Optimum Value for Resistive Fault Current Limiter for Protection of a Power System with Distributed Generation

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ABSTRACT

Renewable energy resources are being used for the last six decades for the generation of electrical power. Electrical safety and protection are main concerns in the successful operation of a power system. Integrating Distributed Generators (DGs) into a power system creates technical problems and thus affecting the safety of the system. When a fault occurs in a power system connected with distributed generator, the DG itself contributes fault current to the system. This causes disturbances to the settings of all protective devices. Original relay protection scheme is affected by the connection of distributed generators and causes mal-operation of both primary and backup relays. The fault current contribution of DG can be limited by placing Fault Current Limiter (FCL) in series with the DG. This paper proposes a novel method for the determination of the optimum resistance value for the FCL and thus to retain the original settings of relays. For optimizing the value of resistance of resistive fault current limiter Genetic Algorithm (GA) is used and the original relay settings are restored. This method is tested for standard IEEE 30 bus system. The effectiveness of proposed method is illustrated in the presence of single and multiple DG existence.

Keywords: Distributed Generators (DG), Directional Over Current Relay Coordination, Fault Current Limiter (FCL)

1. INTRODUCTION

Directional over current relays are major sensing equipments operating in distribution network and proper coordination of these relays are important in order to prevent system failure. There should be a minimum time interval between the operation of primary relay and backup relays for proper coordination.

Major quantities to be minimized in a relay coordination problem are the time setting and plug setting multipliers. Thus the relay coordination problem is generally formulated as a linear programming problem. In linear model only the time multiplier setting is minimized. The pickup current settings are fixed at values between the maximum load current and minimum fault current [1]. A sequential quadratic programming method simultaneously optimizing all the settings of directional over current relay presented in [2]. Optimum relay settings may be found by Genetic Algorithm, Evolutionary Algorithm or Particle swam optimization in [3]-[5]. In [6] optimum coordination is determined by considering configuration changes in the network.

Distributed Generators are electric power generating units with capacities 3 kW to 50 MW which feeds power into the distribution system at the point of use. Popularity of DG is due to the fact that power loss due to long distance AC transmission lines can be eliminated since they are placed close to the load. The process of redesigning the transmission lines can also be eliminated by the use of DG. Distributed Generators mainly use renewable resources and thus they prevent pollution, reduce green house effect, help in saving fossil fuels, reduce fuel cost and ensure energy security.

When a DG is connected to a grid and a fault occurs in grid side, the DG acts as a source of fault current and the total fault current increases. This sometimes reduce the coordination time interval between the back up and primary relays or in certain cases the operating time of back up relay may become less than the primary relay. The original relay setting is disturbed and leads to the malfunctioning of the protective device. Thus each time the circuit breaker needs to be upgraded and the method is not cost effective. Another method is to disconnect the distributed generator following a fault at grid side. But this involves synchronization issues.

An effective solution to limit the fault current from DG is to connect Fault Current Limiter (FCL). FCLs are devices placed in series with the power system to be protected. They offer zero impedance during normal operation but introduce enough impedance during fault so that the fault current flowing through them is limited. The functionality of limiting current is obtained by current limiting reactors, fuses, triggered fuse, superconductive fault current limiter, and fuses and power electronic based current limiters. If the fault occurs the FCL increases its impedance and

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so prevents over-current stress which results as damaging, degradation, mechanical forces, extra heating of electrical equipment.

The main requirements to the FCLs are [14]: to be able to withstand distribution and transmission voltage and currents; to have low impedance, low voltage drop and low power loss at normal operation; to have large impedance in fault conditions; to have a very short time recovery and to limit the fault current before the first peak; to properly respond to any fault magnitude and/or phase combinations; to withstand the fault conditions for a sufficient time;to have a high temperature rise endurance; to have a high reliability and long life; to have fully automated operation and fast recovery to normal state after fault removal; to have a low cost and low volume.

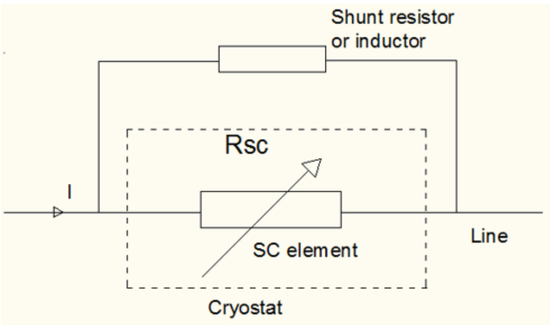

Fig.1: *Resistive type Super conducting fault current limiter(SFCL)in power line.*

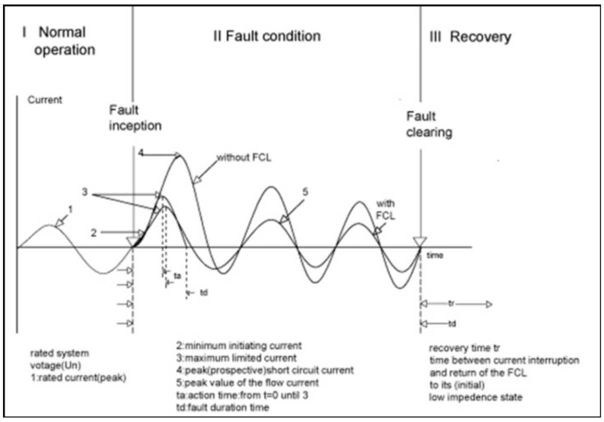

Fig.2: *Typical fault current wave shape with and without Fault Current Limiter(FCL).*

According to the technology used, three main types of FCLs can be identified :(a) Superconducting Fault Current Limiters (SFCL), (b) Magnetic Fault Current Limiters (MFCL) and (c) Solid State Fault Current Limiters. These FCLs are broadly classified as inductive and resistive type based on their impedance seen by a fault. In [7], it is illustrated that resistive FCLs can restore the original relay settings with smaller resistance values than inductive FCLs which require higher inductance. In resistive type FCL, current limiting is achieved by introducing resistive impedance in series with the fault impedance. Solid state FCL with resistive limiting impedance , magnetic FCL with a limiting resistor and a resistive SFCL are examples for resistive type FCLs. Fig.1 shows resistive type SFCL. In Resistive SFCL, the superconducting element is placed inside the cryostat and connected in series with the power line. Fig. 2 shows the shape of fault current without FCL and with FCL[15]. It can be seen that by using the FCL the fault current can be reduced to a small value, once the type of FCL is decided.

Different methods are adopted to connect the fault current limiters and thus to limit the fault current [7]-[10]. A control scheme for determining the impedance of a fault current limiter connected to a distributed generator is suggested in [7] . In this method a resistive fault current limiter is connected which can restore the original relay setting with smaller resistance value than inductive FCLs which require higher inductance. The optimum value of inductance cannot be determined by this method. For multiple DG scenarios, the above method uses same impedance value for the FCLs in series with the DGs, which is not a cost effective method. Optimum location of FCL placement is given in [8]. [13] Proposes a method for lowering the resistance value of SFCL improving the performance of reclosure circuit breaker.

This paper introduces, a new method based on optimization using Genetic Algorithm and is used for finding the optimum resistance of resistive FCL, required to restore the original relay setting. The effectiveness of proposed method in the presence of single and multiple DG existence is also illustrated.

This paper is organised as follows. Section 2explains the relay coordination problem. Section 3 illustrates the problem formulated for the proposed method of selecting optimum resistance value of resistive fault current limiter. Genetic Algorithm is an optimization technique used for a problem of highly nonlinear nature. The effectiveness of the proposed method is illustrated in section 4 using the results. The advantage of this method is explained in section 5.

2. RELAY COORDINATION PROBLEM

2.1 Determination of operating time of relay

For any distribution system, the aim of the relay coordination problem is to minimize the sum of the operating time of the primary relays. If 'n' is the total number of relays, then the objective function is given by

$$min\ z = \Sigma_{i=1}^{n}\ ti,\ f \quad (1)$$

where

ti;f operating time of the primary relay for a fault at f

n number of relays

The constraints for the relay coordination problem are:-**Limits on plug setting of the relay:** The plug setting (PS) of the relay should be selected in such a way that it should not operate for small amount of overload current and at the same time it should be able to detect even the smallest fault current. As a thumb rule, the minimum and maximum value of plug setting can be fixed as 1.25 and 2 times the maximum load current seen by the relay [7].

$$\mathbf{PSi;\ min \leq PSi \leq PSi;max} \quad (2)$$

where

PSi;min minimum value of the PS of the relay Ri

PSi;max maximum value of the PS of the relay Ri

Limits on time multiplier setting of the relay: The time multiplier setting (TMS) of the relay also has an upper limit and lower limit which directly affects the operating time of the relay. These limits have been taken between 0.1 and 1.3. These limits are given below.

$$\text{TMSi;min} \leq \text{TMSi} \leq \text{TMSi;max} \quad (3)$$

where

TMSi;min minimum value of the TMS of the relay Ri

TMSi;max maximum value of the TMS of the relay Ri

Constraint on coordination time: The power system protection is done by a primary relay and a backup relay in each zone. The fault current in a given line is sensed by both the primary relay and backup relay. The backup relay should operate only when the primary relay fails. To ensure this, there should be a minimum time interval between the operating time of the backup relay and that of the primary relay. This time interval known as the coordination time interval (CTI) is the sum of the operating time of the circuit breaker associated with the primary relay and the overshoot time. In this paper, CTI is taken to be 0.2 sec.

$$\text{tj; f - ti; f} \geq \Delta\text{t} \quad (4)$$

where

tj; f operating time of the backup relay Rj for fault at f

ti; f operating time of the primary relay Ri for fault at f Δt CTI

Relay characteristics: The operating time depends on TMS and PS. In this paper, a nonlinear over current relay characteristic with λ and γ equal to 0.14 and 0.02 respectively is used.

$$ti = \frac{\lambda(\text{TMS})}{\frac{(I_{relay})\gamma}{(PS)\gamma} - 1} \quad (5)$$

where

ti operating time of the relay Ri for a fault at f

Irelay fault current seen by the relay

3. PROPOSED METHOD FOR SELECTION OF OPTIMUM RESISTANCE

The idea behind using the FCL in series with the DG, is to introduce an impedance in series with the DG during fault, so that the fault current contribution from the DG is limited. When the fault current contribution from the DG is limited, the original relay settings can be retained for the protection of the distribution system. For a distribution system with multiple DGs connected, there should be a FCL in series with each of the DGs. The impedance of FCL is selected in such a way that the difference in operating time between the backup and primary relay pairs is greater than or equal to the threshold value of coordination time interval [7]. But it is not economical to have very high impedance value for FCLs. This necessitates the need for determining optimum impedance value of FCL which satisfies the coordination time constraint and at the same time is cost effective.

In this paper, resistive type FCLs are considered. Resistive type FCL is used for the protection because the resistance value is lesser compared to the impedance type FCL. The aim of the resistance selection problem should be to minimize the resistance of the FCL in series with the DG. Thus the objective function is to minimize the sum of the resistance of all the FCLs.

$$\text{minz} = \Sigma_{\text{j=1}}^{\text{m}}\text{RFCLj} \quad (6)$$

where

RFCLj resistance of the FCL connected to jth DG

m number of DGs connected to the distribution system

Following are the constraints for the resistance selection problem:-

3.1 Constraint on coordination time

The difference between operating time of the entire backup primary relay pairs should be greater than or equal to the threshold value of coordination time interval (0.2 sec). The operating time of the relay is calculated after fixing the value of TMS and PS at the original relay setting. The resistance of the FCL has an impact on the distribution system only during the fault. It has no effect during normal power flow. RFCL is included in the impedance matrix Zbus during fault. This in turn will reduce the value of the fault current. The operating time of the relay depends on the fault current seen by the relay. Thus the operating time becomes a function of RFCL.

$$tj;f - ti;f \geq \Delta t \qquad (7)$$

where

tj;f operating time of the backup relay Rj for fault at f

ti;f operating time of the primary relay Ri for fault at f

Δt threshold value of CTI (0.2 sec)

3.2 Limits on resistance of FCL

FCLs have a fixed resistance value once they are installed into the system. Thus the resistance of FCLs have a upper and lower limit. These limits have been taken between 0 and 1.00 pu.

$$RFCLj;min \leq RFCLj \leq RFCLj;max \qquad (8)$$

where

RFCLj;min minimum value of the FCL's resistance connected in series with j^{th} DG

RFCLj;max maximum value of the FCL's resistance connected in series with j^{th} DG

4. RESULTS AND DISCUSSIONS

The proposed method is tested on the distribution system of the IEEE 30 bus test system [11] shown in Fig. 3. The distribution system is fed from three primary distribution substations (132kV/ 33kV) at bus 10, 12 and 27. The system has 29 directional over current relays having inverse definite minimum time relay characteristics. The DGs considered for test has a capacity of 10 MVA, 0.9 power factor lagging, synchronous type, with a transient reactance of 0.15 pu Usually DG is connected to the distribution system through transformers. In this paper, a 10 MVA transformer with 0.05 pu transient reactance is considered.

The entire control schematic is shown in Fig. 4. First the relay coordination of IEEE 30 bus distribution system without DG is performed. In order to solve the relay coordination problem, a MATLAB code for performing load flow analysis and short circuit analysis is developed. Load flow analysis of the entire system gives prefault bus voltages and line currents. Short circuit analysis gives fault currents flowing through the lines. Then the near end fault primary and backup relay currents are calculated. Then the directional over current relay coordination problem is solved using the Genetic Algorithm. function available in MATLAB optimization toolbox. The obtained relay settings are shown in Fig. 5.

When a DG is connected to the distribution system, there will be change in both the normal power flow as well as in the fault currents flowing through the system. If the relay settings are kept fixed, some of the backup and primary relay pairs will miscoordinate.

Miscoordination can be in two ways; reduction in the coordination time interval between the backup and primary relay pairs or in certain cases the operating time of backup relay may become lesser than the operating time of the primary relay, that is, a negative CTI value.

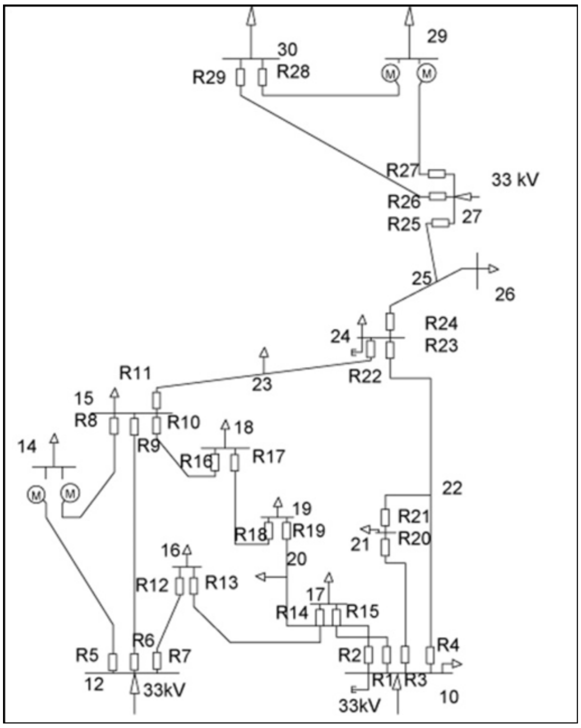

Fig.3: *Distribution system of IEEE 30 bus system.*

The fault current contribution from the DG can be reduced by placing FCL in series with the DG. FCL offer high impedance, only when fault current flows through it. It has no effect on the normal power flow.

The problem is solved using Genetic Algorithm. The solution gives the optimum resistance value required to bring the coordination time interval of all the backup primary relay pairs above the threshold

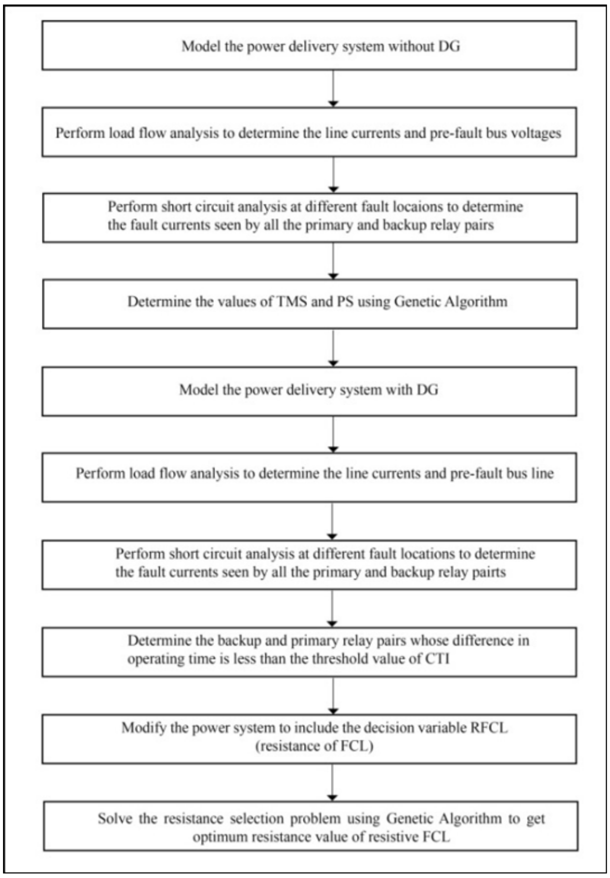

Fig.4: *Control schematic.*

Table 1: *Prefault bus voltages without DG.*

Busno	Voltage Mag.(pu)	Angle (degree)
10	1.0444	-16.024
12	1.0574	-15.3028
14	1.0424	-16.1964
15	1.0378	-16.2765
16	1.0447	-15.8806
17	1.0391	-16.1882
18	1.028	-16.8824
19	1.0253	-17.0512
20	1.0293	-16.8517
21	1.0321	-16.4683
22	1.0327	-16.4544
23	1.0272	-16.6611
24	1.0216	-16.8294
25	1.0189	-16.4235
26	1.0012	-16.8415
27	1.0257	-15.9123
29	1.006	-17.1362
30	0.9945	-18.0146

Table 2: *Load current and near end fault current seen by relays.*

Relay	Load current (A)	Fault current (A)	Relay	Load current (A)	Fault current (A)
1	116.5	6462.3	16	105.68	2006.68
2	162.48	6895.65	17	49.09	2578.71
3	310.87	6947.92	18	49.09	2768.56
4	147.62	7141.38	19	123.3	1892.73
5	136.81	6652.88	20	310.87	2666.87
6	316.48	5850.61	21	41.77	3810.2
7	131.57	5742.1	22	37.4	3895.95
8	28.16	5152.21	23	106.71	2571.97
9	316.48	2876.69	24	35.58	4187.87
10	105.68	4847.76	25	84.77	2906.31
11	98.03	4817.31	26	124.23	4355.32
12	131.57	2479.88	27	109.34	4355.32
13	65.82	2914.11	28	65.27	1323.01
14	65.82	4590.67	29	124.23	914.52
15	116.5	1614.38			

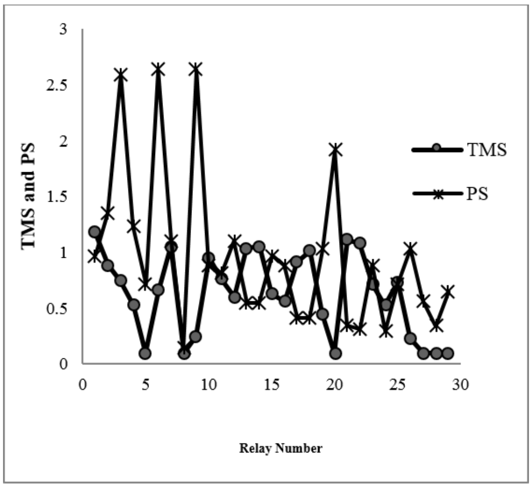

Fig.5: *Time Multiplier Setting (TMS) and Plug Setting(PS) of Relays.*

(0.2 sec).

Fig.6 shows the miscoordinated backup primary relay pairs and the extend of miscoordination, when the DG is placed at bus number 12. These miscordinations are due to backup relay operating before primary relay (negative CTI). With the introduction of resistive fault current limiter(RFCL) the miscoordinated relay pairs are properly coordinated. The optimum value of RFCL is obtained as 2.709 which is an improved value compared to existing method.

Distributed generators are placed at buses 10 and 19 as single DG as shown by Fig 7 and Fig.8. In each case some of the relays are miscoordinated. These miscordinations are due to backup relay operating before primary relay (negative CTI). When the proposed method is applied, the optimum value of resistive fault current limiter is improved.

In the method mentioned in [7], the resistance of FCL is gradually increased from a minimum value till the CTI of all the backup primary relay pairs become

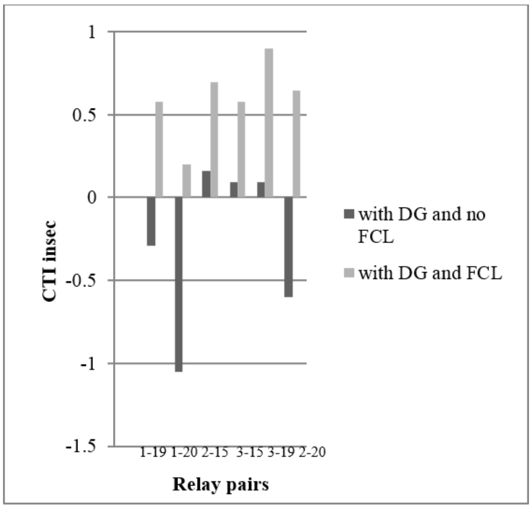

Fig.6: *Restoration of Miscoordinated Relay pairs Using Resistive Fault Current Limiter(RFCL) for DG at 12.*

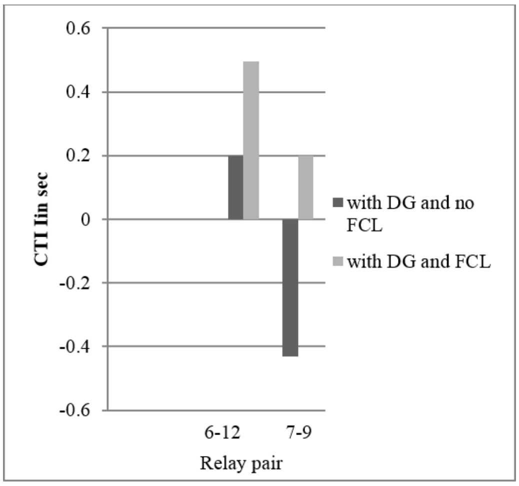

Fig.7: *Restoration of miscoordinated relay pairs using RFCL for DG at bus 10.*

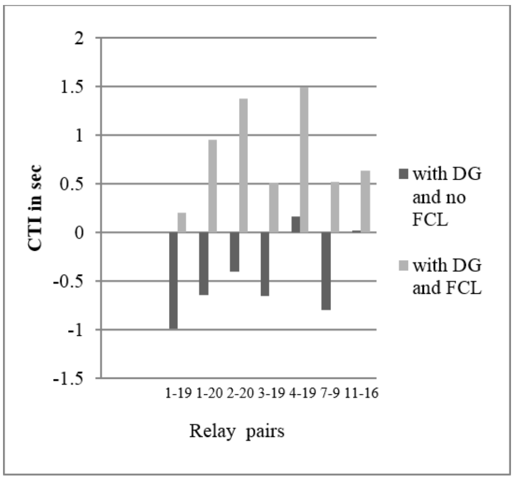

Fig.8: *Restoration of miscoordinated relay pairs using RFCL for DG at bus 10.*

higher than the threshold value of CTI. When there is more than one DG (multiple DG) connected to the system, there should be FCL in series with each DG. In the existing method, all the FCLs were assumed to have equal resistance.

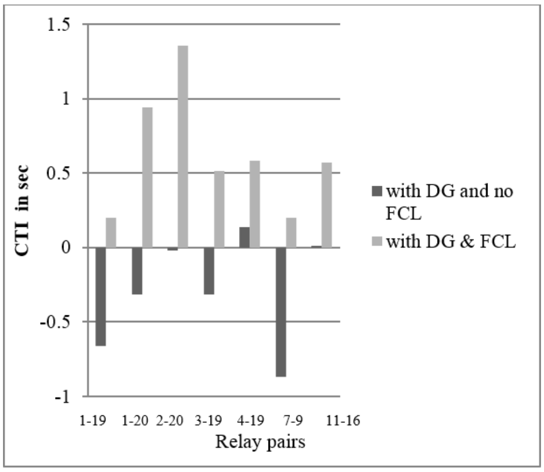

Fig.9: *Restoration of Miscoordinated Relay pairs Using RFCL for DG at Bus 10 and 12.*

This may result in very high resistance value than what is required, for FCLs placed in certain DG connected buses. But when the proposed method is applied in such a scenario, values of resistances are found to be cost effective than the existing method.

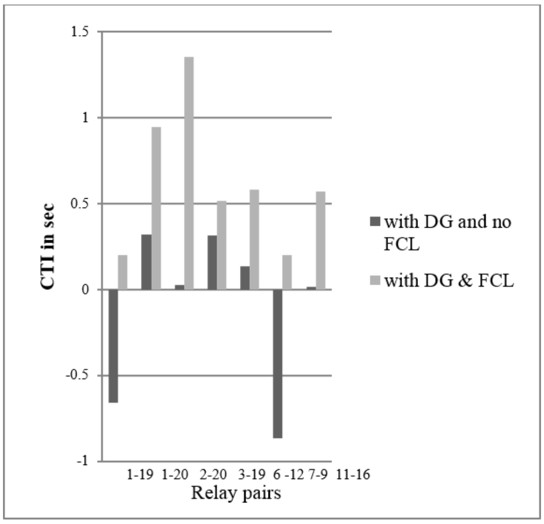

Fig.10: *Restoration of miscoordinated relay pairs using RFCL for DG at bus 10and 19.*

Fig.9 shows the effect of connecting DGs at buses 10 and12 simultaneously and the improvement in the CTI value obtained as a result of using the proposed method. There are four miscoordinated backup primary relay pairs. When the proposed method is used, the value of RFCL required to bring the CTI value above the threshold value is 0.8123pu for RFCL connected to bus 10 and 1.8919 pu for FCL connected to bus 12. With the existing method the value for both the FCL is 3.The proposed method gives an improved resistance value.Fig.10, shows the case of connecting RFCL at 10 and 19, the values of RFCL obtained by the proposed method is 2.1129pu and 8.1348.Compared to the existing value of 11pu for both FCLs. Thus by using the proposed method, FCLs with lower resistance value can be used.

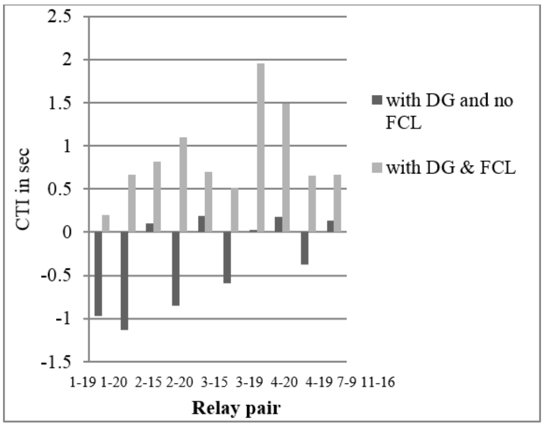

Fig.11: *Restoration of miscoordinated relay pairs using RFCL for DG at bus 12 and 19.*

Fig.11 shows the DG connection at buses 12 and 19 simultaneously. Existing method gives the values as 19 pu and proposed method values as 9.8411pu and 22.8816pu.The resistance of RFCL at bus19,obtained by the proposed method, is higher than the resistance obtained by existing method(19pu). But this increase in resistance value is less compared to the reduction (19pu to 9.8411pu) obtained in the proposed method for resistance value of FCL connected to bus 12.

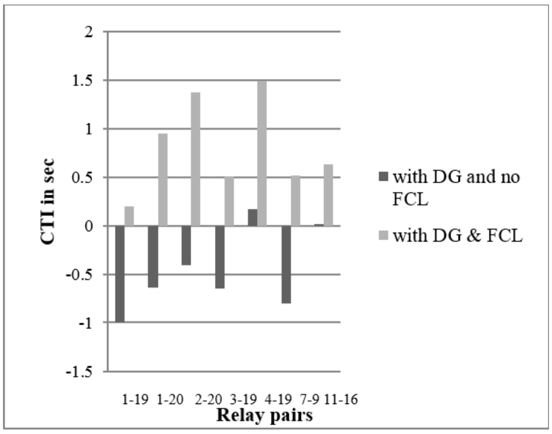

Fig.12: *Restoration of Miscoordinated Relay Pairs using RFCL for DG at Bus 10 ,12 and 19.*

Fig.12 shows the scenario when three DGs are connected to the distribution system at bus 10, 12 and 19 simultaneously with seven miscoordinated relay pairs. When the proposed method is used the values of RFCL are 1.5684pu, 5.7910pu and 9.7188 pu for FCL connected to bus 10, 12 and 19 respectively. The existing method gives a value of 19 pu for all the three FCLs. Thus with the proposed method FCL with lower resistance value can be used for restoring the original relay settings in the presence of DG.

This study is carried out to determine the minimum value of resistance of the FCL in a power system connected with single as well as multiple DG. Table 3 gives a comparison of RFCL values of the existing method and the proposed method. In each case the result obtained gives the optimum solution for the resistance value of the FCL compared with the values obtained in the existing method.

Table 3: *Optimum value of resistance of RFCL with DG at different buses.*

DG connected buses	Optimum value of Resistance of FCL(p.u)	
	existing method	Proposed method
12	3	2.709
10	2	1.0055
19	14	13.7019
10,12	3,3	0.8123, 1.8919
10,19	11,11	2.1129, 8.1348
12,19	19,19	9.8411, 22.8816
10,12,19	19,19,19	1.5684, 5.7910, 9.7188

Thus the method is suitable for a system to restore the original relay coordination in a distribution network with multiple DG connected to the system.

5. CONCLUSION

This paper introduces an effective method for determining the optimum resistance of resistive FCLs used to restore the original protection scheme of distribution systems in the presence of DG. An algorithm was developed for determining the initial settings of the relay. Relay coordination problem and selection of optimum value of resistance are determined by optimizing the problem by genetic algorithm. As the cost of FCL depends on its resistance value this method found to be highly useful. This approach is applicable for single and a multiple DG operation. Moreover the proposed method is suitable to reduce the value of resistance of resistive FCLs by significant margin when compared to existing method and thus economical. There is no need to change the protective devices in the presence of DG, as this method retains the relay coordination without altering the existing relay settings.

The future scope of proposed method is to incorporate dual Fault Current Limiter on both Grid side and DG side to retain the existing relay settings in a distribution network. Dual FCL connection increase the power continuity at the buses connected to DG and to maintain the synchronism of new DG introduction. With dual FCLs, connection of large capacity distributed generators (10MW), as gas turbine generators can be connected to the utility.

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