

Investigation of the Effects of Distributed Generation on Protection Coordination of a Power System

Ayesha Tariq

Department of Electrical Engineering
NED University of Engineering and Technology
Karachi, Sindh, Pakistan
ayesha_0405@hotmail.com

Krishan Lal Khatri

Department of Electrical Engineering
NED University of Engineering and Technology
Karachi, Sindh, Pakistan
engrkrishan@yahoo.com

Muhammad Ibrar ul Haque

Department of Electrical Engineering
Sir Syed University of Engineering and Technology
Karachi, Sindh, Pakistan
mihaque@ssuet.edu.pk

Muhammad Amir Raza

Department of Electrical Engineering
NED University of Engineering and Technology
Karachi, Sindh, Pakistan
amir.eed.neduet@gmail.com

Sadia Ahmed

Department of Electrical Engineering
Sir Syed University of Engineering and Technology
Karachi, Sindh, Pakistan
sadiaa@ssuet.edu.pk

Muhammad Muzammil

Department of Electrical Engineering
Sir Syed University of Engineering and Technology
Karachi, Sindh, Pakistan
muzammil@ssuet.edu.pk

Abstract-The rapid increase of the electrical power demand gave rise to many challenging situations for power system control engineers as the transmission lines are operating at their maximum capacity in most developing economies. To solve this, Distributed Generation (DG), i.e. the generation of electrical power in a distribution network that provides clean energy, is gaining popularity. There are several challenges the protection of distribution networks faces after DG installation, such as variations in short circuit levels, protection blinding, reverse power flow, protection coordination, change in fault impedance, recloser-fuse coordination, selectivity, unsynchronized reclosing, false tripping, etc. In this paper, an IEEE 13-Bus System Radial Distribution System is simulated using Electrical Transient Analyzer Program (ETAP), various scenarios of DG placement are considered, their impact on the protection system is analyzed, and different techniques are proposed to minimize the effect on protection coordination. The use of directional relays, current limiting reactors, and small magnitude DGs is tested and analyzed. The way this effect varies by changing the location of DG is also analyzed.

Keywords-distributed generation; protection coordination; relays; radial distribution network

I. INTRODUCTION

In traditional power generation, large central generators at a remote end control the flow of power in transmission and distribution networks. During the '90s, a revolution caused by the connection of power generators in the distribution network as Distributed Energy Resources (DERs) or Distributed

Generators (DGs). DGs can be connected to voltages from 230V to 150kV. Small power generators are coupled at smaller voltage networks. Larger generators of capacity ranging around 100MW are connected to high voltage buses. With the insertion of DGs, the electricity supply by central generators reduces. DGs need additional facilities for the power system to function with fewer central generators being utilized [1]. There are several types of DGs, e.g. solar, wind, fuel cell, small hydro, and rotating machines [2].

The addition of Distributed Generation in a distribution network effects the power system protection coordination in several ways, e.g. fault currents and short circuit currents from the DG increase, but there are changes in power quality, increase of reliability, and changes in losses and the voltage profile. The contribution of short circuit current depends on the DG location and the location of the fault. The fault current supplied by the substation is decreased and relays are not able or take longer time to detect the fault, which reduces relay sensitivity. Fault currents caused by rotating machine DGs are higher but those by inverter-based DGs are lower. To maintain power quality, Line Drop Compensators (LDCs) or Programmed Timer Distribution Transformers (PTDTs) are used to control voltage of distribution lines. Step Voltage Regulators (SVRs) are used to compensate the line voltage for dense power flow. These voltage regulators work properly if the feeder load is balanced. However, if many DGs are located on a particular line, the power flow gap widens between the feeder lines due to back power flow and results in voltage

Corresponding author: Krishan Lal Khatri

fluctuations. The reliability of system increases due to the addition of DG sources as they locally inject power into the system. However, DGs' power flows in reverse direction and affects usual power flow, which can cause under- or over-voltage problems in the network. On the other hand, reduction in losses is one of the major positive impacts. The location of Distributed Generation units is a major issue that needs consideration in order to result in performance enhancement of the system with fewer losses. In general, the placement of DGs in the network is like placing capacitors, the only difference is that DGs provide both active and reactive power unlike capacitors that provide reactive power only [3].

In this work, the impact of the addition of DGs to a distribution network is analyzed mainly with regard to protection coordination of relays and the sizing and placement of DGs in IEEE 13-bus system is suggested with regard to the demand that there is minimum impact on protection coordination.

II. LITERATURE REVIEW

Authors in [4] proposed an expert system, tested it on a 22kV distribution network, and proposed multiple coordination settings to prevent the ill effects of DG placement. The system operates on Microsoft Windows, the interface modules and knowledge base are in Microsoft Access via Open Data Base Connectivity (ODBC). The expert system is used for the modification of protection settings. The method of "Adaptive Inverse Time Over Current Protection" was proposed in [5]. The authors suggested the calculation of newer values of Plug Setting Multiplier (PSM) by taking information from over current, fault current, voltage drop, and zero sequence fault current in the network. However, their results are not valid in changing network conditions. Authors in [6] simulated the Tunisian distribution network using directional relays and changing coordination settings on ETAP. Directional over current relays were used for correct tripping and to ensure time grading between primary and backup relay and the settings of over current relays were revised. To avoid the miss coordination problem of relays after the DG insertion, a directional feature was employed in relays. Relays and recloser settings were updated. The 11kV distribution feeder of El-Gharbia was simulated on ETAP in [7]. The directional protection scheme with relays of microprocessor type offered in [8] was used and the islanded mode with Distributed Generation was discussed. For achieving least-disturbance optimal protection settings and failure timings, the Time Coordination Method was introduced. With the new DGs, a new relay setting is generated and proposed every time on the ring system for achieving zero interruption frequency and supply failure rate [9]. Voltage sag coordination technique is based on disconnecting the DG when the voltage falls in the system to 0.5pu in less than 6 cycles. This technique is limited to small DGs [10, 11]. A method based on neural networks and fuzzy logic was proposed in [12]. The neuro-fuzzy protection scheme was based on finding the optimal settings of Inverse Definite Minimum Time (IDMT) relays constructed on the position of DG and also on power system network conditions. By this technique, the results were improved through a current and voltage phasor-based Discrete Fourier

Transform (DFT) algorithm. A Genetic Algorithm (GA) method based on finding the optimum Time Multiplier Setting (TMS) values of over current relays and circuit breaker's operating time for proper coordination of relays after DG insertion was proposed in [13]. This method is not suitable if the relays are conventional and they should be replaced by new relays which are costly. In [14], sizes and locations of DGs were found on MATLAB by using the GA on a 33-node system by allowing the relays to work on their conventional settings. The effect of three different sources (induction machines, wind turbine, and synchronous machines) on distribution network's fault current was checked on ETAP. By adding DGs, "Blind Zones" are created and different fault currents by different DGs were observed on a 4-bus system in [15]. Some major challenges in distribution systems were discussed in [16], including protection blinding, false tripping, fuse-recloser coordination, impedance variations during fault, unsynchronized reclosers, change in power flow's direction, loss of mains, deviations in levels of short-circuit currents, and the selection of a protection device. Fault Current Limiters (FCLs) were added to the system to limit the level of fault current and to avoid miss coordination issues [17].

In a nutshell, some methods that have been proposed work on changing protection device's settings after the DGs' insertion in the system. Methods that are used for solving coordination issues like Directional Relays, and FCL work with small DGs and will be discussed in detail below.

III. RESEARCH METHODOLOGY

We used the ETAP 12.6 simulation software to analyze the impact of the addition of DG units on the protection coordination of the network. ETAP is specialized software used for the analysis, monitoring, simulation, control, automation, and optimization of electrical systems. ETAP software in electrical engineering has the most complete collection of combined power system enterprise solutions. An IEEE 13-bus radial test system, as shown in Figure 1, is used in this study. The system is first modeled on ETAP and Load Flow Analysis is executed on the network to find out the power ratings of system. Short Circuit Analysis is done for finding the systems' behavior during fault conditions. Standard IEEE 13 bus is a radial feeder system with a small number of components, however it contains numerous features and can be used as an exemplary to find out the performance of power system. This system contains underground and overhead lines, distributed and spotted loads, a 500 KVA transformer, and capacitor banks. The following assumptions are considered:

- The Voltage regulator at bus 650 is not considered.
- The loads that were distributed between bus 671 and 632 are not considered.
- All the loads are three phase and constant impedance loads differentiate from one motor load.

For the protection of IEEE 13 bus system, fuses and over current relay devices are used. Current Transformers (CTs) are used for current measurement. High Voltage Circuit Breakers (HVCBs) and Low Voltage Circuit Breakers (LVCBs) are used as interrupting devices at 4.16kV and 0.4kV respectively. To

find the overall behavior of the system, and for the selection of ratings of fuses, relays, and circuit breakers, load flow analysis and short-circuit analysis is performed. Maximum 3-phase and minimum single line-to-ground short circuit currents are considered and further studied because maximum short circuit current is used for protection device's selection (devices should be capable to withstand short circuit current without damage). Minimum values are used so that protection devices should not mal-operate at minimum short circuit current. The pickup current of relays should be more than the overload current in the system and less than Single Line-to-Ground (SLG) fault current. For the selection of protection devices SLG and 3-phase fault current values are calculated on the buses as shown in Figure 2 [17].

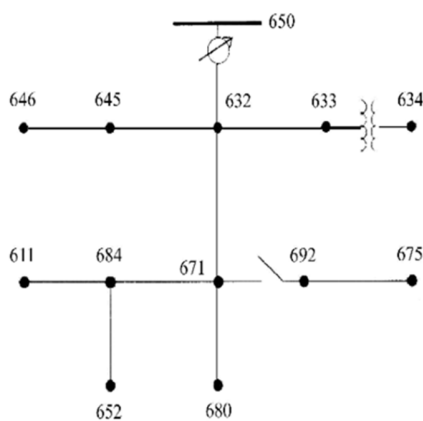


Fig. 1. Standard IEEE 13 bus system.

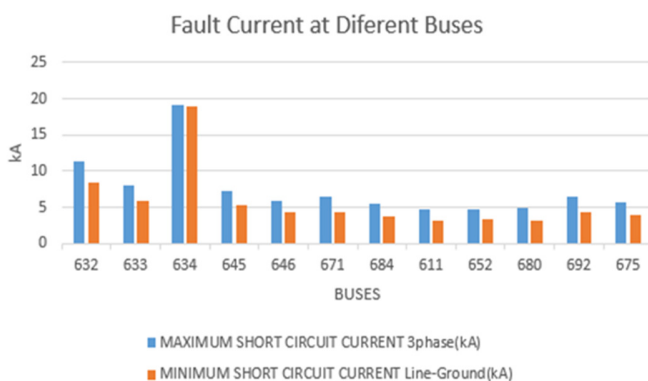


Fig. 2. Fault current at different bus.

As per calculations, maximum short circuit current is seen at Bus 634. Bus 634 is the bus with the 500KVA transformer 4.16/0.48 and is rated at 0.48kV while all the remaining buses are operating at higher voltage of 4.16kV. Fault current level is low at higher voltage levels. Inverse time over-current relays are used for feeder protection. Fuses are used for load protection. These relays operational time is inversely proportional to the fault current as shown (1)-(3). The different types of IEC curves are shown in (1), (2), and (3). Standard Inverse (SI) relays are used for the coordination of relays and the time of operation can be found with (1) [17]. ALSTOM P125 relay is used in the network. As PSM is required in (1), it

can be calculated by (4) whereas the pickup current in (4) is calculated by (5). Relays should operate when current in the CTs exceeds the 25% of normal current. Time Dial Setting (TMS) varies from 0.025 to 1 in steps of 0.025. The operating time of the circuit breaker is considered as 0.4s and 10% overshoot is considered for proper coordination between the primary and the backup relay. The time of operation of backup relays should be greater than the time of operation of the primary relay and the operating time of circuit breaker [18, 19].

TABLE I. IEC 60255 CHARACTERISTIC CURVES

Relay types	Equation
Standard Inverse (SI)	$top = \frac{0.14 * TMS}{PSM^{0.02} - 1} \quad (1)$
Very Inverse (VI)	$top = \frac{13.5 * TMS}{PSM - 1} \quad (2)$
Extremely Inverse (EI)	$top = \frac{80 * TMS}{PSM^2 - 1} \quad (3)$

$$PSM = \frac{\text{Fault current in relay coil}}{\text{Pickup current}} \quad (4)$$

$$\text{Pickup current} = \text{Rated secondary current of CT} * PS \quad (5)$$

$$PSM = top(p) + 0.4 + 10\%top(b) + 0.4 \quad (6)$$

In (6), top(p) is the primary relay's operating time and top(b) is backup relay's time of operation. An arrangement of thirteen over-current relays is used on ETAP. The TMS of relays that are closest to the load is 0.1s and the TMS of other relays is found by (1) and (6), making sure that the difference of 0.4s is maintained between the primary and the backup relay. In order to find out the impact of DG on the power system, different scenarios will be considered.

- Scenario 1: The impact on protection coordination of distribution network with the addition of DGs in the system.
- Scenario 2: The impact on protection coordination of distribution network with non-directional relays replaced by directional relays.
- Scenario 3: The addition of small DGs in the system instead of larger DGs.
- Scenario 4: The use of current limiting reactors or fault current limiters to limit the impact on protection coordination.

IV. RESULTS AND DISCUSSION

The standard system with supply from the grid only is considered. The protection of the IEEE 13-bus system is done by fuses and over current relays. Setting of fuses and relays is done on ETAP. System is perfectly coordinated before the placement of DGs in the system as verified on ETAP.

A. Scenario 1: The Effect on Protection Coordination when Adding DGs

Directly connected motors and generators are spinning as usual and supply a high amount of fault current. This extremely

high short circuit current is dangerous because it may over stress equipment that is being used in the network to break the current, such as circuit breakers. If the value of short circuit current is very small, then it is also of concern, because fault will not be detected if this is too low and there is a possibility that protection devices will not operate correctly. Reliable fault detection from GDs can be difficult due to their small ratings. Designing the scheme of DG protection should be done carefully [1]. When the size of DG increases, the contribution of upstream fault current from grid will decrease which can cause a decrease in protection device sensitivity. Short circuit current increases in the downstream network as the size of DG increases or location of the DG is moved closer to the fault

location. This may cause false tripping of relays. Some such examples are considered below. The relay settings are the same.

1) 3 MW DG at Bus 611

In this case, when a fault occurs at Bus 692, Relay 12 should operate primarily to isolate the fault. However, what happens in the system is that Relay 16 is operated first as shown in Figure 3 [16] because of the DG interconnection at Bus 611. Maloperation of relays has occurred, and protection coordination is lost. The Coordination Time Interval (CTI) between relays is below 0.3s.

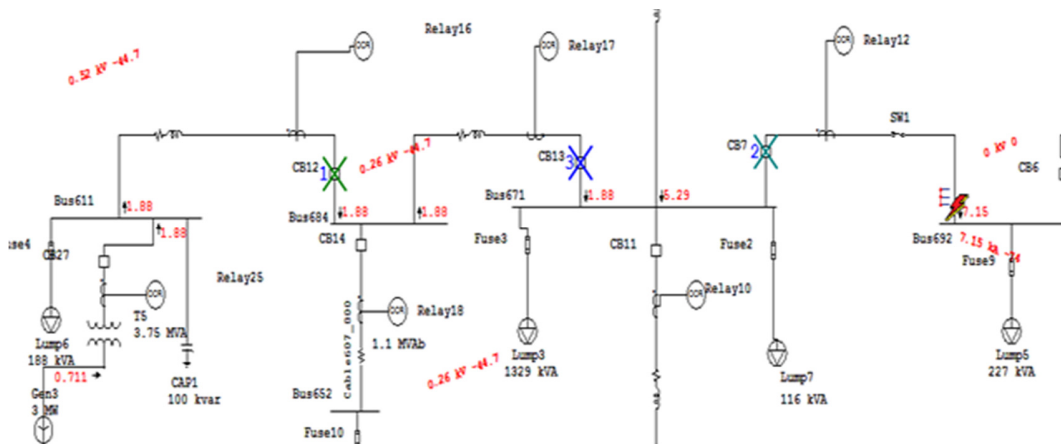


Fig. 3. 3MW DG at Bus 611.

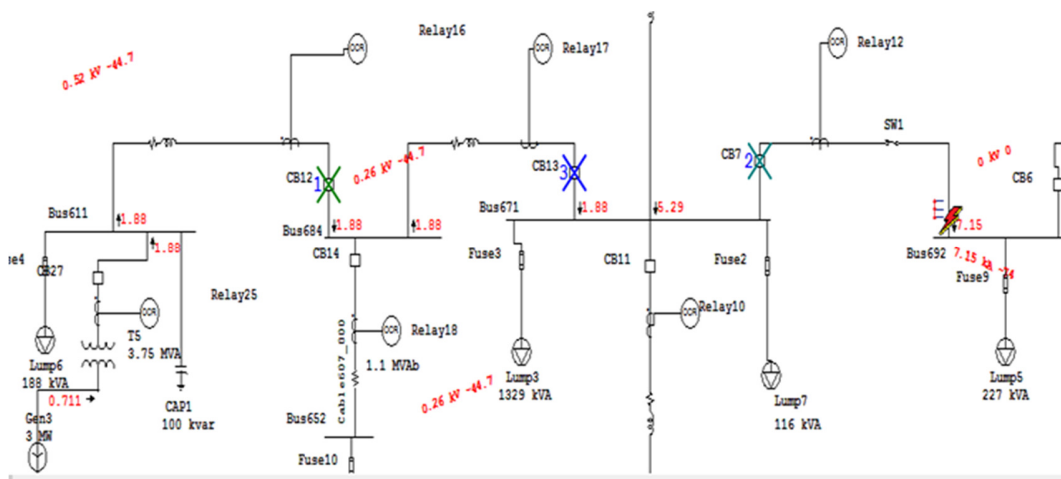


Fig. 4. 4 DGs at three different buses.

2) Three 1.5MW DGs at Bus 611, 675, and 646

In this case, 3 different DGs, each of 1.5MW are placed at 3 different points, 611, 675, and 646. A fault near Bus 692 is shown in Figure 4. False tripping occurs in this case as fault current is coming from 4 different points (the grid and the 3 DGs). The condition worsens by increasing the number of DGs in the system. Selectivity and sensitivity between the relays is disturbed. It is concluded that by the addition of DG in the system, the protection system is no more perfectly coordinated

and some changes in relay settings are required. The following three techniques can be used for solving the protection coordination issues.

- Conventional (non-directional over current) relays should be replaced by directional relays.
- Adding small DGs in the network in order to have minimum effect on the protection.
- Use of fault current limiter.

B. Scenario 2: Conventional (Non Directional Over Current) Relays Replaced by Directional Relays

Electromechanical relays were used for protection in the above scenario. With the advancement of technology, microprocessor (numerical) based devices are utilized today but there are still a lot of conventional power systems utilizing electro-mechanical relays. A directional feature can be added in modern microprocessor-based relays, but our simulation system doesn't have this capability. Hence, we used digital relays: three 1.5 MW Synchronous (diesel) DGs at Buses 611, 675, and 646. The rest of the scenario is the same with the one considered above. Conventional non-directional relays were replaced by directional relays. The system is perfectly coordinated during the fault. For the 3-phase fault in the system between fuse 9 and lump 5 as shown in Figure 5, fault current is as high as 7.5kA in Fuse 9 which operated primarily at 15.8ms, then Relay 12 at 680ms, and finally Relay 11 at 1138ms. This can make relays insensitive for fault detection or to distinguish between load and fault current. By the addition of the directional feature in over current relays, the selectivity and all other protection issues are solved. There are certain situations where coordination interval can be disturbed. To correct this, relay settings need to be changed if there is any such coordination issue.

- Voltage range should be within limits, i.e., 95%-105%.
- The thermal limit of equipment should not be exceeded.
- The protection devices should be perfectly coordinated.

Small synchronous DGs are installed in the system at Buses 611, 633, 645, 692, and 671 simultaneously. The total load connected in the distribution system is of 3.5MW. To meet the total load demand, 3.5MW of generation which consists of small DGs are added in the system and the impact on protection coordination is checked and verified as shown in Figures 6 and 7. Small DGs are installed at distant buses having low TMS values as the fault current of DG increases. Increased fault current has maximum impact on the relay that has low TMS because the time of operation of the relays is proportional to TMS as shown in (7).

Line-to-Ground (Symmetrical) fault on connector between Fuse9 & Lump5. Adjacent bus: Bus692					
Data Rev.: Base		Config: Normal		Date: 02-19-2020	
Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
35.2	Fuse9	3.876	15.2	35.2	
680	Relay12	3.525	680		Phase - OC1 - 51 - Forward
764	CB7		83.3		Tripped by Relay12 Phase - OC1 - 51 - Forward
1485	Relay11	3.182	1485		Phase - OC1 - 51 - Forward
1568	CB10		83.3		Tripped by Relay11 Phase - OC1 - 51 - Forward
3155	Relay1	2.997	3155		Phase - OC1 - 51
3238	CB2		83.3		Tripped by Relay1 Phase - OC1 - 51

Fig. 5. Fault placed at Bus 692.

C. Scenario 3: Addition of Small DGs in the Network

Replacement of conventional relays by the addition of each DG in the network is not possible sometimes due to cost and system redesign issues. Another solution is adding small DGs that have overall very small impact on the fault currents of the system. In order to penetrate Distributed Generation into the network for this scenario, power flow is performed on the network so that the voltage range is not violated. As it is discussed above, over-voltages occur on the nodes by the addition of DGs in the network. Thermal limits should not be violated, any of the equipment should not be overloaded by the addition of DGs. Protection coordination and CTI should not be violated. We analyzed DGs in the range of 100kW~10MW with a step size of 100kW. Bus 632 cannot be considered for the addition of DG because of it is connected to the grid. Maximum increase, of the order of 100%, in short circuit current is observed on Bus 634, hence it is also not considered for the addition of DG. The required conditions to maintain power quality and system integrity are:

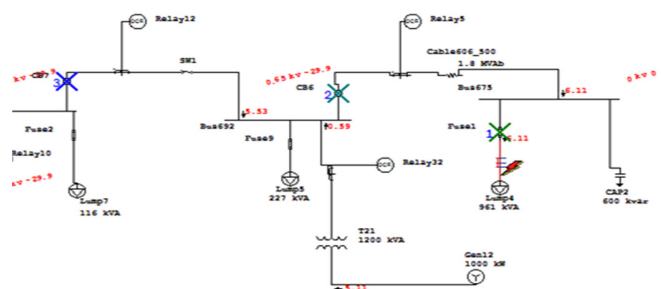


Fig. 6. Fault near Bus 675.

3-Phase (Symmetrical) fault on connector between Lump4 & Fuse1. Adjacent bus: Bus675					
Data Rev.: Base		Config: Normal		Date: 02-25-2020	
Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
9.7	Fuse1	6.108	< 9.7		Phase - OC1 - 51
227	Relay5	6.108	227		Phase - OC1 - 51
310	CB6		83.3		Tripped by Relay5 Phase - OC1 - 51
680	Relay12	5.531	680		Phase - OC1 - 51
764	CB7		83.3		Tripped by Relay12 Phase - OC1 - 51
1155	Relay16	0.099	1155		Phase - OC1 - 51
1200	Relay11	4.888	1200		Phase - OC1 - 51
1239	CB12		83.3		Tripped by Relay16 Phase - OC1 - 51
1284	CB10		83.3		Tripped by Relay11 Phase - OC1 - 51
1934	Relay14	0.349	1934		Phase - OC1 - 51
1999	Relay1	4.296	1999		Phase - OC1 - 51
2018	CB15		83.3		Tripped by Relay14 Phase - OC1 - 51
2082	CB2		83.3		Tripped by Relay1 Phase - OC1 - 51
3798	Relay17	0.099	3798		Phase - OC1 - 51
3882	CB13		83.3		Tripped by Relay17 Phase - OC1 - 51

Fig. 7. Sequence of operation for the fault near Bus 675.

$$\text{Time of Operation (TOP)} = \text{TMS} * \text{PSM} \quad (7)$$

DGs are installed at 4.16kV Buses and should not be installed at 0.48kV Bus 634 as it shows the highest impact on the system. This is because of the placement of the step down transformer between Buses 633 and 634. The over-voltages on buses are within the allowed range. The system is coordinated as observed in the two different examples discussed above and the operating time of protection devices is checked.

D. Scenario 4: Use of Fault Current Limiter (FCL)

Working with small DGs is costly and technically challenging. Large DGs can be placed in the system in the presence of FCLs. We used Current Limiting Reactors (CLRs) that limit the fault current. A CLR is used for limiting current

because it produces small loss in real (active) power. However, the use of FCL has limitations because of the power loss it causes in normal conditions. An example is considered, and the results are shown below with and without the presence of FCL in the system. In Figure 8, a DG of 3.5MW at Bus 684 with a reactor is shown. For a fault near Bus 611, the time of operation without FCL is shown in Figure 9. Relay 17 operates as a backup of Relay 16. After Relay 16 any other relay should operate after a time interval of 0.4s but in this case Relay 12 is operating simultaneously with Relay 17. This can be restricted by using FCL in series with the DG. When we did this, the relays operated sequentially as shown in Figure 10.

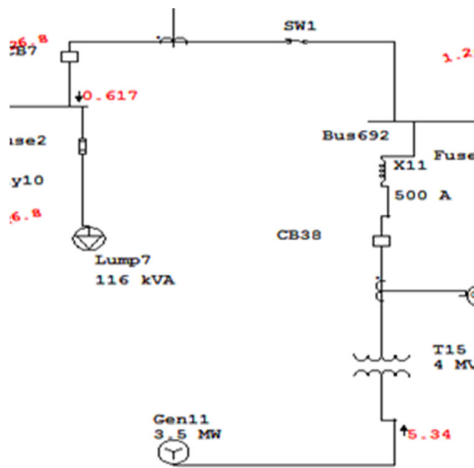


Fig. 8. 8 DGs of 3.5MW with CLR.

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
9.9	Fuse4	5.395	< 9.9		
453	Relay16	5.395	453		Phase - OC1 - 51
537	CB12		83.3		Tripped by Relay16 Phase - OC1 - 51
850	Relay17	5.395	850		Phase - OC1 - 51
912	Relay12	1.864	912		Phase - OC1 - 51
934	CB13		83.3		Tripped by Relay17 Phase - OC1 - 51
995	CB7		83.3		Tripped by Relay12 Phase - OC1 - 51
1358	Relay11	3.771	1358		Phase - OC1 - 51 - Forward
1441	CB10		83.3		Tripped by Relay11 Phase - OC1 - 51 - Forward
2389	Relay1	3.717	2389		Phase - OC1 - 51
2472	CB2		83.3		Tripped by Relay1 Phase - OC1 - 51

Fig. 9. Sequence of operations without the CLR.

V. CONCLUSION AND RECOMMENDATIONS

In this paper, the effect caused by DGs on the power system's protection network is analyzed and possible techniques for the addition of DGs to the distribution network have been proposed that result in minimum impact on protection coordination in the IEEE 13-bus system. Since it is costly and technically challenging to improve the settings of original relay systems or to upgrade the relays, the proposed techniques would help network operators install DGs with minimum impact on the distribution network. Different scenarios have been established in order to investigate the effects of DG and to find solutions to the emerging issues.

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
9.9	Fuse4	4.582	< 9.9		
453	Relay16	4.582	453		Phase - OC1 - 51
537	CB12		83.3		Tripped by Relay16 Phase - OC1 - 51
850	Relay17	4.582	850		Phase - OC1 - 51
934	CB13		83.3		Tripped by Relay17 Phase - OC1 - 51
1321	Relay11	3.984	1321		Phase - OC1 - 51 - Forward
1405	CB10		83.3		Tripped by Relay11 Phase - OC1 - 51 - Forward
1647	Relay12	0.617	1647		Phase - OC1 - 51
1730	CB7		83.3		Tripped by Relay12 Phase - OC1 - 51
2231	Relay1	3.927	2231		Phase - OC1 - 51
2314	CB2		83.3		Tripped by Relay1 Phase - OC1 - 51

Fig. 10. Sequence of operations with the CLR.

Coordination issues and other problems related to protection can be solved by the use of directional over current relays in the network. The drawback is the difficulty of replacement of the conventional electromechanical relays that are already installed in the system. This will not be the case for numerical relays. Another solution is using small DGs with very low power ratings and low fault currents. This will have minimum impact on protection system coordination and very few protection coordination issues will arise. However, it can be economically and technically challenging due to the issue of protection blinding. The third method proposed is using FCLs to limit the current from the DG. FCLs can be used in the network for limiting the fault current from the DGs. For this optimal value, CLR's need to be calculated as they produce power loss in normal conditions also. By using FCLs in the network, DG selection is based on the trade between minimum impact on protection coordination with low real power loss in normal conditions.

VI. FUTURE WORK

Simple CLR's were analyzed in this work and their effects on protection coordination of relays were studied on ETAP software. By the use of limiters in the network, working with DGs of different types and sizes will have minimum impact on system in terms of current injection from the devices. However, it results in a tradeoff in terms of power loss in usual network operation. With the recent advances in conductor materials, advanced technologies have been introduced for limiting currents from DGs such as the use of superconducting materials. Superconducting FCLs have very small resistance and have almost no impact on normal real power flows. However, in order to use such current limiters in the system, a comparison between the cost of power loss and the cost of changing of relays should be analyzed before implementing. In future work, we aim to study and analyze limiters that operate in fault conditions only and do not cause any power loss during normal operating conditions.

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