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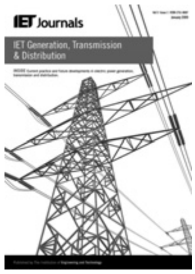

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New adaptive digital relaying scheme to tackle recloser–fuse miscoordination during distributed generation interconnections

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Abstract: Nuisance fuse blowing because of miscoordination between fuse and recloser in power distribution network is very critical issue particularly when distributed generations (DGs) are incorporated. This study presents a new adaptive digital relaying scheme for power distribution network containing DG, which circumvents miscoordination between recloser and fuse. It is based on calculation of the ratio of feeder current and recloser current. With the help of this philosophy, the proposed scheme automatically modifies the time dial setting of the relay and hence enhances margin between fuse and recloser in order to avoid miscoordination between fuse and recloser. The proposed scheme has been extensively tested for various types of faults in radial distribution network containing DG. Fault data are generated by modelling an existing part of 11 kV Indian power distribution network using PSCAD/EMTDC software package. Furthermore, the impact of different DG capacities on the margin (coordination) between fuse and recloser are also analysed. It has been observed that the proposed scheme maintains proper coordination between fuse and recloser for all types of fault. Moreover, it also provides satisfactory operation during high resistance single line-to-ground faults.

1 Introduction

Proper selection of protective devices plays a key role in preventing degradation of reliability of radial distribution network. Most of the protective schemes used for radial distribution systems involve the coordination of fuses, reclosers and overcurrent relays. Coordination between fuse and recloser is more difficult as they have total clearing characteristic of different shapes [1].

The magnitude of current (during normal as well as during fault) is redistributed by incorporation of distributed generations (DGs) in power distribution network. This can create interference in the operating margin available between recloser and fuse. In practice, the recloser in fast mode should discriminate temporary faults, occurring mostly in the distribution system, and operate faster than a lateral fuse. However, a lateral fuse may operate faster than the recloser because of the additional fault current supplied by DG [2, 3].

To mitigate miscoordination between recloser and fuse, several methods have been proposed by researchers [4–8]. Fazanehrafat *et al.* [4] proposed analytical-based method, which determines the maximum capacity of DG that would ensure proper coordination between fuse and recloser. However, the prime limitation of the said method is that it is very difficult to define an equation for each fuse on a feeder as it is characterised by different curves. Thereafter, Brahma and Girgis [7] presented microprocessor-based adaptive method, which maintains proper coordination between recloser and fuse for faults on a feeder with a high penetration level of DG. However, the requirement of continuous monitoring of DG status is the main disadvantage of the above scheme. Moreover, the proposed scheme may provide unreliable operation because of disconnection of DG at every fault occurrence even when faults are temporary in nature. Chaitusaney and Yokoyama [9] proposed a method to find the threshold value of DG capacity beyond which recloser–fuse coordination is lost. Although the above scheme has investigated the issue of recloser–fuse miscoordination, they have not suggested any solution to enhance coordination margin between recloser and fuse. Later on, Naiem *et al.* [10] presented a classical technique for coordination assessment of protective devices used in distributed systems in the presence of DG. However, the said scheme has not provided any solution to avoid miscoordination between recloser and fuse.

Therefore, to achieve proper coordination between recloser and fuse in the presence of DG in radial distribution system, an adaptive digital relaying scheme is presented in this paper. The proposed scheme is based on derivation of the ratio of recloser current (I_R) and fuse current (I_F). By using this ratio and without changing fuse characteristic, the recloser fast characteristic is shifted down from its original characteristic, which in turn enhances coordination margin

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between recloser and fuse. The proposed scheme has been tested extensively using PSCAD/EMTDC software package with fault data generated by modelling an existing 11 kV Indian power distribution network.

2 Problem formulation

2.1 Modelling and simulation

Fig. 1 shows single-line diagram of a portion of power distribution network of Madhya Gujarat Urja Vikas Nigam Limited, Gujarat, India. Two 66 kV sub-transmission lines (emanated from 220 kV Karamsad substation) are connected between buses B1 and B2. Two power transformers (TR-1 and TR-2) are used to step-down the voltage at 11 kV. Thirteen different distribution feeders are emanated from bus B3 for further distribution of power. In this paper, the proposed scheme has been implemented on Feeder-1. Two DGs (each of 1 MVA rating) are connected to 11 kV systems through step of transformers (TR-3 and TR-4). The parameters of Feeder-1, synchronous generators and exciter are given in Appendix. Test data for verifying the proposed adaptive scheme have been generated by modelling the complete system of Fig. 1 using the PSACD/EMTDC software package. The test data include different types of fault such as L–L–L–G, L–L–L, L–L–G, L–L and L–G. The transmission and distribution lines are represented using the Bergeron line model. The other components of the power system such as synchronous generator, transformers, loads etc. are designed according to the collected data and specifications. Some of the components such as fuse model and recloser model are developed by the authors using PSCAD/EMTDC software package. A sampling frequency of 4 kHz (80 samples/cycle) for a system operating at a frequency of 50 Hz is used in this study.

2.2 Setting of protective devices

In distribution system, proper coordination among various protective devices such as circuit breaker (CB), recloser and a lateral fuse behind the recloser is required (refer Fig. 1). To achieve correct operation, the fuse must be coordinated with upstream recloser on the main feeder. The coordination philosophy is such that the fuse should only operate for a permanent fault on the load feeder whereas recloser should disconnect the circuit with fast operation during temporary fault. In this way, the load feeder does not get disconnected for every temporary fault. At the same time, recloser also provides backup to fuse through slow mode. The CB is responsible for the fault that occurs in front of the recloser. In addition, the CB is used as the whole backup protection for the complete feeder when both the recloser and the lateral fuse fail in their functions.

The CB and recloser are normally equipped with inverse-time overcurrent trip devices. The general characteristics of such devices can be described by the following equation [11].

$$t = \left[\frac{A}{(\mathrm{MP})^p - 1} + B\right] \times \mathrm{TDS} \tag{1}$$

where t is the operating time of device, TDS is the time dial setting, MP is the multiple of pickup current and given by (2) and A, B, p are constants for particular characteristic.

$$\mathrm{MP} = \frac{I_{\mathrm{f(CTS)}}}{I_{\mathrm{pickup}}} \tag{2}$$

where I_f is the fault current seen by the device (on secondary side of CT), I_{pickup} is the recloser current set point. The value of TDS is set to be 1.0 for the slow-mode recloser whereas 0.5 is considered for the fast-mode recloser.

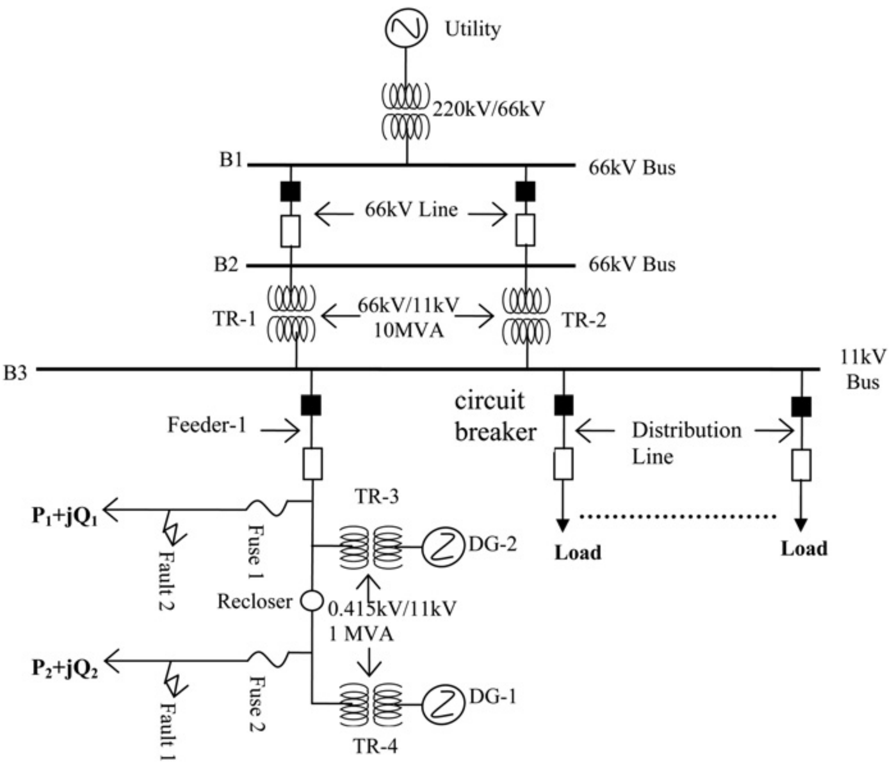

Fig. 1 *Single-line diagram of a portion of power distribution network*

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Similarly, fuse also has an inverse-time overcurrent characteristic. The general equation describing the fuse characteristic curve can be expressed as shown by (3).

$$\log(t) = a\log(I) + b \tag{3}$$

where t and I are the associated time and current whereas the coefficients a and b can be obtained from the curve fitting technique [12]. Here, the constant 'a' represents the slope of the straight line on I^2t log–log graph. It is fixed at a specified value for all fuses in the system. This condition is practically acceptable because all fuses in the system should be of the same type. The constant b is calculated from three-phase fault current on load feeder. The operating time of fuse is obtained by dividing the time range of reclosers (i.e. the difference between the operating times of the slow and fast operating modes). After performing simulations, the value of constant 'a' is selected as '-1.8' whereas the value of constant 'b' is chosen as '5.1429' and '5.39' for Fuses 1 and 2, respectively.

2.3 Different cases considered for recloser–fuse miscoordination

To evaluate the performance of the proposed adaptive scheme, four different cases, based on various locations of DG (after/before the recloser), are considered. These cases are shown in Table 1. Through the entire paper, I_R and I_F indicate the fault current seen by the recloser and the fuse, respectively, and I_S and I_{DG} indicate the fault current flows from the utility and DG, respectively.

It is well understood from the literature [9] that the problem of miscoordination is highly pronounced only during Case-1, in which the fault current seen by the fuse is the vector summation of fault currents flow from the substation and the DG. In this situation, there may be chances of miscoordination between recloser and fuse. Hence, miscoordination will occur whenever DG source and fault location are located behind the recloser. For rest of the cases as mentioned in Table 1, the problem of miscoordination is not very severe. Hence, in this paper, the proposed adaptive scheme is discussed only for Case-1.

Fig. 2 shows operating curves of recloser and fuse for Case-1. It is clear from Fig. 2 that the Margin-I is sufficient for DG having 2 MVA capacity. There is no miscoordination between recloser and fuse. This is clear from Fig. 3 in which recloser operates before fuse. However, the coordination between recloser and fuse is lost if the capacity of DG exceeds 3.0 MVA (Margin-II), which is clear from Fig. 2. In this situation, the fuse can operate prior to the intended operation time of the recloser. Thus, it can result in no actual operation of the recloser, as we can see in Fig. 4.

Table 1 Different cases considered for recloser–fuse miscoordination

Case	DG source	Fault location	Current seen by protective device
1	DG-1	fault 1	$I_R = I_S$ and $I_F = I_S + I_{DG}$
2	DG-1	fault 2	$I_R = I_{DG}$ and $I_F = I_S + I_{DG}$
3	DG-2	fault 1	$I_R = I_F = I_{DG} + I_S$
4	DG-2	fault 2	$I_R = 0$ and $I_F = I_S + I_{DG}$

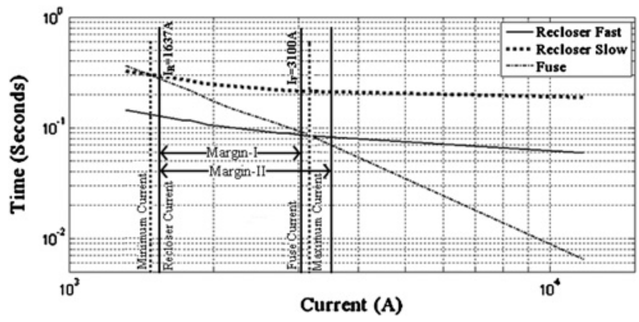

Fig. 2 *Operating curves of recloser and fuse for Case-1*

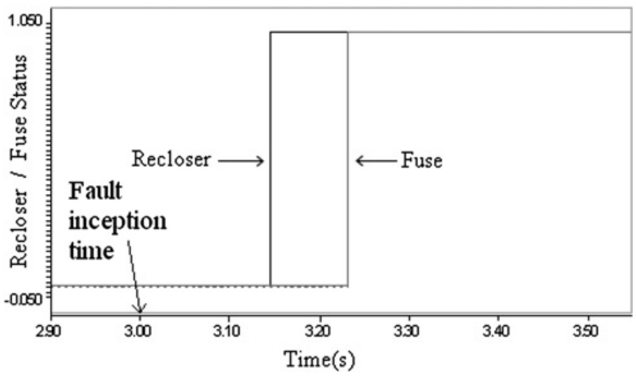

Fig. 3 *Operating time of recloser and fuse given by the conventional scheme for L–L–L fault on Feeder-1 with DG capacity 2.0 MVA*

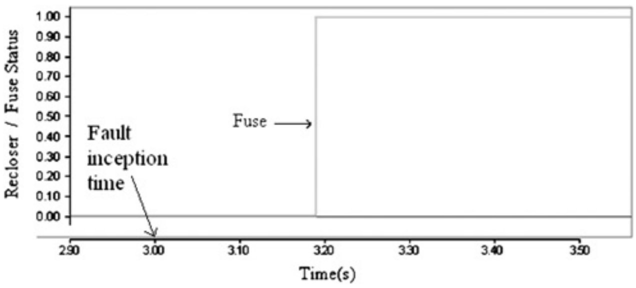

Fig. 4 *Operating time of recloser and fuse given by the conventional scheme for L–L–L fault on Feeder-1 with DG capacity 3.0 MVA*

3 Proposed adaptive digital relaying scheme

3.1 Proposed scheme

Fig. 5 shows flowchart of the proposed adaptive digital relaying scheme. At the time of commissioning of the proposed adaptive relay, characteristics of recloser and fuse are stored in the relay. After acquiring recloser and fuse currents with the help of data acquisition system, peak value of both currents are found out for a period of one cycle duration. Thereafter, the ratio of I_R/I_F is calculated on per phase basis. In case when the ratio of I_R/I_F is lower than unity (which is true for the situation when the recloser fault current is smaller than the fuse current because of incorporation of DG), the recloser fast characteristic (obtained with original TDS), is revised by multiplying the above ratio with original TDS. Hence, the recloser fast

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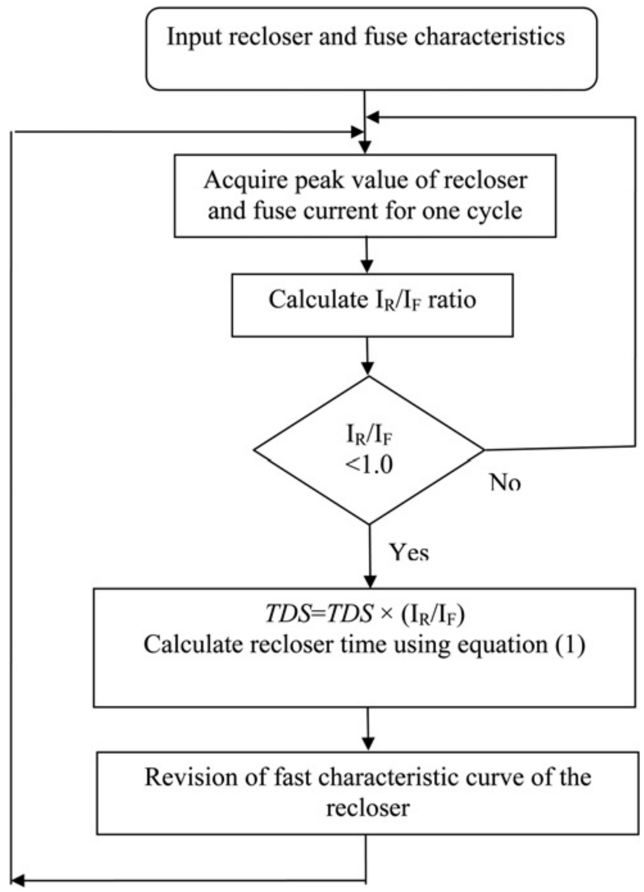

Fig. 5 *Flowchart of the proposed adaptive digital relaying scheme*

characteristic (with lower value of TDS) is shifted down with reference to previous recloser fast characteristic.

3.2 Selection of I_F/I_R ratio

To select the ratio of I_R/I_F as the index, we have carried out various simulations on the sample system, as shown in Fig. 1, with and without DG. Table 2 shows the simulation results for two types of faults (L–L–L and L–G) having two different locations (fault at fuse end and far end). It is to be noted from Table 2 that the ratio of I_R/I_F remains constant for a given type of fault irrespective of the location of fault on the feeder [6].

The above fact is well understood from Fig. 6, which shows the distribution of fault current in the presence of DG. By neglecting the load current with respect to the fault current, the current through the fuse (I_F) depends on the impedance

Table 2 Simulation results obtained for different types of fault in different locations with and without DG

Location of fault	Fault type	Fault current through fuse I_F, A		Fault current through recloser I_R, A		Ratio I_R/I_F with DG
		No DG	With DG	No DG	With DG	
fault at fuse end	L– L–L	3075	7059	3075	3087	0.437
	L–G	2159	2941	2159	1879	0.639
fault at far end	L–L–L	1871	3202	1871	1404	0.438
	L–G	1311	1579	1311	1001	0.634

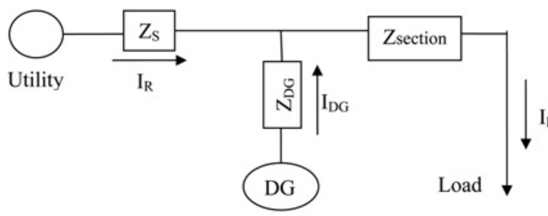

Fig. 6 *Single-line diagram of the sample system*

of the DG (Z_{DG}) and impedance towards the source (Z_s). Since, for a given location of DG, these impedances are fixed, the I_R/I_F ratio would obviously be constant. However, this value would be different of course, for a three-phase fault and a phase-to-ground fault. This property was exploited to coordinate a fuse and a recloser in a distribution system with significant penetration of DG. Hence, we have selected I_R/I_F ratio in the proposed schemes [6].

4 Simulation results

4.1 Comparison between the proposed scheme and the conventional scheme for different types of fault

Tables 3 and 4 show the simulation results in terms of recloser/fuse current ratio and their time of operation for different types of fault using the conventional scheme and the proposed scheme, respectively. It has been observed from Table 3 that the coordination between recloser and fuse is lost. This is true for all types of fault except single line-to-ground (L–G) fault. In contrast, the coordination between recloser and fuse is maintained for all types of fault (Table 4). It is clear from Table 4 that as the ratio of recloser current to fuse current decreases, the TDS of

Table 3 Results of the conventional scheme for different types of fault with 3 MVA DG

Fault type	Ratio I_R/I_F			TDS			Time of operation, s	
	A	B	C	A	B	C	t_R	t_F
L–G	0.670	5.000	2.360	0.500	0.500	0.500	0.31	0.33
L–L	0.600	0.500	3.360				NO	0.21
L–L–G	0.570	0.570	3.500				NO	0.19
L–L–L	0.560	0.550	0.590				NO	0.19
L–L–L–G	0.560	0.550	0.590				NO	0.19

t_R and t_F are the time of operation of recloser and fuse, respectively
NO, no operation of recloser

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Table 4 Results of the proposed scheme for different types of fault with 3 MVA DG

Fault type	Ratio I_R/I_F			TDS			Time of operation, s	
	A	B	C	A	B	C	t_R	t_F
L–G	0.670	5.000	2.360	0.339	0.500	0.500	0.21	0.32
L–L	0.600	0.500	3.360	0.302	0.256	0.500	0.12	0.21
L–L–G	0.570	0.570	3.500	0.286	0.286	0.500	0.11	0.19
L–L–L	0.560	0.550	0.590	0.284	0.279	0.299	0.09	0.19
L–L–L–G	0.560	0.550	0.590	0.284	0.279	0.299	0.09	0.19

t_R and t_F are the time of operation of recloser and fuse, respectively

Table 5 Results from the conventional scheme for different type of faults with 5 MVA DG

Fault type	Ratio I_R/I_F			TDS			Time of operation, s	
	A	B	C	A	B	C	t_R	t_F
L–G	0.580	6.501	3.190	0.500	0.500	0.500	NO	0.32
L–L	0.444	0.450	4.311				NO	0.16
L–L–G	0.483	0.380	4.150				NO	0.16
L–L–L	0.431	0.430	0.470				NO	0.17
L–L–L–G	0.432	0.440	0.471				NO	0.17

t_R and t_F are the time of operation of recloser and fuse, respectively
NO, no operation of recloser

Table 6 Results from the proposed scheme for different type of faults with 5 MVA DG

Fault type	Ratio I_R/I_F			TDS			Time of operation, s	
	A	B	C	A	B	C	t_R	t_F
L–G	0.581	6.501	3.190	0.293	0.500	0.500	0.22	0.32
L–L	0.441	0.452	4.311	0.221	0.226	0.500	0.09	0.16
L–L-G	0.480	0.377	4.150	0.241	0.189	0.500	0.09	0.16
L–L–L	0.430	0.430	0.470	0.219	0.219	0.239	0.08	0.17
L–L–L–G	0.430	0.440	0.470	0.219	0.220	0.239	0.08	0.17

recloser fast characteristic also decreases (which remains constant in the conventional scheme as observed from Table 3). Therefore the margin between recloser and fuse increases as the recloser fast characteristic (with lower value of TDS) is shifted down with reference to previous recloser fast characteristic.

Table 7 Simulation results of the proposed scheme for different types of fault having different DG capacities

DG capacity, MVA	Fault type	Ratio I_R/I_F	TDS	Time of operation, s	
				t_R	t_F
2.0	L–G	0.751	0.376	0.20	0.32
	L–L–L	0.663	0.335	0.09	0.20
4.0	L–G	0.626	0.313	0.20	0.32
	L–L–L	0.501	0.252	0.08	0.19
6.0	L–G	0.550	0.277	0.19	0.31
	L–L–L	0.409	0.205	0.06	0.16
8.0	L–G	0.507	0.254	0.18	0.29
	L–L–L	0.351	0.176	0.03	0.12

t_R and t_F are the time of operation of recloser and fuse, respectively

Similarly, Tables 5 and 6 shows the simulation results obtained from the conventional scheme and the proposed scheme, respectively, for 5 MVA DG capacity. It is impossible to obtain coordination between recloser and fuse using the conventional scheme as the recloser is not in a position to operate for all types of fault. This is clear by observing NO (no operation of recloser) from Table 5. Hence, the prime objective of fuse saving is violated, particularly, for temporary faults in the distribution system. On the other hand, proper coordination between recloser and fuse is achieved by the proposed scheme for all types of fault (Table 6) as the recloser (in fast mode) always operates prior to the fuse.

4.2 Effect of higher value of DG capacities on the proposed scheme

Table 7 shows the simulation results given by the proposed scheme in terms of time of operation of recloser and fuse for different capacities of DG.

It is to be noted from Table 7 that, the TDS of recloser fast characteristic decreases as the capacity of DG increases. Therefore the margin between recloser and fuse increases as the recloser fast characteristic (with lower value of TDS) is

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Table 8 Simulation results given by the proposed scheme during low capacities of DG

DG capacity, MVA	Fault type	I_R, A	I_{DG}, A	Ratio I_R/I_F	TDS			Time of operation, s	
					A	B	C	t_R	t_F
0.15	L–G	1316	59	0.974	0.487	0.500	0.500	0.13	0.42
	L–L–L	1959	124	0.967	0.484	0.482	0.484	0.08	0.21
0.25	L–G	1304	95	0.958	0.479	0.500	0.500	0.13	0.42
	L–L–L	1945	203	0.947	0.474	0.471	0.474	0.08	0.21
0.5	L–G	1274	176	0.920	0.460	0.500	0.500	0.13	0.42
	L–L–L	1908	389	0.891	0.449	0.443	0.451	0.08	0.20
1.0	L–G	1220	309	0.851	0.427	0.500	0.500	0.13	0.33
	L–L–L	1838	722	0.802	0.405	0.396	0.409	0.08	0.20

t_R and t_F are the time of operation of recloser and fuse, respectively

Table 9 Simulation results of the proposed scheme for high resistance single L–G fault at different DG capacitates

DG capacity, MVA	Fault resistance R_F, Ω	Ratio I_R/I_F			TDS			Time of operation, s	
		A	B	C	A	B	C	t_R	t_F
2.5	5.0	0.755	3.151	1.160	0.377	0.500	0.500	0.54	0.94
	10	0.788	2.112	1.141	0.394	0.500	0.500	1.09	1.95
	20	0.842	2.183	1.278	0.421	0.500	0.500	2.93	4.69
	30	0.890	2.012	1.360	0.444	0.500	0.500	5.60	7.96
	40	0.932	1.901	1.409	0.466	0.500	0.500	10.42	11.45
5.0	5.0	0.653	4.310	1.539	0.326	0.500	0.500	0.65	0.89
	10	0.708	3.542	1.396	0.354	0.500	0.500	1.43	1.88
	20	0.802	2.941	1.600	0.401	0.500	0.500	4.46	4.63

t_R and t_F are the time of operation of recloser and fuse, respectively

shifted down with reference to previous recloser fast characteristic. Hence, the coordination between recloser and fuse is maintained for all types of fault even with enhancement in DG capacities. The proposed adaptive scheme is capable of maintaining proper coordination between recloser and fuse for very high capacity of DG (8 MVA) during which conventional scheme fails.

4.3 Effect of lower value of DG capacities on the proposed scheme

To validate the performance of the proposed scheme during various scenarios of the distribution system with low capacities of DG, we have carried out various simulations. The simulations results are shown in Table 8. It has been observed from Table 8 that the proper coordination is maintained between fuse and recloser even though the fault current through DG is much smaller than utility. Therefore, even though the fault current provided by DG (I_{DG}) is much smaller than provided by the system (the situation of a strong system), the index I_R/I_F changes significantly. This effectively shifts down the curve which in turn enhances coordination margin between fuse and recloser.

4.4 Effect of high resistance single L–G fault

When an overhead distribution phase conductor breaks and falls on a high-impedance surface or trees, high-impedance fault occurs [13]. The conventional scheme fails to preserve the coordination between recloser and fuse even at lower value of fault resistance (0.01 Ω). In contrast, the proposed adaptive scheme gives satisfactory results during high resistance faults. Table 9 shows the simulation results obtained from the proposed scheme for L–G faults having two different DG capacitates (2.5 and 5 MVA) with varying fault resistances. Although the time of operation of recloser as well as fuse increases as the value of fault resistance increases, the proposed scheme is capable of maintaining proper coordination between recloser and fuse.

5 Conclusion

In this paper, a new adaptive relaying scheme is presented which uphold proper coordination between recloser and fuse connected in the distribution network along with DG. This is achieved by modifying the TDS of the recloser fast characteristic. The proposed scheme has been tested extensively by simulating various types of faults on distribution system in the presence of DG. Fault data are generated using PSCAD/EMTDC software package by modelling an existing 11 kV Indian power distribution network. The proposed scheme is capable of maintaining proper coordination between recloser and fuse irrespective of types of fault. Moreover, it enhances margin between recloser and fuse during higher capacity of DG (3.0–8 MVA) by shifting down recloser fast characteristic with reference to previous recloser fast characteristic. Furthermore, the proposed scheme also preserves correct coordination between recloser and fuse during high resistance single L–G faults.

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7 Appendix

7.1 Line parameters

Type of conductor	Voltage, kV	Area of cross-section, mm^2	Resistance, Ω/km	Reactance, Ω/km
rabbit	11	61.9	0.5449	0.305
dog	66	118.45	0.2745	0.283

7.2 Synchronous generators parameters

Rated RMS line-to-neutral voltage (V_{rms}): 0.239 kV
Rated RMS line current (I_{rms}): 1.391 kA
Base angular frequency (ω): 314.15 rad
Inertia constant (H): 3.117 s
Mechanical friction and windage (D_m): 0.04 pu
Neutral series resistance (R_s): 1.0×10^5 pu
Neutral series reactance (X_s): 0 pu
Iron loss resistance (R_m): 0.5 pu

7.3 Exciter parameters

Rectifier smoothing time constant (T_1): 0.02 s
Controller lead time constant (T_A): 1.5 s
Controller lag time constant (T_B): 1.0 s
Exciter time constant (T_E): 0.02 s
Exciter gain (K): 100 pu
Maximum field voltage (E_{MAX}): 5 pu
Minimum field voltage (E_{MIN}): −5 pu
L–G voltage base (kV, RMS): 0.239 kV
Line current base (kA, RMS): 1.39 kA

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