Applying Superconductive Fault Current Limiter to Minimize the Impacts of Distributed Generation on the Distribution Protection Systems

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Abstract—**Distributed Generation Resources are increasingly used in distribution systems due to their great advantages. The presence of DG, however, can cause various problems such as miss-coordination, false tripping, blinding and reduction of reach of protective devices. Using superconducting fault current limiters (SFCLs) is one of the best methods to minimize these problems comparing to the other conventional methods. In this paper, with defining the protection evaluating indices, the number of protection problems and the worst case among them are specified. Thus, the optimum impedance of limiter is determined. The suitability of the selected value of the minimum impedance is verified by the resolving all of the protection problems. Furthermore, comparison between the three types of superconductive limiters, i.e. resistive, inductive, and impedance has been done. According to the study, to control the fault current contribution of a DG resource and minimize the protection issues, the limiter which is placed in series with the DG unit has the most beneficial impact among other locations. Efficiency of the proposed approach is evaluated with various simulations on a real radial distribution system in two cases, having one DG unit and also two DG units with different capacities.**

Keywords- distributed generation resources; distribution protection system; superconductive fault current limiter

I. INTRODUCTION

In recent years, power generation companies have tended to the use of distributed generation resources due to several reasons, like deregulation, restructuring, advances in technology, environmental policies and increased demand for the electricity. Along with its benefits, distribution generation may have negative impacts on the distribution system since it increases the fault current level and changes the direction of the flow of current in the lines during the fault situation. The most important negative consequences can be mentioned as false tripping, blinding and/ or reduction of reach of protective devices and missing the coordination between such devices. This side effect will reduce the degree of immunity of the system.

Several corrective actions are performed to reduce the negative effects of distribution generation units on the distribution system such as checking the coordination of the protection devices every time that DG connects to the system [1], using microprocessor-based reclosers [2], taking advantage of adaptive protection [3], decreasing the generation capacity or delayed operation of DGs and changing the circuit breakers and protective devices [4], [5]. These methods impose lots of expenses, are complex and do not use the total capacity of DG units; therefore, they are not accepted widely. Using Fault Current Limiters (FCL) is a new solution to reduce the undesired impacts of DG on the distribution system. In the normal condition of the system, FCL will cause no voltage drop or loss in the system; while in fault condition, it will decrease the mentioned impacts of the DG. By the use of FCLs, the number of protection devices which should be changed after installing DG in the system will be minimized and the coordination of the protection system would be restored. Moreover, this method is not so costly and does not need performing complicated protection algorithms.

In [6] the increase of the fault current with the introduction of DGs can be limited using SFCL. Further the instantaneous voltage sag on the normal lines can be prevented. Reference [7] describes a study to determine the optimal resistance of a

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SFCL connected to a wind-turbine generation system in series considering its protective coordination. In [8], the protection coordination of the protective devices with a SFCL due to the DG introduction in a power distribution system was analyzed through short-circuit tests for the simulated power distribution system, which was comprised of the transformer, the DG, the distribution line and the load, protected by the protective devices and the SFCL. In [9], applying the FCL in series with DG and determining the limiting impedance, the problem of miss-coordination of over current relays has been solved. These papers have not studied the protection system of the distribution network and the impedance limiter used for minimizing the results has equal real and imaginary parts. In [10], optimum limiting impedance has been determined in a distribution network containing one DG unit. However, this paper has not considered other protection problems caused by DG.

In this paper, besides the studies done in other references, effect of DGs on the operation of protection devices of distribution network and the coordination between them has been analyzed. Along with the coordination issues, other protection problems have also been studied. Then, instead of applying conventional methods for reducing the effects of DG and/ or setting the protection system again, improvement of protection system and coordination between its component; is tried to be achieved using SFCL. In this process, the minimum value for the limiting impedance needed for the worst case is detected and the verification of applying this limiter for other occurred protection problems has been studied. The optimum type and size of two limiters is defined in a system containing two DG units with different capacities. The impedances of these limiters are different from each other and proportional to the short circuit impedance seen from each unit. The studies have been done on a radial feeder containing one or two DG units with different capacities and the derived results have been reported.

This paper has following structure: The second part describes setting the protection system of distribution network and coordinating the protection devices. Third part discusses the negative effects of DG on protection system of distribution network and defines protection evaluating indices according to these negative effects. Fourth part of the paper proposes utilizing SFCL to minimize these negative effects. Finally, results of simulating a case study distribution network are presented in the fifth part.

II. Setting and Coordinating the Distribution Protection System

Since distribution network in directly connected to the consumer, its optimum protection can play an important role in reducing loss of electricity, increasing reliability and augmenting the efficient lifetime of devices. Protective devices in distribution networks are mainly over-current relays, fuses and reclosers which should be properly coordinated with each other [11]. The main purpose of the coordination algorithm of distribution network is to minimize the operation time of the protective devices such that the coordination criteria between these elements are met. The objective function and the most important criteria for coordinating relays, fuses and reclosers in the distribution network are presented in the following equations:

A. Objective Function:

$$OF = \mathrm{Min}_{TMS,Is} \left(\sum_{i=1}^{nrel} trel_i + \sum_{j=1}^{nrec} trec_j + \sum_{k=1}^{nfus} MCT_k \right) \quad (1)$$

B. Fuse-Fuse Coordination Constraint:

$$MCT(P,I_{MF}) < 0.75MMT(B,I_{MF}) \quad (2)$$

C. OCR-Fuse Coordination Constraint:

$$trel(I_{MF}) > MCT(I_{MF}) + 0.2 \quad (3)$$

D. Recloser-Fuse Coordination Constraint:

$$trec(F,I_{MF}) < MMT(I_{MF}) \quad (4)$$

$$trec(D,I_{mf}) < MMT(I_{mf}) \quad (5)$$

E. OCR-Recloser Coordination Constraint:

$$trel(I_{mf}) > trec(D,I_{mf}) + 0.2 \quad (6)$$

The parameters used in above equations are defined in Table 1.

According to the (1) time multiplier setting and current setting are the decision variables.

III. Negative Effects of DG on The Distribution Protection System

Installing a DG unit in the distribution network will decrease the Thevenine`s impedance seen from the fault point, since a new impedance is being paralleled to the system, which will increase the fault current level. Furthermore, presence of DG in a radial distribution network, in which all the currents are flowed from the source to the consumers, may change the current direction in some lines. The most important negative effects of the DG on the protection system of the distribution network will be reviewed in the following sections: [12].

A. Miss-coordination Between The Protective Devices

Since the DG unit will increase the fault current flowed through the protective devices, the coordination between protective devices may be lost and there may be a disorder in the sequence of operation of the main and backup protection systems.

TABLE I. PROTECTIVE PARAMETERS OF THE SYSTEM

Time Multiplier Setting	TMS	Objective Function	OF
Current Setting	Is	Relay operation time	trel
Maximum Fault Current	I_{MF}	Recloser operation time	trec
Minimum Fault Current	I_{mf}	Backup Protection	B
Minimum Melting Time	MMT	Primary Protection	P
Maximum Clear Time of Fuse	MCT	Number of Relay	nrel
Delayed Operation	D	Number of Recloser	nrec
Fast Operation	F	Number of Fuse	nfus

B. *Protection System Blinding*

This case may happen when the impedance between the beginning of the initial feeder of the network and the fault point is significantly more than the impedance between the DG unit and this point. In this situation, the fault current from the main source decreases according to the current division law between two paralleled impedances, which may be less than the setting current of the protection device.

C. *False Tripping of The Protective Devices*

Due to the presence of the DG units in the distribution network, false tripping is mainly caused by the current flowed through the protective devices in the opposite direction in which they have been set and may cause unnecessary interrupt of part of the network.

D. *Reduction of Reach of Protective Devices*

Presence of DG units in distribution network may cause the upstream protective devices to sense a portion of the actual fault current. Hence, these devices will have inappropriate operation due to this reduction of their reach.

The effect of DG units on the power system depends on several factors such as the technology, size and the capacity of the unit, the location of installing the unit and how the unit is connected to the system.

Recent studies show that, among all other technologies, the units which use synchronous generators have the most negative impact of increasing the fault current. In order to consider the worst case in the presented study, the DG capacity is assumed to be the maximum available, which is a function of the total load of the feeder. Common installation points of DG are selected based on the environmental conditions, fuel limitations and different positions with respect to the protective devices.

E. *Detecting The Worst Case for The Protection System*

The number of all possible protection problems and the worst case among them should be defined in order to minimize the effect of each of them on the distribution network; since satisfying the protection criteria in the worst case will assure the prevention of other problems caused by the presence of DGs in the network. After defining the protection-evaluating indices, detection of the worst case is consisted of determining the worst fault location and finding the worst protective device or the worst pair of protective devices. Fig. 1 shows the effect of DG on increasing the fault current in case of a downstream fault.

As seen in this figure, the impedance from the main generation/ source to the DG common coupling point is Z_{Net} and the impedance from the DG source to this point is Z_{DG}. Z_{th} denotes the Thevenine`s impedance seen from the main source. According to these notations, the contribution of the main source and the DG unit to the fault current are obtained from the following equations, denoted by I_{Net} and I_{DG}, respectively.

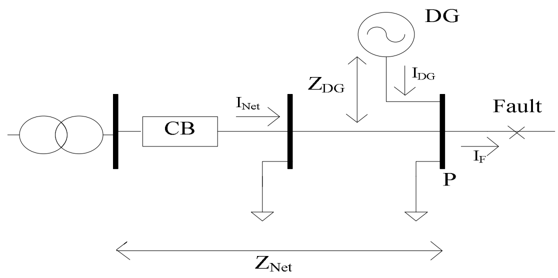

Figure 1. The Typical System to Show the Participation of the DG in the Fault Current

$$I_{DG}=\frac{Z_{th}+Z_{Net}}{Z_{th}+Z_{Net}+Z_{DG}}I_F \tag{7}$$

$$I_{Net}=\frac{Z_{DG}}{Z_{th}+Z_{Net}+Z_{DG}}I_F \tag{8}$$

According to the above equations, the negative effect of DG on the protection system becomes more severe by an increase in the distance from the main source to the fault point, hence an increase in the amount of Z_{Net}, and also a decrease in the distance between DG and the fault point which is the same as a decrease in the amount of Z_{DG} with an increase of the capacity of the unit.

The protection-evaluating indices for determining the number of protection problems and the worst case among all of them are defined in Table 2.

In this table, i denote the location of fault and j denotes the different protective devices. t_i is the operational time and CTR_i is the operational time interval required for coordinating the main and backup device. $I_{(i,j)}$ is the current flowing through the j-th protective device due to a fault in its protection zone. $I_{rev(i,j)}$ is the current passing in the opposite direction from the device and I pick-up is the setting current for the device. I_{fault} is the fault current and $I_{main\_protect(i,j)}$ is the current passing the upstream protective device located in the main path of the initial feeder. The permitted difference between I_{fault} and $I_{main\_protect}$ required for determining the index of reduction of reach is selected to be 0.1 in some papers.

According to these indices, the most critical locations of faults and the none-coordinated involved devices are determined and the worst case is obtained among them.

IV. APPLYING SUPERCONDUCTIVE FAULT CURRENT LIMITER

Despite the conventional fault current limiters such as reactors, high impedance transformers and etc., SFCLs allow the current to pass without any voltage drop or power loss in the normal conditions. In the fault conditions, however, the transition from the superconducting state to the limiting state occurs and the fault current is hence decreased significantly passing through the limiting impedance [13]. Moreover, SFCLs are more widely used in comparison with the solid state fault current limiters, since it does not require external excitation and fault detection unit.

TABLE II. DEFINITION OF PROTECTION-EVALUATING INDICES

Protection Problems	Protection Evaluating Indices
Miss-coordination	$t_i(B) - t_i(P) < CTR_i$
Blinding	$I_{(i,j)} < I_{pick\_up(j)}$
False Tripping	$I_{rev(i,j)} > I_{pick\_up(j)}$
Reduction of Reach	$I_{fault(i)} - I_{main\_protect(i,j)} > 0.1$

In order to use SFCLs to decrease the negative effects of DGs, the minimum value of required limiting impedance, the minimum required number of limiters and also the optimum location and type of SFCL are to be determined.

In a step by step algorithm, the minimum limiting impedance for the worst location of fault is defined such that the coordination criteria are met and the negative effects of the DG are minimized. The process of determining the minimum value of limiting impedance has been accomplished based on the enumeration method. The algorithm starts with an initial value for the impedance and analyzes the protection evaluating indices for this value. Then, the value of impedance is increased in specified steps and the protection evaluating indices are calculated again for each derived value of the limiting impedance. The minimum value of limiting impedance in which the protection criteria are satisfied is the desired value.

This algorithm is repeated comparing three types of limiters, i.e. resistive, inductive and impedance. In order to minimize the cost of the process of limiting the fault current in a distribution network containing two DG units, the type and value of each series limiter has chosen to be different from each other. Firstly, the impedance limiter used for minimizing the results has equal real and imaginary parts. However inductive fault current limiter is more effective in reducing the negative impacts of DGs and restoring the coordination in comparison with a resistive limiter of the same size. Since the resistive limiter costs twice than the inductive type, impedance limiter has been used in one different condition, in which the value of the reactance of this limiter is chosen twice the value of the resistive part of it. In case of impedance fault current limiter, since the reactive part is to be twice than the resistive part, minimizing the limiter means calculating the minimum resistive part. It is clear that in resistive and inductive FCLs, the minimization is done to achieve the minimum resistance and reactance, respectively.

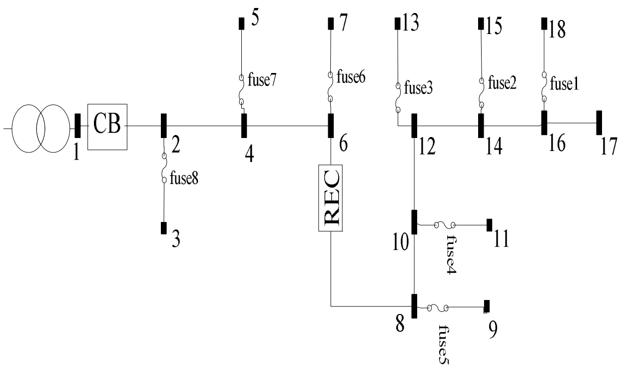

Figure 2. Case Study System with Protection Devices

According to the authentic references, the fault current limiter in series with DG has the most suitable installing location in comparison with other proposed locations, like the beginning of the main feeder or any of the laterals [14].

For defining the activation parameters of the SFCL, i.e. the activation time and the amount of activation current, it should be noted that the activation time should be less than the operation time of the fastest protection device according to the maximum fault current and the activation current should be less than the minimum contribution of DG in the fault current passing through SFCL.

V. RESULTS

A. Case Study System

Fig. 2 depicts the single line diagram of a real distribution network of nominal voltage equal to 24.9kV and nominal capacity of 2.5 MVA with specific protective devices. In addition to the over-current relay in the beginning of the main feeder, the main path of the network is protected with a recloser having a fast and also delayed operation in the line between nodes 6 and 8. Furthermore, eight fuses are used for protecting laterals. Table 3 shows the calculated values for current setting of devices.

B. Effects of Distributed Generation on The Protection System

In this section, two different cases are studied. In the first case, a DG unit based on a synchronous generator with a capacity equal to 50% of the total load of the feeder is studied. The second case contains two DG units with different capacities equal to 20% and 50% of total load of the feeder. In order to evaluate the effects of different situations on the protection system, nodes 5, 6, 11 and 17 are selected as the installing locations of DG units. The effect of the DG on miss-coordination, blinding, false tripping and reduction of reach of the protective devices are categorized and the number of events, the worst location of fault and the miss-coordinated devices are detected. The results of this analysis in a network containing one DG unit is shown in Table 4.

TABLE III. SETTING VALUES OF PROTECTIVE DEVICES

Protective Devices	Maximum Fault Current (A)	Current Setting (A)	Time Multiplier Setting
Fuse1	89.83	25	-
Fuse2	91.03	25	-
Fuse3	92.57	25	-
Fuse4	93.91	25	-
Fuse5	105.33	25	-
Fuse6	113.49	1	-
Fuse7	117.75	3	-
Fuse8	458.55	1	-
Recloser (Fast)	113.49	49.9	0.05
Recloser (Delay)	113.49	49.9	0.3
Over-Current Relay (OCR)	718.98	57.2	0.25

TABLE IV. DEFINING THE NUMBER OF PROBLEMS AND DETERMINING THE WORST CASE AMONG THEM IN PRESENCE OF ONE DG UNIT

Protection Problems	Location of DG	Worst Location of Fault	Number of Problems	Worst Protection Devices
Miss-coordination	17	18	10	Rec-Fuse1
	11	18	9	Rec-Fuse1
False Tripping	17	6	7	Rec
	11	6	7	Rec
	11	10	17	Fuse4
	5	2	17	Fuse7
Reduction of Reach	17	17	18	OCR
	17	17	11	Rec
	11	11	18	OCR
	11	11	11	Rec
	6	6	18	OCR
	5	5	18	OCR

Table 5 demonstrates the results of the second case, where two DG units are installed in the network. The presence of one or two DGs in the network has not led into blinding in this system. Furthermore, there have been some specific protection problems for two or three devices, where the number of these problems and also the worst case has been different.

C. Placement of SFCL for Minimizing The Protection Problems Caused by DGs

In this part of the paper, the SFCL has been placed in series with the DG unit in the distribution network and makes the fault current contribution of this unit to the minimum value required for the coordination.

TABLE V. THE NUMBER OF PROBLEMS AND DETERMINING THE WORST CASE AMONG THEM IN THE PRESENCE OF TWO DG UNITS

Protection Problems	Location of DG	Worst Location of Fault	Number of Problems	Worst Protection Devices
Miss-coordination	17&11	15	10	Rec-Fuse2
	17&6	15	10	Rec-Fuse2
	17&5	15	10	Rec-Fuse2
	11&6	18	9	Rec-Fuse1
	11&5	18	9	Rec-Fuse1
False Tripping	17&11	6	7	Rec
	17&11	10	17	Fuse4
	17&6	6	4	Rec
	17&5	6	4	Rec
	17&5	4	17	Fuse7
	11&6	6	4	Rec
	11&6	10	17	Fuse4
	11&5	6	4	Rec
	11&5	10	17	Fuse4
	11&5	3	17	Fuse7
	6&5	3	17	Fuse7
Reduction of Reach	17&11	17&17	18	OCR
	17&11	17	11	Rec
	17&6	17&17	18	OCR
	17&6	17	11	Rec
	17&5	17&17	18	OCR
	17&5	17	11	Rec
	11&6	11&11	18	OCR
	11&6	11	11	Rec
	11&5	11&11	18	OCR
	11&5	11	11	Rec
	6&5	4	18	OCR

The minimum per unit value for the in series limiter in the system containing one DG unit has been shown in Table 6, for different types of limiters which are resistive, inductive, impedance with equal resistive and inductive parts and also impedance with resistive part half of the inductive part. The maximum value of the limiter required for minimizing all protective problems for each of the installing locations of the DG can be chosen as the final suitable value for the limiter in that particular installing location.

The final values for the limiters in series with each of the DG units in the network containing two DG units with different capacities are presented in Table 7. In this table, the DGs are assumed to have six different combinations of installing locations in two out of four nodes, (nodes 5,6,11 and 17). The first row of each situation is related to the limiter in series with DG unit having the greater capacity.

As seen from the table, the inductive limiter restores the coordination with a less impedance in comparison with the resistive limiter, which proposes the idea of using an inductive limiter or an impedance limiter with the reactance twice than the resistance.

The obtained results are verified by checking all the derived impedances for all of the occurred protection problems as well.

TABLE VI. DETERMINING THE MINIMUM LIMITATION IMPEDANCE IN THE PRESENCE OF ONE DG UNIT

Protection Problems	Location of DG	Rsfcl (pu)	Xsfcl (pu)	Zfcl (R=X) (pu)	Zfcl (X=2R) (pu)
Miss-coordination	17	10.6	10.2	10+10i	6.2+12.4i
	11	10.3	9.7	9.8+9.8i	5.9+11.8i
False Tripping	17	0.75	0.5	0.5+0.5i	0.5+1i
	11	3.8	3.35	2.5+2.5i	1.5+3i
	5	10.3	9.85	7+7i	4.4+8.8i
Reduction of Reach	17	7.5	7.05	6.8+6.8i	4.05+8.1i
	11	7.4	7.1	6.8+6.8i	4.05+8.1i
	6	7.15	7.3	6.8+6.8i	4.1+8.2
	5	7.6	6.85	6.8+6.8i	4+8i
Final Value	17	10.6	10.2	10+10i	6.2+12.4i
	11	10.3	9.7	9.8+9.8i	5.9+11.8i
	6	7.15	7.3	6.8+6.8i	4.1+8.2
	5	10.3	9.85	7+7i	4.4+8.8i

TABLE VII. DETERMINING THE MINIMUM LIMITATION IMPEDANCE IN THE PRESENCE OF TWO DG UNITS

	Location of DG	Rsfcl (pu)	Xsfcl (pu)	Zfcl (R=X) (pu)	Zfcl (X=2R) (pu)
Case1	17	33.5	32.8	31.4+31.4i	18.9+37.8i
	11	15.3	14.9	14.3+14.3i	8.6+17.2i
Case2	17	20.2	19.2	18.2+18.2i	11+22i
	6	9.2	8.8	8.3+8.3i	5+10i
Case3	17	22.4	20.1	17.8+17.8i	10.7+21.4i
	5	10.2	9.2	8.1+8.1i	4.9+9.8i
Case4	11	20.7	19.9	18.8+18.8i	11.4+22.8i
	6	9.4	9.1	8.6+8.6i	5.2+10.4i
Case5	11	20.3	19.6	18.3+18.3i	11+22i
	5	9.3	8.9	8.3+8.3i	5+10i
Case6	6	22.8	23.2	21.3+21.3i	13+26i
	5	10.4	10.6	9.7+9.7i	5.9+11.8i

D. Determination of the Activation Parameters of SFCL

There are two points to be considered for using SFCL, the current in which the limiter starts to limit the current and also the time required for the limiter to reach to its final value. Hence, the transition current from the superconductivity state to the limiting state as well as the maximum permitted activation time are defined for each of the studies done in the system with one or two DGs and presented in Table 8.

VI. CONCLUSION

In this paper, superconductive fault current limiter is used in series with the DG unit to minimize the negative effects of the DG on the protection system of the distribution network. The main negative effects of DG on the protection system are miss-coordination, false tripping, blinding and reduction of reach of the protection devices. With defining protection-evaluating indices for each of these effects, the number of protection problems occurred and the worst case among them is detected and the minimum value of limiting impedance for minimizing this worst case is calculated. These studies have been done on a real distribution network in two cases, having one DG unit and also having two DG units with unequal capacities.

TABLE VIII. DETERMINING THE ACTIVATION PARAMETERS OF SFCL

System	Location of DG	Maximum Activation Time (s)	Activation Current of SFCL1 (A)	Activation Current of SFCL2 (A)
With one DG	17	12	43.86	-
	11	12.1	48.95	-
	6	11.6	43.95	-
	5	12	42.83	-
With two DGs	17&11	10	42.31	13.91
	17&6	10	43.47	17.38
	17&5	10.3	42.89	16.81
	11&6	10	44.63	16.81
	11&5	9.8	44.63	16.23
	6&5	10	51.58	15.07

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