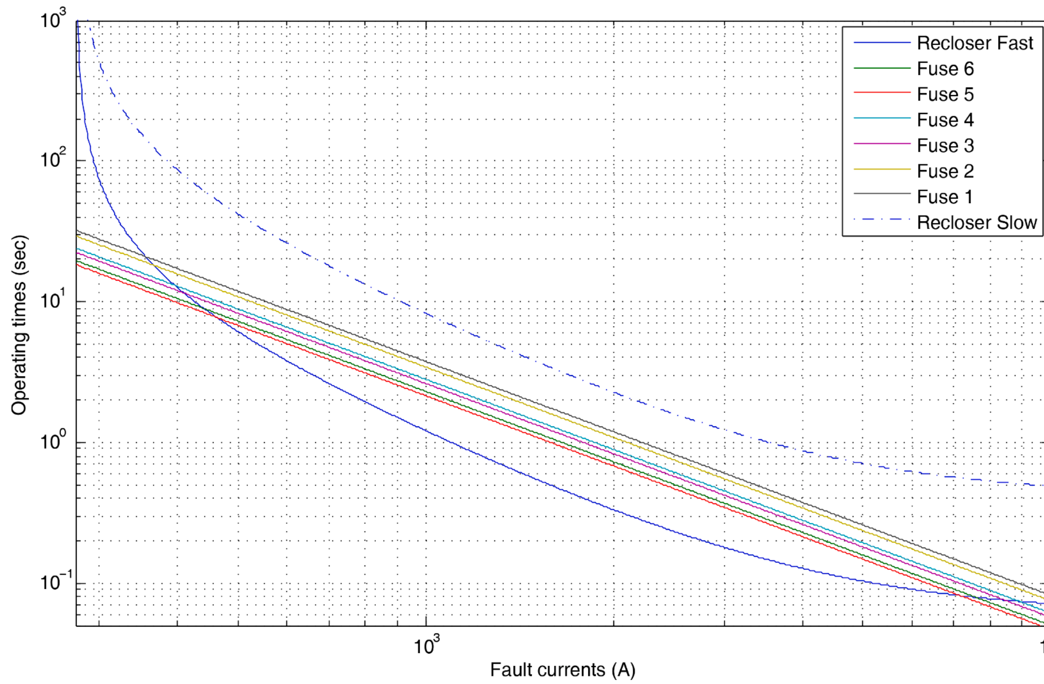

Fig. 6. Optimum TCC curves of various protective devices without DG in the IEEE 33-bus system.

Table 3
Optimum Coordination Results with the Single DG in the IEEE 33-bus System.

Recloser settings			Fuse settings						
Modes	PCS (A)	TDS	Constants	F1	F2	F3	F4	F5	F6
Fast	275	0.5000	*a*	- 2.1906	- 2.1906	- 2.1906	- 2.1906	- 2.1906	- 2.1906
Slow	275	4.9913	*b*	17.5857	17.5857	17.1324	17.3857	16.9097	17.1857

Similar to the previous cases, from Fig. 8, it can clearly be observed that the TCC curves of fuses lie well within the TCC curves of the fast and slow modes of the recloser and the operating sequences of the fuses are also maintained as mentioned in Table 1. Thus, the obtained protection coordination results can provide protection in all feasible radial configurations in the presence of multiple DGs in this test system.

7.2. Results on the IEEE 69-bus system

Fig. 9 shows the IEEE 69-bus system having 68 branches and 5 tie-switches (a total of 73 line) supplied by a substation with 100 MVA short-circuit capacity [34]. This system requires one recloser and 13 fuses for providing complete protection as shown in the figure. The all possible operating sequences of various protective devices are given in Table 5. The total number of operating sequences with these 13 fuses and recloser fast and slow modes of operation is 14 for a fault anywhere in the system under any configuration.

7.2.1. Selection of feasible configurations in the system

In the IEEE 69-bus system there are a total of 407,924 possible radial network configurations. Out of these possible radial network configurations, feasible power flow solutions are obtained for only 126,169 radial network configurations. Further, branches 1 to 12 are always kept connected so that power flow from substation to the junction points in the network is always maintained. This results in a further reduction of 75,811 configurations. Thus, the total number of credible radial network configurations is 50,358 only. Corresponding to fault on each branch of a feasible radial network, there are 68 cases of operation with different values of fault currents (using the fourteen original operating sequences given in Table 5).

Hence, there are a total of 50358 $\times$ 68 cases of operation for coordination of recloser with downstream fuses.

7.2.2. Constraint reduction strategy in the system

In this system, the total number of operating devices present in all the fourteen operating sequences given in Table 5 is 57. Thus, the total number of critical values of fault currents in a given network configuration is 114 (2 $\times$ 57). It is to be noted that the maximum possible number of the critical values is 114 as each protective device of a sequence has 2 critical values of fault currents. However, the minimum possible number of the critical values of fault currents is 28 (2 $\times$ 14) as each sequence may have only 2 critical values (the maximum and

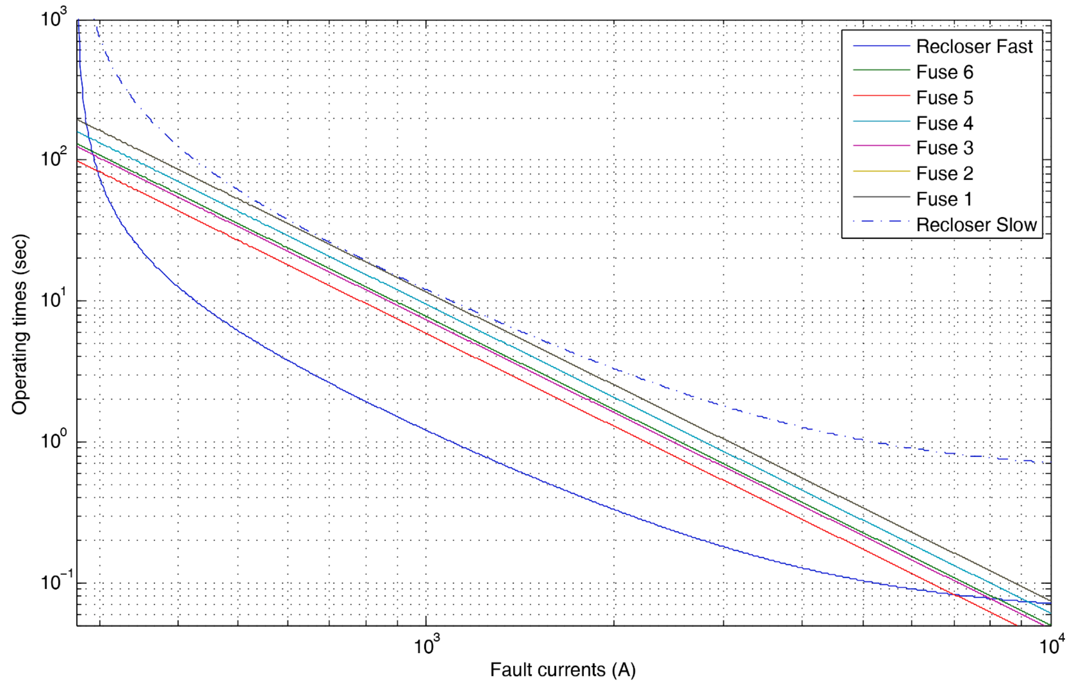

Fig. 7. Optimum TCC curves of various protective devices considering a single DG in the IEEE 33-bus system.

Table 4
Optimum Coordination Results with Multiple DGS in the IEEE 33-bus System.

Recloser settings			Fuse settings						
Modes	PCS (A)	TDS	Constants	F1	F2	F3	F4	F5	F6
Fast	275	0.5000	*a*	- 1.9483	- 1.9483	- 1.9483	- 1.9483	- 1.9483	- 1.9483
Slow	275	3.7889	*b*	15.5010	15.5010	15.0626	15.3010	14.7143	15.1010

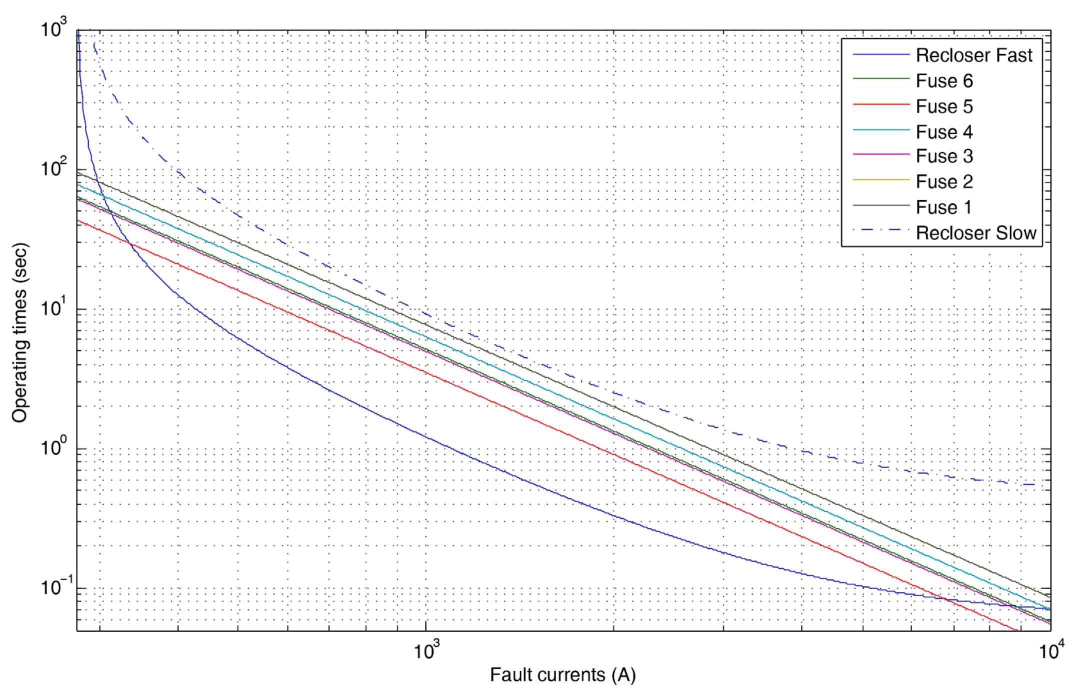

Fig. 8. Optimum TCC curves of various protective devices considering multiple DGs in the IEEE 33-bus system.

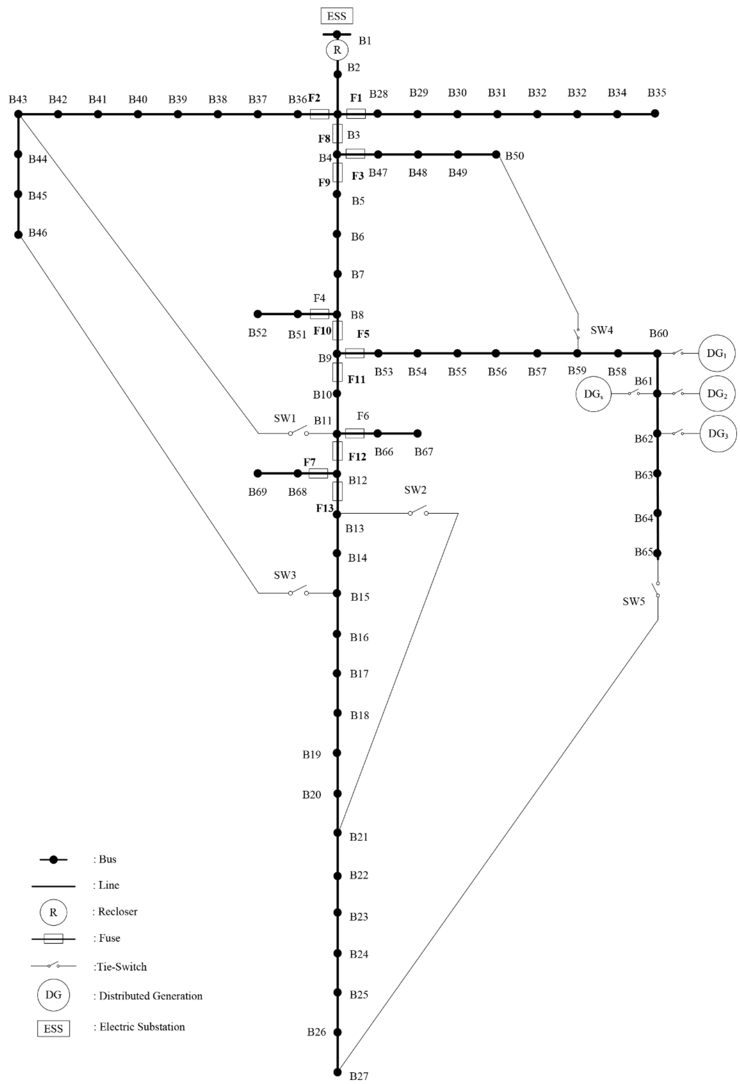

Fig. 9. IEEE 69-bus system with tie-switches and protective devices.

Table 5
Operating Sequences in the IEEE 69-bus System.

Sl. No.	Correct operating sequences	No. of operating devices
1	$R_{FM} - R_{SM}$	1
2	$R_{FM} - F1 - R_{SM}$	2
3	$R_{FM} - F2 - R_{SM}$	2
4	$R_{FM} - F8 - R_{SM}$	2
5	$R_{FM} - F3 - F8 - R_{SM}$	3
6	$R_{FM} - F9 - F8 - R_{SM}$	3
7	$R_{FM} - F4 - F9 - F8 - R_{SM}$	4
8	$R_{FM} - F10 - F9 - F8 - R_{SM}$	4
9	$R_{FM} - F5 - F10 - F9 - F8 - R_{SM}$	5
10	$R_{FM} - F11 - F10 - F9 - F8 - R_{SM}$	5
11	$R_{FM} - F6 - F11 - F10 - F9 - F8 - R_{SM}$	6
12	$R_{FM} - F12 - F11 - F10 - F9 - F8 - R_{SM}$	6
13	$R_{FM} - F7 - F12 - F11 - F10 - F9 - F8 - R_{SM}$	7
14	$R_{FM} - F13 - F12 - F11 - F10 - F9 - F8 - R_{SM}$	7

minimum values of fault currents of one device may remain the same corresponding to the minimum and maximum values of fault currents for some other device of the sequence).

By utilizing these observations, all the cases of operation in the fourteen operating sequences (which is equal to 50358 × 68) can be reduced drastically to a number (depending on the network operating conditions) which lies between 28 to 114 as discussed above.

7.2.3. Results without DG and with single and multiple DGs

In this test system, a single DG having a short circuit capacity of 20 MVA has been considered at bus 61 with 1.81 MW generation at unity power factor, whereas, multiple DGs are assumed to be located at three different locations, i.e., bus 60, 61 and 62 with respective injections of 0.3525 MW, 1.0666 MW and 0.4527 MW, respectively, at unity power factor [31,32]. The short-circuit capacity of each DG is considered as 10 MVA.

The optimum values of TDSs for recloser and (‘*a*’ and ‘*b*’) constants for all the fuses for all feasible radial configurations without DG, with a single DG and with multiple DGs are given in Table 6. The corresponding TCCs for these cases (without DG, a single DG and multiple DGs) are shown in Figs. 10, 11 and 12, respectively.

From Table 6, it is observed that the optimum recloser settings in all the three cases (no DG, single DG and multiple DGs) are the same. However, fuse constants *a* and *b* are different for fuses in the presence of multiple DGs than those obtained without DG and with single DG in this system. Similar to the IEEE 33-bus system, fuse constant *b* for all the fuses are progressively higher than those corresponding to the primary

Table 6
Optimum Coordination Results in the IEEE 69-bus System.

Settings	Parameters	Values of settings parameters		
		No DG	Single DG	Multiple DGs
Recloser	PCS (A)	300	300	300
	TDS (fast)	0.5	0.5	0.5
	TDS (slow)	7.4544	7.4544	7.4544
Fuse	*a*	- 1.4602	- 1.6146	- 1.6343
	*b*1	11.9659	13.4838	13.7530
*b*2	11.9659	13.4838	13.7530	
	*b*3	11.8159	13.3084	13.5812
	*b*4	11.2291	12.7677	13.0102
	*b*5	10.9992	12.3831	12.6970
	*b*6	10.6007	12.0621	12.4210
	*b*7	10.3715	11.8280	12.2168
	*b*8	12.0159	13.5126	13.7812
	*b*9	11.8159	13.3126	13.5812
	*b*10	11.6159	13.1126	13.3812
	*b*11	11.4159	12.9126	13.1812
	*b*12	11.2159	12.7126	12.9812
	*b*13	11.015 0	12.5126	12.7812

fuses. This confirms the correct coordination sequence 1–14 mentioned in Table 5. Further, from Figs. 10,11 and 12, it is clear that the TCC curves of fuses lie well within the TCC curves of the fast and slow mode operation of the recloser. Thus, the obtained results can provide proper coordination among the protective devices for any fault in the system under all the feasible configurations in all the three cases in the IEEE 69-bus system.

7.3. Assessment of the proposed optimum settings

In this section, the effectiveness of the proposed optimum recloser-fuse settings has been examined. To investigate the effectiveness of the proposed protection coordination scheme, the number of constraint (operating sequence) violation has been identified. These investigations have been performed under the three different network conditions (without DG, a single DG and multiple DGs) in both the test systems (IEEE 33 and 69-bus). Here, the optimum coordination results obtained under any network condition (No DG, a single DG and multiple DGs) are applied to all the three network conditions and cases of constraint violations has been noted. Table 7 gives the results of this investigation for the IEEE 33 and 69-bus RDNs.

From Table 7, it is observed that in the IEEE 33-bus system, there are 78,620 and 12,203 cases of constraint violations when the recloser-fuse settings calculated without considering any DG are applied to the network in the presence of single and multiple DGs, respectively. Further, there is no case of constraint violation when the recloser-fuse settings calculated with a single DG and multiple DGs cases are applied to any of the three cases in the IEEE 33-bus test system. However, in the IEEE 69-bus system, there are 115,073 and 147,456 cases of constraint violations when the recloser-fuse settings calculated without considering any DG is applied to the network in the presence of single and multiple DGs, respectively. Also, there are 9400 cases of constraint violations when the recloser-fuse settings calculated in the presence of a single DG is applied to the network in the presence of multiple DGs. In the other cases, there is no constraint violation. Thus, it is observed from this table that the recloser-fuse settings calculated in the presence of multiple DGs is robust as there is no constraint violation under any operating conditions of the DGs and network topology of the systems.

Thus for practical implementation, the setting obtained with multiple DGs should be used.

7.4. Comparison of conventional and proposed settings

Conventional settings of recloser-fuse protection coordination scheme has been obtained as mentioned in [22]. The values of TDSs for fast and slow modes and PCS for protection of the IEEE 33-bus system have been fixed as 0.5, 3.5 and 275 A, respectively, whereas those for protection of the IEEE 69-bus system have been fixed as 0.5, 4.5 and 300 A, respectively. Fuse constant *a* for all the fuses in both test systems has been taken as - 1.8 [22] and fuse constant *b* for all the fuses in both test systems have been calculated using time-grading method [14,22] and are given in Table 8. Here, it has been considered that the fuse characteristics must lie within the fast and slow mode of TCC plots of the recloser as discussed in [14,22]. These settings are obtained considering faults in the presence of multiple DGs. Also, the optimum settings

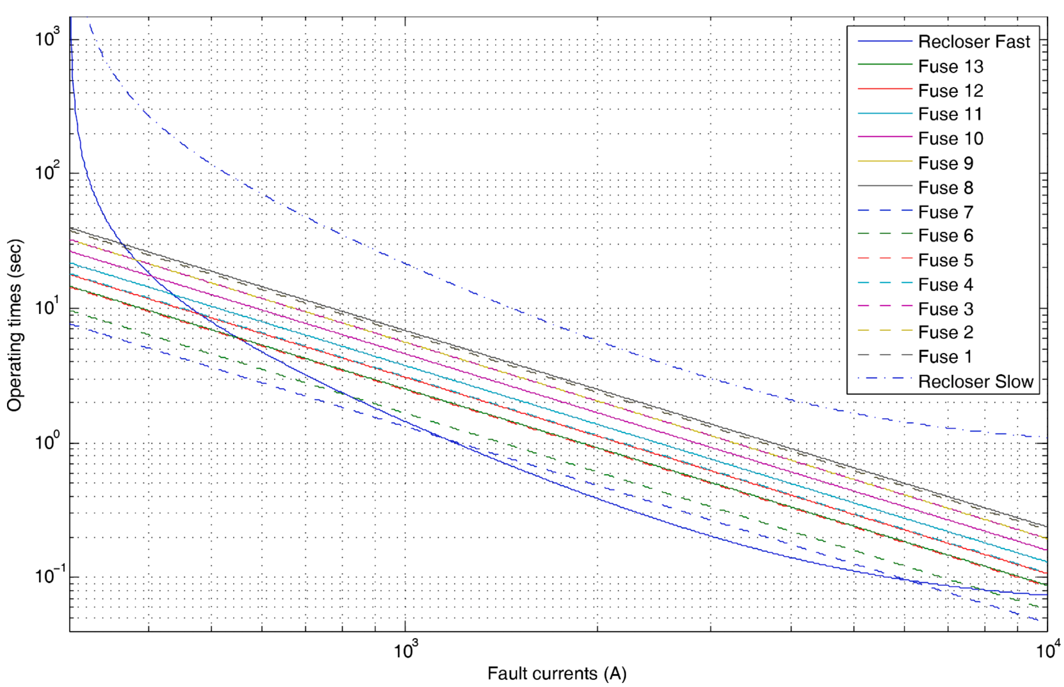

Fig. 10. Optimum TCC curves of the protective devices without considering DG in the IEEE 69-bus system.

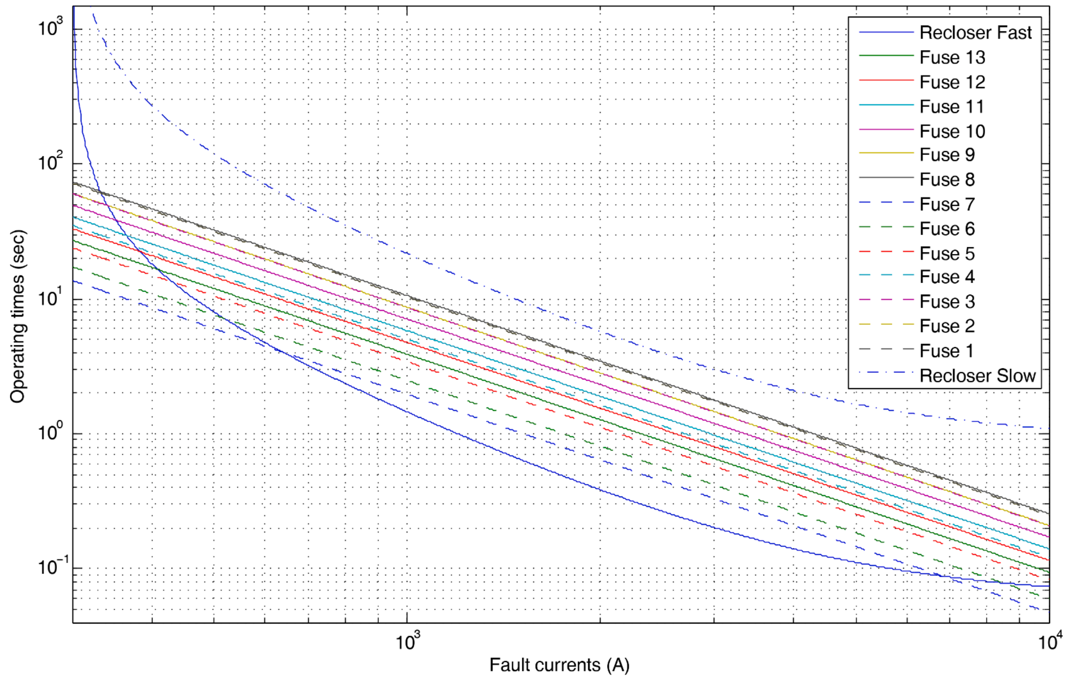

Fig. 11. Optimum TCC curves of various protective devices considering single DG in the IEEE 69-bus system.

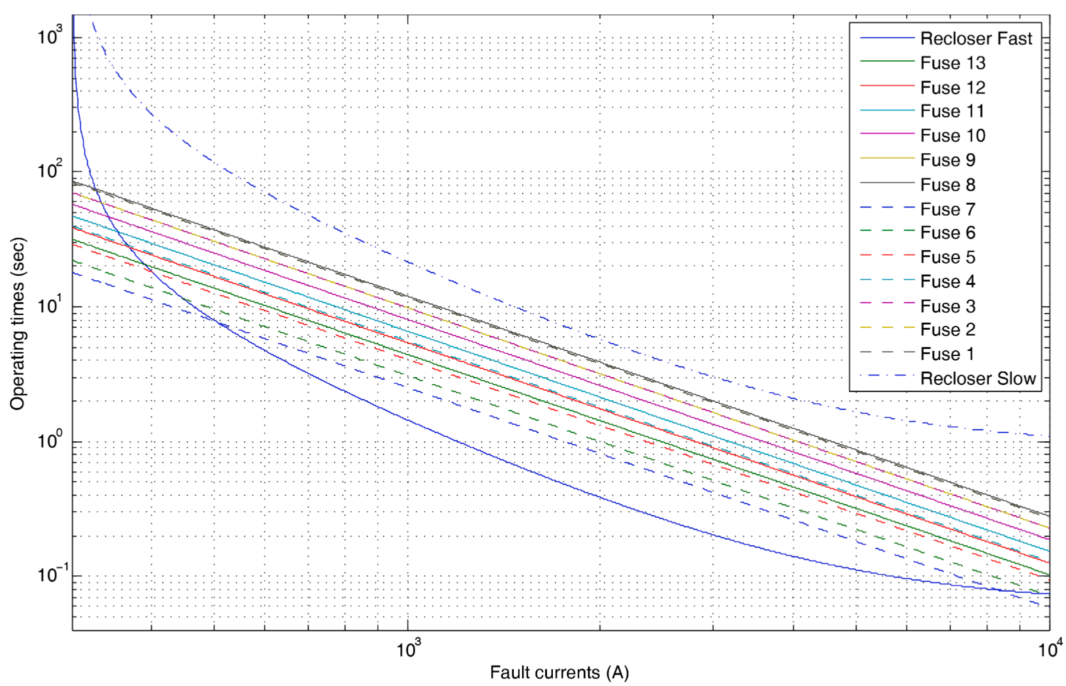

Fig. 12. Optimum TCC curves of various protective devices considering multiple DGs in the IEEE 69-bus system.

Table 7
Effectiveness of the Proposed Recloser-fuse Protection Scheme.

System	Settings obtained	Constraint violations with network condition		
		No DG	Single DG	Multiple DGs
IEEE 33-bus	No DG	0	78,620	12,203
	Single DG	0	0	0
	Multiple DGs	0	0	0
IEEE 69-bus	No DG	0	115,073	147,456
	Single DG	0	0	9400
	Multiple DGs	0	0	0

obtained by the proposed method are corresponding to the faults in the presence of multiple DGs.

The number of miscoordinations with the proposed and the conventional recloser-fuse coordination settings for both the test systems have been given in Table 9. From this table, it can be observed that there are large number of miscoordinations with conventional recloser-fuse settings when they are applied to protect the system in all possible configurations with and without DG. On the other hand, the proposed optimum recloser-fuse settings coordinate properly.

Table 8
Conventional Fuse Settings.

System	Fuse constant *b*						
IEEE 33-bus	*b*1	*b*2	*b*3	*b*4	*b*5	*b*6	-
	13.6148	13.7884	14.0848	14.2584	14.4033	14.5768	-
IEEE 69-bus	*b*1	*b*2	*b*3	*b*4	*b*5	*b*6	*b*7
	13.5804	14.0078	14.3063	14.5359	14.7225	14.8797	15.0290
	*b*8	*b*9	*b*10	*b*11	*b*12	*b*13	-
	13.7297	14.1571	14.4556	14.6852	14.8718	15.0290	-

Table 9
Number of Miscoordination with Conventional and Proposed Settings.

System	Recloser-fuse setting	Miscoordination with network condition		
		Without DG	Single DG	Multiple DGs
IEEE 33-bus	Conventional	203,803	131,555	199,583
	Proposed	0	0	0
IEEE 69-bus	Conventional	264,986	223,572	2,656,105
	Proposed	0	0	0

7.5. Comparison with the previous results

In the literature, optimization based settings of recloser-fuse coordination for the IEEE 33-bus test system are available in [18]. The optimum settings of recloser-fuse coordination for the IEEE 33-bus test system obtained using the proposed approach and those of [18] are given in Table 10. To compare these two settings, following Section 7.4, the total number of cases of violations of operating sequences obtained by these two sets of settings have been determined. Table 11 gives the detailed results. For simplicity, the settings corresponding to multiple DGs only have been considered in this comparison.

From Table 11, it is observed that there are several cases of miscoordination (violation of operating sequence) with the results of [18], whereas there is no single case of miscoordination with the results obtained by the proposed method for IEEE 33-bus test system. This is due to the fact that the results of [18] are obtained for a fixed topology of the system and therefore it is unable to coordinate properly when topology of the network changes. On the other hand, the results with the proposed method are obtained considering all possible network topologies, and therefore, they can coordinate properly under changing network topology of the RDN.

From the above results, it can be seen that the proposed methodology is capable of ensuring appropriate protection coordination for a reconfigurable distribution system in the presence of multiple DGs. Hence, for designing the appropriate protection scheme for modern distribution systems with reconfiguration ability and high penetration of DG at several locations, the required settings of the reclosers and the fuses can be obtained through off-line studies by the proposed optimum recloser-fuse coordination scheme and subsequently, these settings can very easily be implemented in the existing reclosers and fuses in the system.

Table 11
Number of Miscoordination with [18] and Proposed Method.

Optimum settings	Miscoordination with network condition		
	Without DG	Single DG	Multiple DGs
Method [18]	291,028	291,028	291,028
Proposed method	0	0	0

8. Conclusions

This paper proposes a novel optimum protection scheme of recloser and fuses for reconfigurable RDNs in the presence of distributed generators (DGs). Through various case studies carried out on the IEEE 33 and 69-bus systems, the following conclusions can be drawn;

1. The recloser-fuse coordination problem can be formulated as an optimization problem.
2. The proposed constraint reduction strategy reduces the number of constraints substantially.
3. The optimum recloser-fuse settings obtained considering all the possible network configurations without DG cannot coordinate properly when DGs are present in the system.
4. The optimum recloser-fuse settings obtained considering all the possible network configurations and the presence of DGs coordinate properly in any situation.
5. The presence of DGs at multiple locations have relatively more impact on recloser-fuse coordination than that at a single location.

Future works on the optimum recloser and fuses coordination will focus on providing suitable protection scheme for microgrids. Also, it will focus on consideration of different types of renewable distributed generation and their low voltage ride through capabilities in the protection scheme.

Table 10
Comparison of the Optimum Settings of the IEEE 33-bus Test System.

Settings	Parameters	Optimum settings of [18]			Optimum settings of proposed method		
		No DG	Single DG	Multiple DGs	No DG	Single DG	Multiple DGs
Recloser	PCS (A)	300	300	300	275	275	275
	TDS (fast)	0.5	0.5	0.5	0.5	0.5	0.5
	TDS (slow)	7.6200	7.6318	7.6284	3.4268	4.9913	3.7889
Fuse	*a*	- 1.4343	- 2.1788	- 1.6614	- 1.6146	- 2.1906	- 1.9483
	*b*1	11.5935	18.1341	17.2922	12.8043	17.5857	15.5010
	*b*2	11.4735	17.9122	16.9709	12.7127	17.5857	15.5010
	*b*3	10.9563	17.3490	16.5192	12.4436	17.1324	15.0626
	*b*4	11.2340	17.7122	16.7709	12.5127	17.3857	15.3010
	*b*5	10.5662	16.8358	15.2999	12.2441	16.9097	14.7143
	*b*6	11.0340	17.5122	16.5709	12.3127	17.1857	15.1010

CRediT authorship contribution statement

Mahamad Nabab Alam: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **Biswarup Das:** Visualization, Investigation, Supervision. **Vinay Pant:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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