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Comprehensive study of protection issues related to the integration of distributed generation into the main power grid

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A Comprehensive Study of Protection Issues Related to the Integration of Distributed Generation into the Main Power Grid

Submitted by

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Abstract

Distributed generation presents a futuristic form of power generation and consumption system which employs different technologies to generate electric power close to the point of consumption. Distributed generation is characterized by high efficiency, low emission of greenhouse fumes, high reliability, and high quality of power. However, the effectiveness of distributed generation is limited by several protection issues that arise from the disturbances induced by the incorporation of distributed generation in the main grid. The incorporation of distributed generation in the main grid causes bi-directional power flow and impacts fault current levels which in turn affects the performance of the protection equipment of the conventional grid. The direction of power flow in conventional grid is unidirectional, power flows from the generation and the transmission side to the distribution side. Inserting distributed generation in parallel with the utility grid cause the power to flow in more than one direction in which power flows to the distribution side and to the transmission side.

The main protection issues associated with distributed generation include the blinding of protection, false tripping, and increase of fault current level. These issues have been explained and simulated using an IEEE 13 node model using MATLAB (Simulink) software. Simulation results validate these issues and shows how these issues depend on factors such as the size, location and type of distributed generation and the specific fault. With the increasing demand for electricity and growth of distributed generation, these issues will negatively affect the protection system currently integrated with the grid. Gaining a clear understanding of these issues represents a first step in solving these problems that have slowed the integration of distributed generation into the main power grid.

Table of Contents

Acknowledgments

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List of Tables

List of Figures

List of Abbreviations

CHP	Combined Heat and Power
DERs	Distributed Energy Resources
DG	Distributed Generation
DNs	Distributed Networks
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
MV	Medium Voltage
OCRs	Over Current Relays
PCC	Point of Common Coupling
SCCR	Short Circuit Current Rating

Chapter 1: Introduction

For the past several years, there have been changes in the electric grid such as efficiency improvement, reliability, and the introduction of the smart grid. The concept of a Microgrid is one of the technical approaches that have been considered actively for improving the grid. According to the US Department of Energy, "A microgrid, a local energy network, offers integration of Distributed Energy Resources (DERs) with local electric loads, which can operate in parallel with the grid or in an intentional island mode to provide a customized level of high reliability and resilience to grid disturbances." [1]. Microgrids are advanced, integrated distribution systems that are mainly applied in locations where there are constraints of electric supply, in remote sites, and in areas where protection of economically sensitive development and critical loads is needed. They are independent of the bulk electric power network.

As the complexity of the local infrastructure grows, microgrids strive to meet all the local objectives. Most of the times, microgrids work along with the main distribution network. At times, it can be transitioned into an island operation mode also. In this mode, the microgrid is totally disconnected from the main grid. This occurs when the objectives of the community are challenged in such a way that the microgrid's intelligence determines that in island mode, the community can be served more reliably, economically, and environmentally. Once the challenges have passed, the transition of the microgrid can be seamlessly done to grid-connected operations. Thus, a microgrid can be connected and disconnected from the grid to make it operate in both island-mode and grid-connected mode.

An example of a microgrid is the Combined Heat and Power (CHP) system which is based on a natural gas combustion engine, fuel cells, renewable energy, or diesel generators. A true microgrid is not just a backup power system, but much more than that. A microgrid also has to include methods to interact with the grid, real-time, and at-site controls in order to match the generation and storage capacity of the microgrid to provide power in real-time.

Chapter 2: Background

Microgrids are medium-voltage or low-voltage networks that can interconnect various storage devices and Distributed Generations (DGs) micro-sources with loads. They can be either DC or AC grids. Resources such as biomass, wind, photovoltaic, hydro-, and CHP plants are used by the DG micro-sources. The main storage devices are batteries, flywheels, and super-capacitors. The loads, storage devices, and DG sources are connected to the microgrid via power electronic interfaces. The maximum load capacity of an individual microgrid is around 10 MVA.

A microgrid can operate in stand-alone (island) mode or connected to the main distribution grid. Microgrids can successfully be deployed in urban and rural communities, commercial areas, and at industrial sites. A grid-connected microgrid can either export power to the main voltage distribution grid or import power from it [2]. The microgrid from which excess generated power is exported to the MV distribution grid is known as Net Generator.

The balance between the load and generation is changed dynamically within the grid-connected microgrid due to variable load demand and intermittent generation from renewable sources of energy. Variations in demand of load and generation also takes place because of seasonal changes in temperature, wind, and intensity of sunlight. Thus, microgrids not only increase the capacity of energy and efficiency but also provide complementary solution of power grid and improve the reliability of power quality and power supply.

The key features of a microgrid include the following functions [3]:

- Can operate in both grid-connected or autonomous (island) mode
- Designed in such a way that it accumulates the requirements of total system energy
- The interconnected loads and the sources of co-located power generation are combined
- The microgrid is presented as a single-controlled entity
- Varied levels of reliability and power quality are available for end-users

2.1 Types of Microgrids

There are three key types of Microgrids depending on their bus connections and energy exchanging method with the utility which are categorized as follows:

2.1.1 AC Microgrid

AC microgrid is one in which a three-phase AC bus is normally employed as the Point of Common Coupling (PCC). The only power interface that is available between the microgrid and the utility grid is the PCC. A fast switch is placed in between the utility grid and PCC which acts as the cutoff point between the utility grid and microgrid [4]. Figure 2.1 shows the basic connectivity structure of AC Microgrid connected into the grid.

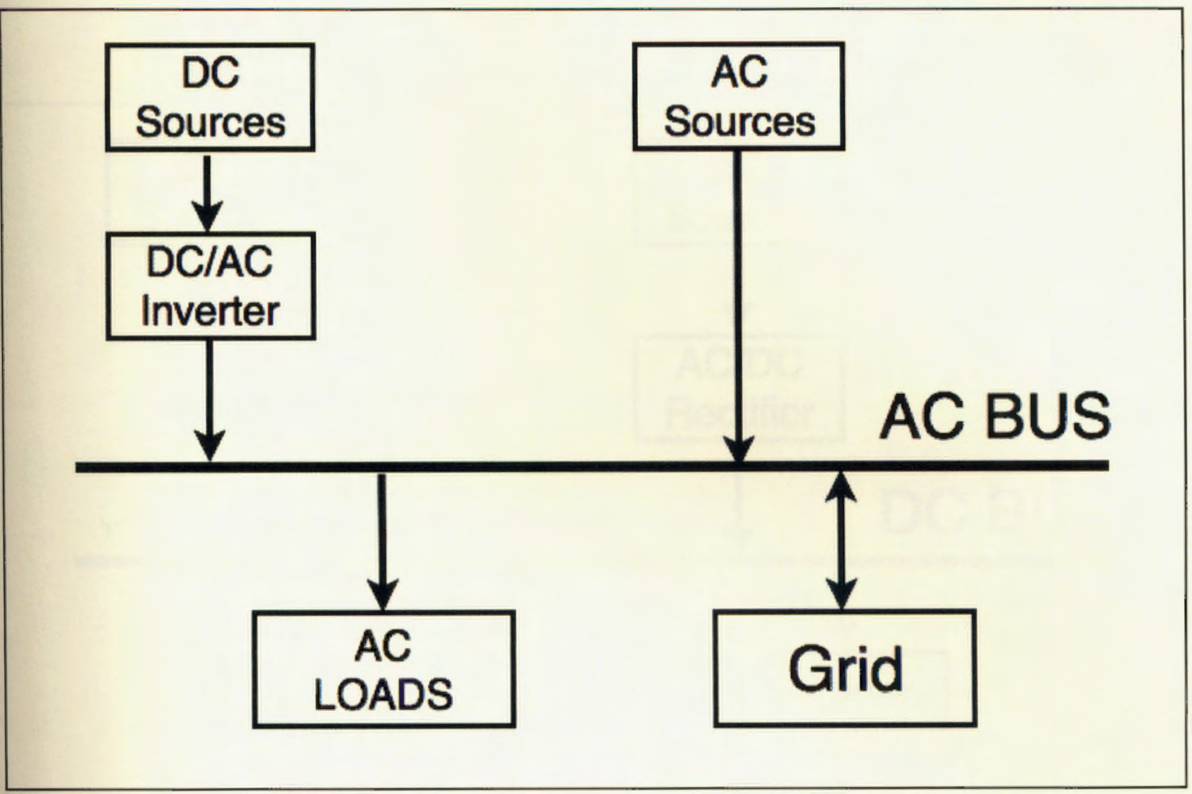

Figure 2.1: Basic structure of AC bus

2.1.2 DC Microgrid

DC microgrids are commonly designed for a distributed DC power source which connects intermittent renewable power sources, DC loads, and energy storages. Unlike the AC microgrids, it is not directly connected to the three-phase AC utility grid but through a bi-directional AC or DC converter for common integration. The operation and control of the DC microgrid is very important in order to achieve cost benefit, enhanced performance, and improved reliability [5]. Figure 2.2 shows the basic structure of a DC microgrid which is mainly represented by DC loads and the DC bus is connected to the the grid throgh an inverter.

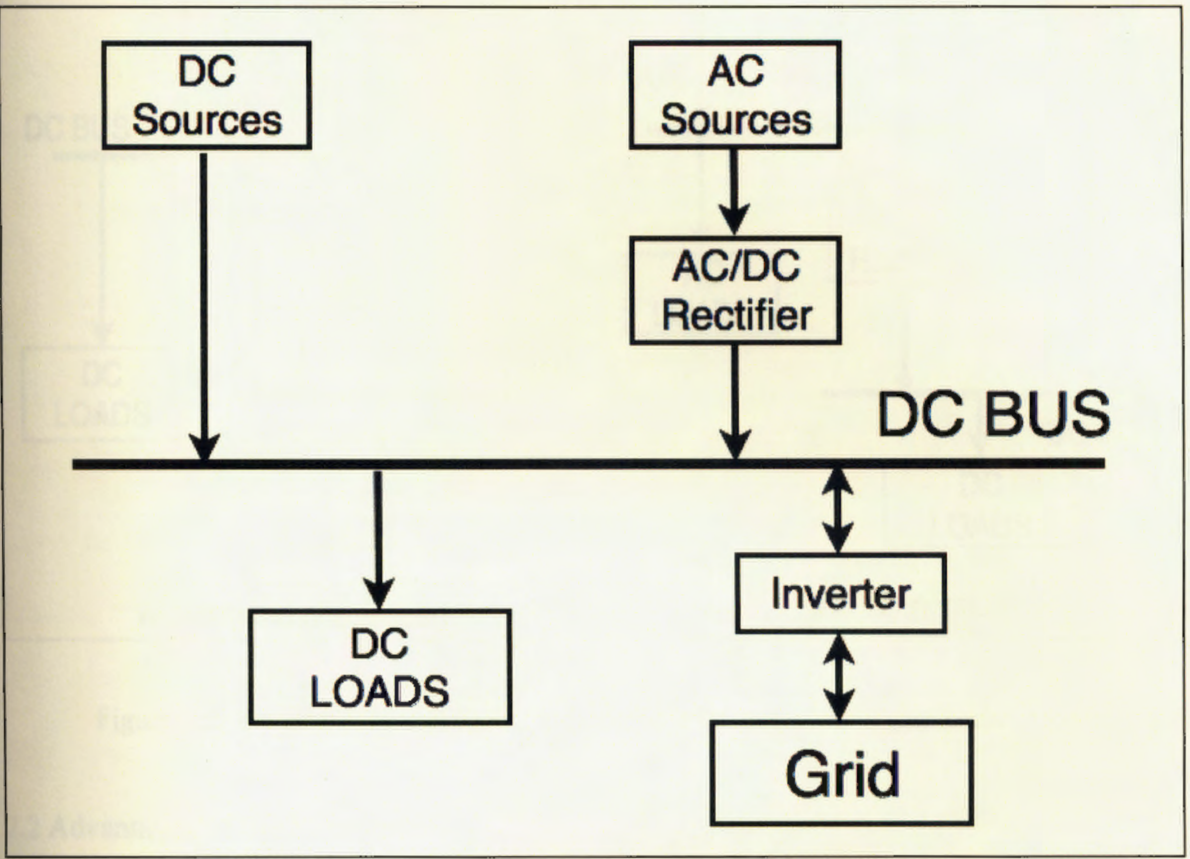

Figure 2.2: Basic structure of DC bus

2.1.3 Hybrid Microgrid

The benefit of conventional and renewahle power generation is combined in the hybrid microgrid while offsetting their weaknesses. Lower long-term operating cost and lower total cost of ownership are delivered by the hybrid microgrid as compared to pure conventional power generation. Figure 2.3 shows the mixed connection of AC and DC buses with and without the grid.

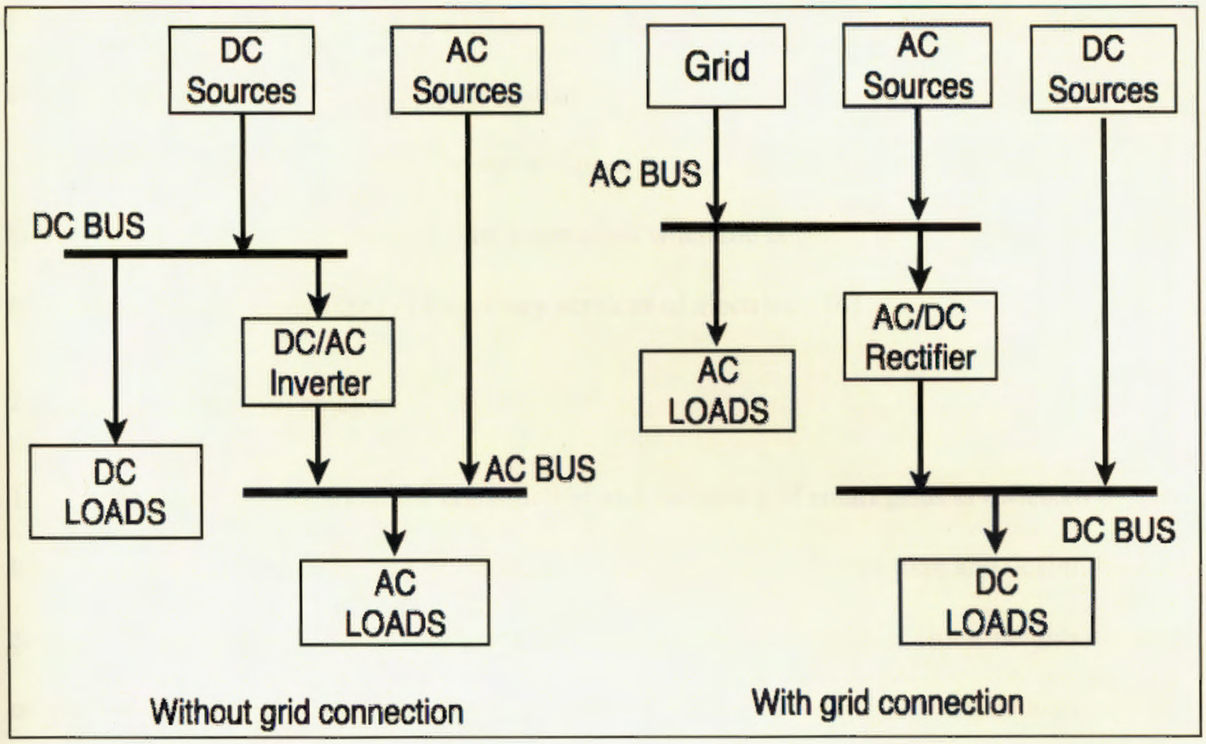

Figure 2.3: Basic structure of hybrid microgrid with and without grid connection

2.2 Advantages of the Microgrid

From the perspective of an electric grid, the primary advantage of microgrids is their ability to operate as a single collective load with the power system. There are various advantages of microgrids which are discussed as below:

2.2.1 Reliability Advantages:

The creation of a specific reliable improvement plan through smart microgrids increases reliability through which integration of the power storage, network distribution, smart switches, power generation, automation, and other smart technologies takes place. Blackouts are minimized by local power storage and generation by which independent operation of the grid and critical facilities is possible at the time of need. The use of smart technologies such as sensors and switches automatically fix disturbances in power distribution. Continuous flow of power is ensured by the micro-sources when interruption of power is caused by ice, storms, or any other circumstance. The bulk power grid is also backed up by the microgrids when the cost and power demand are highest by ensuring a continuous supply of ancillary services of electricity [6].

2.2.2 Improvement Advantages:

The new thought process about the construction and designing of smart grids is reflected by the term 'microgrid'. The approach of the microgrid is focused on creating a plan and design for local energy delivery that meets the exact needs of business parks, universities, cities, neighborhoods, or major mixed used development. The integration of the buildings and consumers with the generation and distribution of electricity is done by the smart microgrids in an efficient and effective manner [6]. In some of the cases, power is restored immediately to an entire operation or building by the microgrid in such a way that occupants are barely aware of the occurrence of any disturbance.

2.2.3 Economic Advantages:

Generation of Revenue: Valuable services can be supplied by businesses and consumers to the grid in return for payments from the independent service operator or serving utility. Real-time price response, capacity support, voltage support, spinning reserve, day-ahead price response, and demand response are some of the sources of generation of revenue. Additional consumer revenues can be collected from plug-in electric vehicles, carbon credits, and distributed power generation. Depending upon the programs and regulations of the local market, the electricity bills are reduced significantly by the use of microgrids and savings are generated by the reduction of peak load charges [7].

Encouragement of Economic growth: The economies of more and more nations and communities get a lot of benefit from microgrids by the creation of new jobs at the local level. The stakeholders also get new business opportunities. By encouraging the development of microgrids, a new electricity business model has been established by some of the countries that are more responsible environmentally and is more efficient also. Implementation of the microgrid approach is best followed in Denmark and Japan [8].

Saves money for consumers: In the United States, businesses and consumers lose a lot of money due to power outages. These costs are significantly reduced by the reliability of smart microgrids. Power can be procured easily from smart microgrids in real-time at considerably lower costs. Financing and long-term modernization plans are usually included in the model of the microgrid by which the infrastructure improvement costs, that are normally passed on to the ratepayers are reduced [8].

2.2.4 Environmental Benefits:

Carbon Reduction: Microgrids offer a most important environmental benefit in that they have the ability to use local renewable generation. Natural gas or other renewable sources of energy can be used to generate local power. It is possible for smart microgrids to get most of the energy from clean and renewable sources because they have the necessary flexibility needed to integrate a wider range of sources of energy. Microgrids currently integrate energy from solar and wind sources, particularly, more readily than the "regular" grid [6]. Microgrids are better positioned, than the centralized grid, to meet the growing need to integrate energy from renewable, environmentally friendly sources.

Chapter 3: Protection issues in Microgrid

The implementation of bidirectional flow of electric power in Distributed Networks (DNs) is faced with numerous challenges related to issues such as system protection, frequency control, energy management, power flow control, security, adequacy, power quality, and voltage profile [9, 10,11]. Microgrids facilitate the transmission and distribution of power from DG sources to the point of consumption. Ever since the concept of microgrids was introduced, it was realized that designing efficient protection scheme for them would not be easy and the current use of protective relays would need advancement. The variation in the magnitude and the direction of the fault current that is caused by the introduction of DGs in DNs renders the conventional short-circuit protection systems ineffective [12].

The difference of microgrids in terms of their feeder sizes, topology, locations, types of fault interruption devices, and generation mix are some of the main challenges that are being faced in the development of standardized microgrid protection. Several operational aspects of power systems are affected by the introduction of DGs during the operation of island and grid-connected modes of microgrids [13]. The implementation of the microgrids protection systems is limited by two major factors which include the dynamic nature of the networks and the ability to operate in island mode and grid-connected mode with different short-circuit currents [14].

In both modes of operation in microgrid, island and grid-connected, the fault currents are different. There is a loss of sensitivity, disconnection of generators, earth leakage, islanding, overcurrent, single phase connections, and loss of stability due to these faults. Depending upon where the fault is located with respect to existing protection equipment and distributed generators, issues such as the change in voltage profile and bidirectional power flow occurs [15].

Moreover, the implementation of the bidirectional microgrid is limited by several challenges related to system protection such as the complexities associated with the adaptation of the grid to variations of the network topology induced by the connection or disconnection of active sources [16]. The ability of microgrid systems to incorporate different power generation technologies such as synchronous generators and induction generators that have varying electric and voltage characteristics creates disturbances in the microgrid which interferes with the integrity of the protection systems. The synchronization of the frequencies, phase sequences, and the phase angles of the voltage generated from the DG sources with those in grid and microgrid networks is critical for alleviating catastrophic disturbances in the transmission and distribution networks. The synchronization process ensures that the voltages at the terminal of the DG sources are equal to the voltages of the main grid before connecting the two systems. The lack of adequate synchronization causes heavy disturbances in the grid which damages delicate and unprotected DG sources and power equipment.

The protection of DGs and the microgrid is limited by several challenges such as variations in short circuit levels, false tripping, blinding of protection, and unsynchronized reclosing [17]. The insertion of DG to the utility grid increases the level of fault current flowing through the grid network. The incorporation of the synchronous generators in the DG unit causes the fault current generated by adjacent feeders to multiply significantly leading to the false tripping of healthy feeder lines [18]. The connection of the DG unit and the substation in parallel causes the reduction of the fault current contributed from the main grid which limits the ability of the Over-Current Relays (OCRs) to detect it [19]. The reduction of the fault current limits the protective zone of the relays and other protection leading to the formation of a phenomenon called the blinding of protection. The following section describe these critical fault situations in more detail. The three main protection issues are:

- Blinding of protection
- False tripping
- Increase of fault current level

3.1 Blinding of Protection

The implementation of short-circuit protection for conventional distribution network is mainly done with OCRs which are coordinated to protect the overall grid [20]. Short-circuit protection of the conventional distribution networks is implemented using a variety of relays such as definite-time relays and inverse-time relays. Introduction of a DG in the network leads to a situation where the substation and the DG unit feed the fault in parallel creating a phenomenon known as blinding of protection.

There is a reduction in the contribution of fault current coming from the grid because of the contribution of the DG. The connection of the DG unit in parallel to the substation of the main network generates short circuit impedances which reduce the amount of fault current of the main substation flowing through the feeder relay. Due to this reduction, there are fair possibilities that the short-circuit remains undetected or there is a delay tripping of the OCRs. This is mainly due to the reason that the short-circuit current contributed by the grid is decreased or never able to reach the feeder relay's pick up current [21]. This phenomenon takes place when a large-scale conventional DG unit is connected at any location between the fault location and the feeding substation. Due to the contribution of the Distributed Energy Resources (DERs), the measurement of the fault current by the feeder relay which is normally connected at the feeder's starting position is decreased hecause in comparison to the network situation in which no DER is connected and thus, the relays malfunctioning operation is observed [22]. Figure 3.1 below shows the phenomenon of blinding protection when the DG unit is connected to a distribution feeder between the location of the fault and the main grid. The fault contribution from the grid is reduced due to the DG unit's partial contribution, and the lower short-circuit current value is sensed by all the upstream relays R3, R2 and R1. This results in delayed tripping or no tripping at all, thus, suffering from 'blinding'.

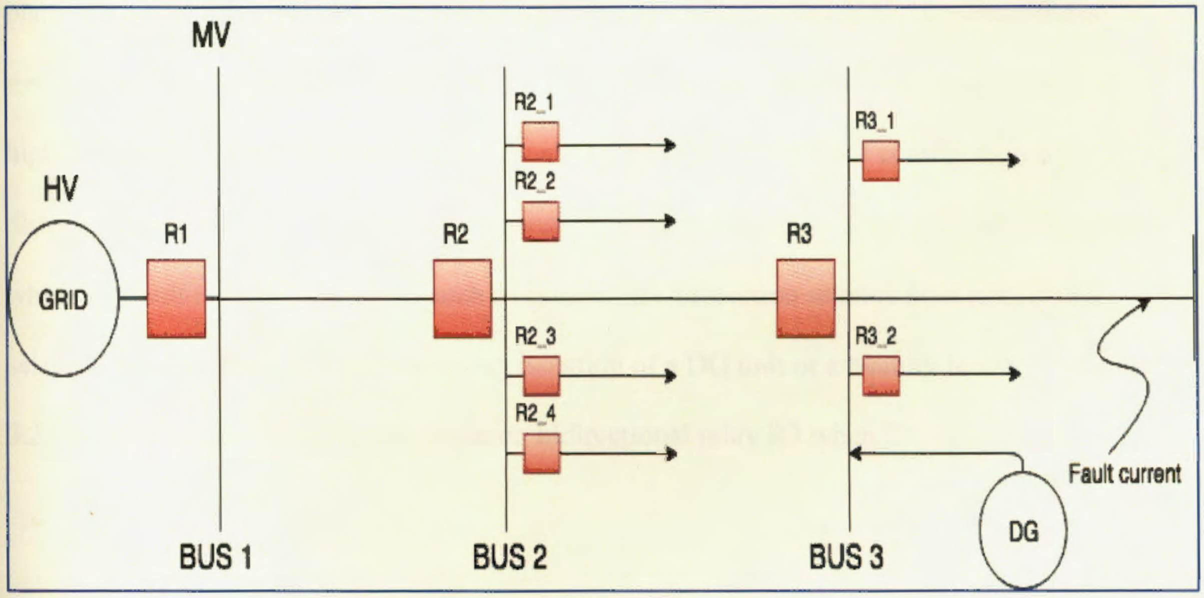

Figure 3.1: Blinding protection on R3, R2 and R1

The impact of the blinding phenomenon is also dependent on the type and location of the faults. Faults with high levels of impedances and single-phase faults tend to have more effect on the blinding of protection compared to other faults. The occurrence of the inverse-time relay blinding causes delays in the responsiveness of the protective equipment and the thermal instability of lines and relays. On the other hand, the occurrence of definite-time relays blinding renders the operation of the protection equipment ineffective due to low levels of fault currents [23].

3.2 False Tripping

The protection of the conventional distribution network is implemented with relays and protection equipment designed to monitor and withstand unidirectional fault currents.

False Tripping (Sympathetic tripping) occurs when the operation of a protective device takes place in an outside protective zone for faults. Sometimes distributed generator contributes towards the fault on a feeder which is being fed from the same substation or even to a fault at higher voltage levels [24]. There can be situations when an unexpected contribution from a distributed generator's unit leads to the operation of the bidirectional relay with another relay by which the fault is actually seen. In such a scenario, the protection scheme does not remain selective and the result is the unnecessary isolation of a DG unit or a healthy feeder [25]. Figure 3.2 below shows the false tripping issue on bidirectional relay R3 when DG is connected.

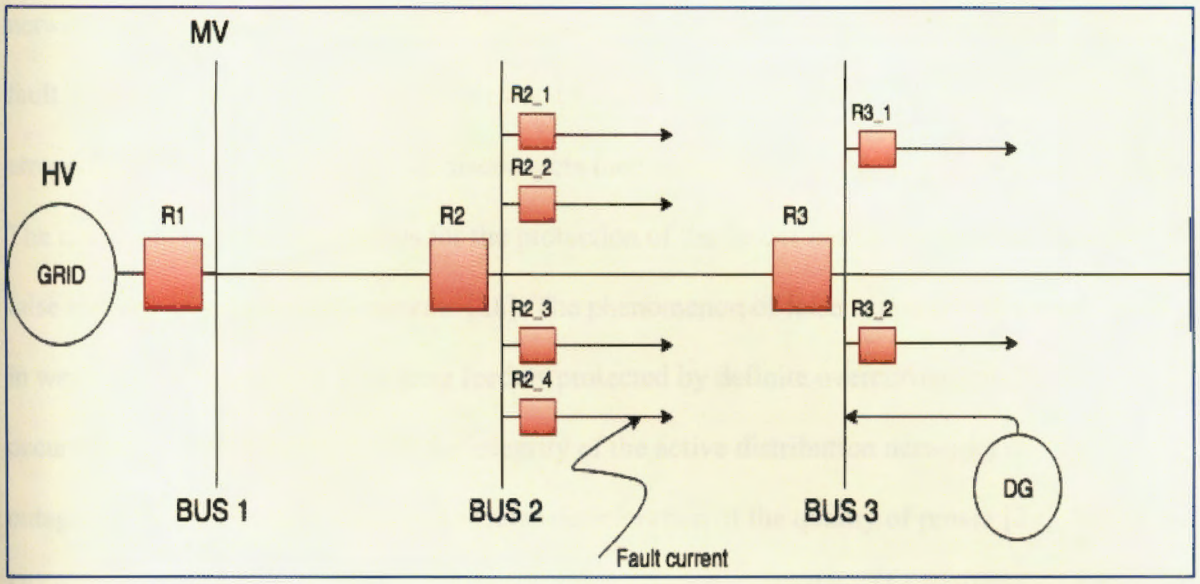

Figure 3.2: false tripping on R3

The occurrence of the fault at the indicated point is expected to trip relay R2_4 due to its close proximity to the fault. The addition of the DG to the grid network increases the amount of the fault current in the circuit which leads all the hidirectional relays located between the DG and the fault to sense the fault.

False tripping is a common protection problem in DG systems which limit the transmission and distribution of power. The occurrence of false tripping is determined by the location of the DG unit on the feeder and its capacity [26]. The proximity of the DG unit to the fault increase the likelihood of false tripping to occur as does the size of the DG, the larger the DG, the higher the chance of false tripping.

Occurrence of false tripping is a complex process which is initiated when a healthy feeder line is exposed to a surge current after the clearance of a fault on an adjacent faulted transmission line [27]. The change of direction of the fault current due to the addition of the DG unit in the main network interferes with the operation of the auto recloser system which limits its ability to clear a fault. The exposure of the healthy feeder line to the faulty current causes the relay to make an erroneous tripping command which disconnects the transmission or the distribution of the power. The use of the definite-time relays for the protection of the feeder has been observed to cause false tripping in adjacent DG systems [28]. The phenomenon of false tripping is more prevalent in weak grid networks that have long feeders protected by definite overcurrent relays. The occurrence of false tripping limits the integrity of the active distribution networks such as the outages of the non-critical loads and adverse deterioration of the quality of power [29]. Without a DG present, a grid fault is contained by the nearest transmission relay. The occurrence of the fault between the grid and the DG causes the relays on the DG side to sense the contributed fault current coming from the DG which leads to their tripping.

3.3 Increase of the Fault Current Level

Insertion of the DG into the main grid increases the magnitude of the fault current generated by the two systems which exceeds the capacity of the protection relays and other protective equipment [30]. The generation of excessive fault current limits the ability to coordinate protection of the transmission lines, the distribution network, and the feeder lines. Moreover, the generation of the excessive fault currents causes false tripping and destruction of the protection relays.

The increase of fault currents in the DG is caused by several factors which include the increment of the generation capacity, the reconfiguration of the network, implementing changes to the connected DG units, and the addition of new sources of power [31]. The installation of new transmission and distribution facilities such as transformers, transmission lines, and distribution networks among others, to meet the increasing demand reduces the overall impedance of the system which causes an increase in the amount of fault current in the network.

Additionally, an increase in the output capacity of the connected generators enhances the overall capacity of the sources of power which consequently leads to an increase in the amount of fault current generated in the grid [32]. The reconfiguration of the electric system network leads to critical changes such as the restructuring of the sources of power, interconnection of adjacent lines, transmission lines which leads to the increase of voltage levels at various distribution nodes and subsequently the occurrence of large fault currents. Moreover, the addition of new sources of power in the DG unit or the addition of DG units on the main grid increases the amount of fault current.

The increase in the amount of fault current in the grid network poses several challenges to the management of the grid protection system. The prolonged exposure of the protection relays to high fault currents beyond their ratings tends to deteriorate their responsiveness to faults. The increment of the fault current causes thermal and mechanical damage to the relays and the circuit breakers. The intensity of the fault occurring in busses close to the DG unit tends to be high compared to those occurring a distance from the DG unit due to low impedance. This phenomenon is well described by Ohm's law which observes that the amount of current increases with a decrease in the impedance when the voltage is held at a constant.

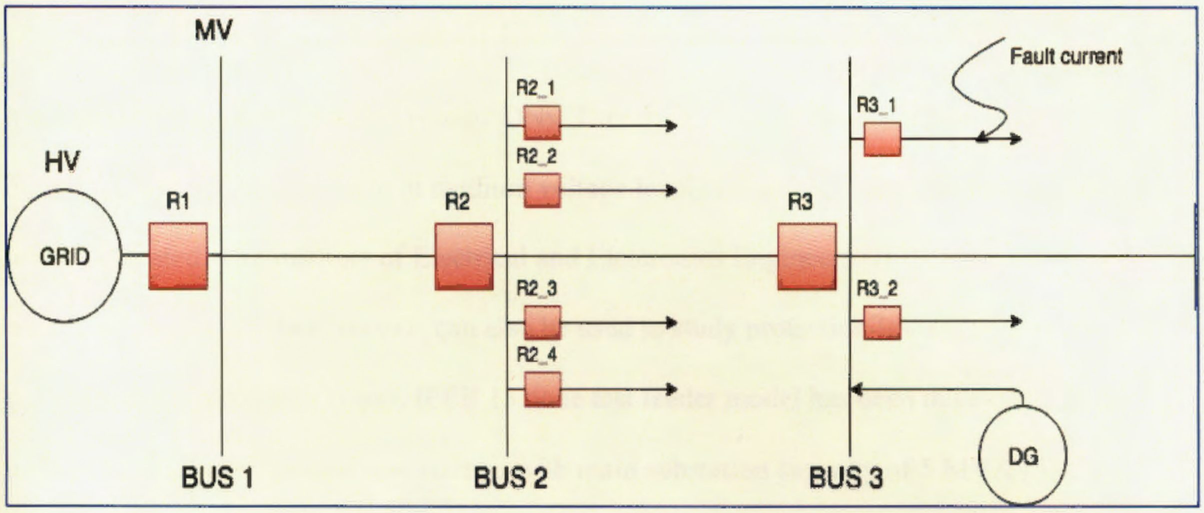

Figure 3.3: Increase of fault current level on R3_1.

The high fault currents generated by the DG are caused by changes in the line voltage due to the damping of voltages at the point of fault in adjacent feeder lines. The reduction of voltage in the feeder line causes generation of excessive fault current. Figure 3.3 shows an increase of fault current on relay R3_1. The insertion of the DG at BUS 3 increases the amount of the fault current flowing through the network which may cause thermal and mechanical failure of the relays.

Chapter 4: Simulation and Results

Microgrids are medium and low voltage DNs. Therefore, most of the protection issues described in chapter three occur at medium voltage levels where the integration of DGs and the utility is located. The Institute of Electrical and Electronics Engineers (IEEE) has developed several grid models. These models can also be used to study protection issues. To simulate and represent these protection issues, IEEE 13 node test feeder model has been developed. IEEE 13 node is a DN of medium and low voltage with main substation capacity of 5 MVA [33].

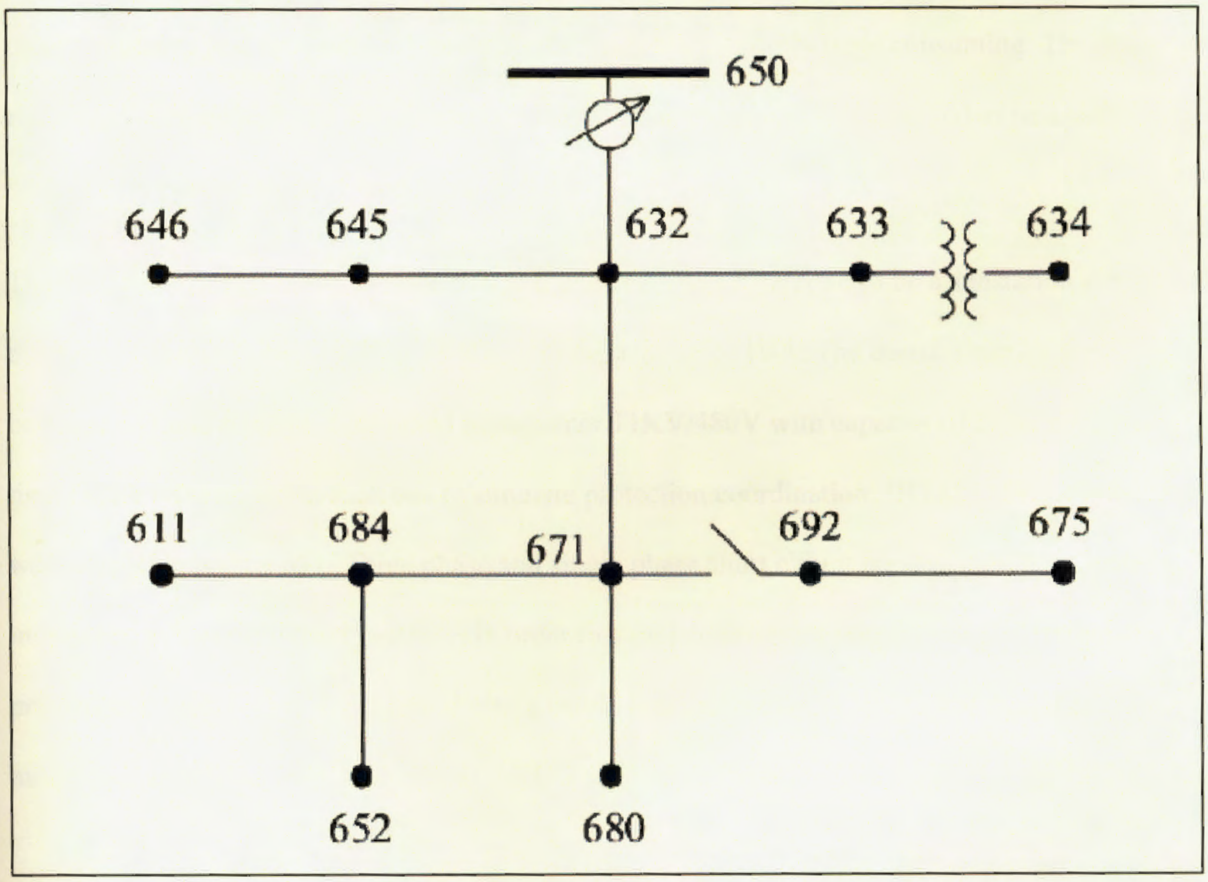

Figure 4.1: IEEE 13 node test feeder

To investigate the impact of DG on the protection system, MATLAB (Simulink) software was used. For the results presented in this chapter, IEEE 13 bus modified for several reasons. One of them is the speed of the simulation and the propagation limit of the transmission line. The maximum length of transmission line in the model is 2000 ft which is equal to 0.6 km. The length of the transmission line is related to the sample time of the simulation tool. Since we are simulating protection issues, the sample time has to be very small which causes propagation speed errors in the simulation tool. Therefore, the length of all the transmission lines was scaled up to simulate a real time network since all the loads are relatively large consuming. The other reason is the complexity of the unbalanced system thus the model was changed to be a balanced system with power factor of load equal to 0.85.

The voltage regulator between node 650 and node 632 was converted to be a substation step down transformer from 33 KV to 11 KV with capacity of 5MVA. The transformer located between 633 and 634 is a distributed transformer 11KV/480V with capacity of 200KVA. Invers-time OCRs were added at each bus to simulate protection coordination. DG of 1MVA capacity was connected on bus 671. Three phase and single phase short circuit current fault have been introduced at three different locations in order to simulate different scenarios and different protection issues. Figure 4.2 below shows a single line diagram of IEEE 13 bus modified. The model was simulated with and without the DG to observe the effects of the DG on the OCRs.

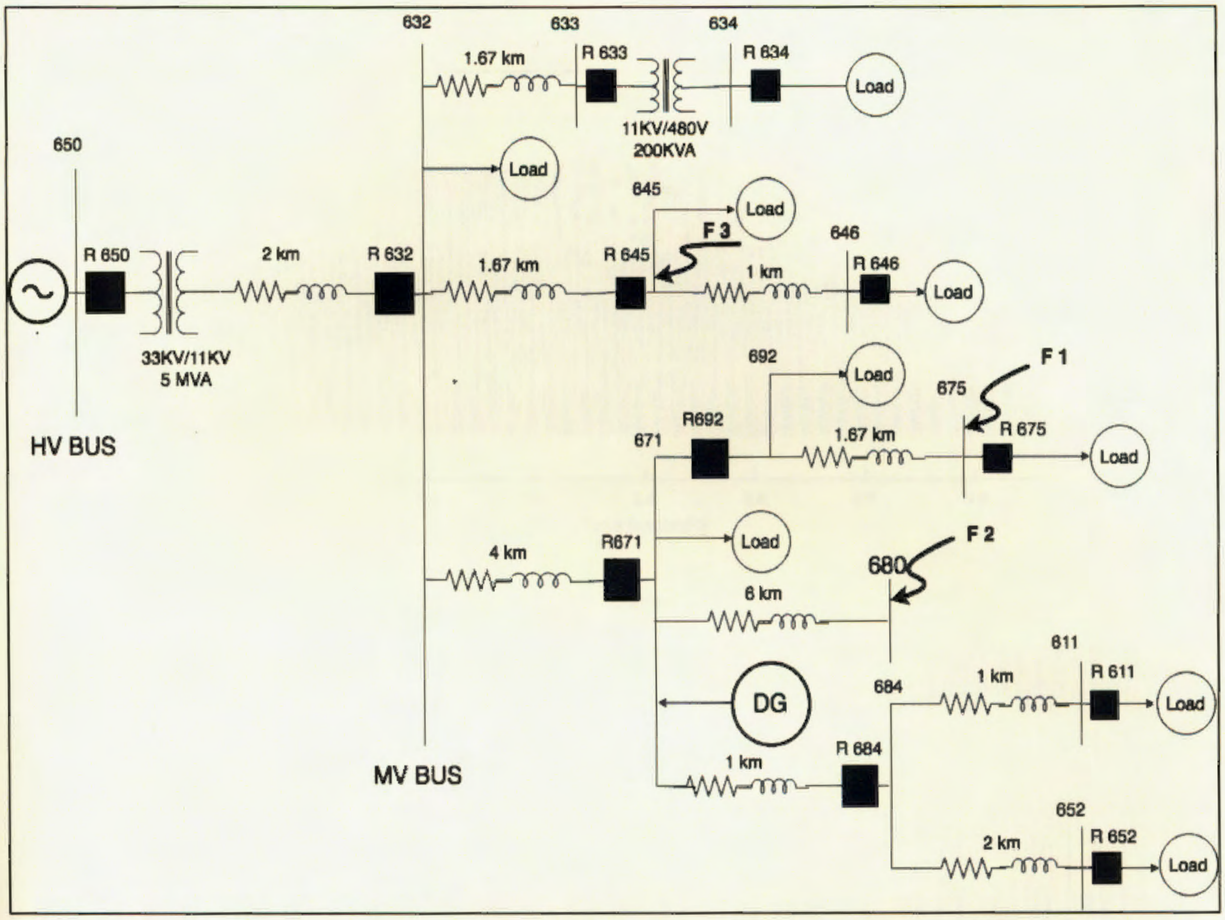

Figure 4.2: Single line diagram of IEEE 13 bus connected with DG.

The coordination of inverse time OCRs is based on their locations. The maximum current flowing through the OCRs and the time grading of their operation depends on their locations. Therefore, it is critical that their coordination ensure timely operation to protect the grid and maintain system reliability. There was no change in the setting of the relays when there is a DG connected to the network. Short circuit faults were introduced at 0.4 seconds after starting the simulation to ensure that the system have reached the steady state condition. Figure 4.3 shows the model running over one second in steady state condition with DG connected.

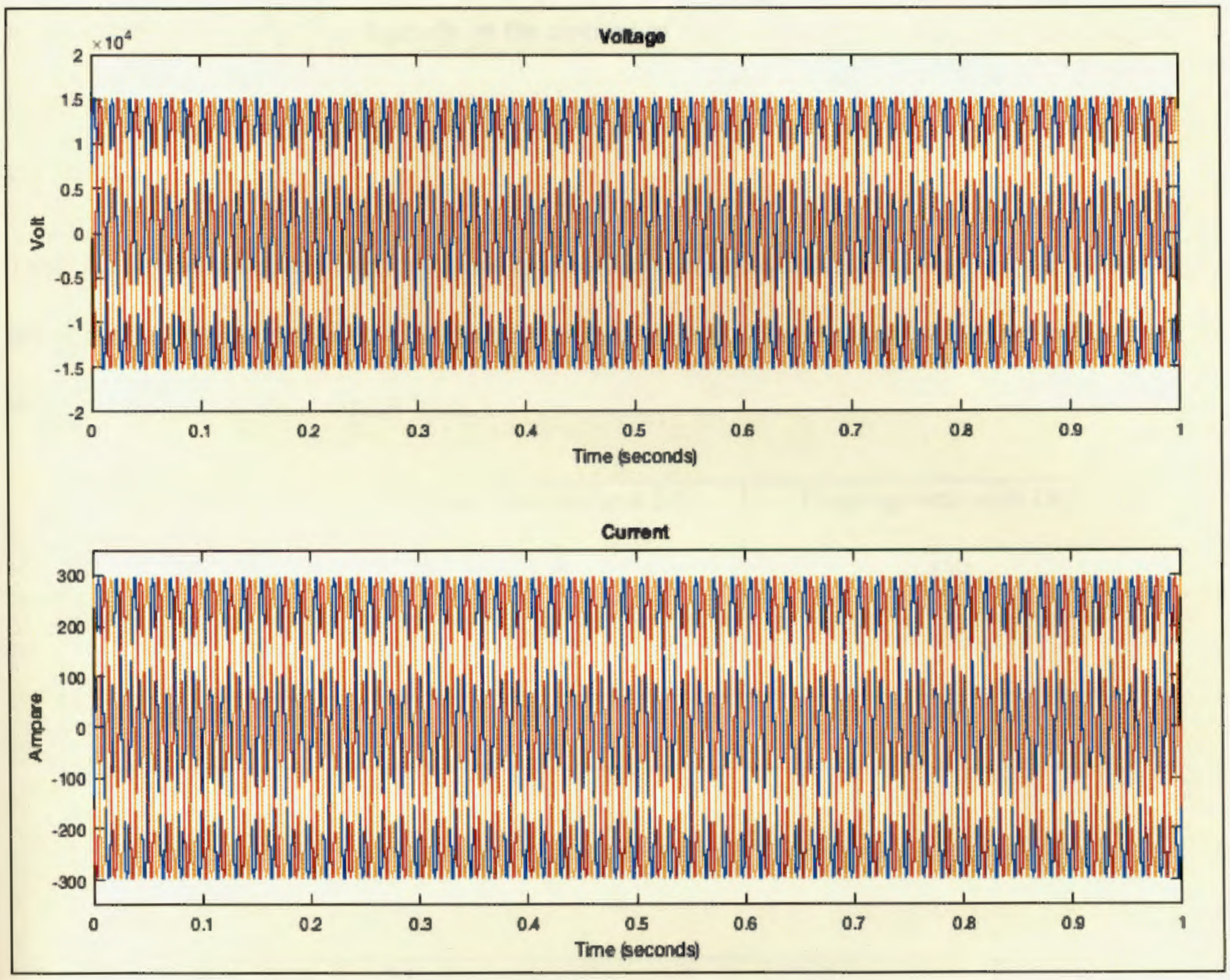

Figure 4. 3: System running in steady state condition with DG connected

4.1 Blinding of protection simulation

To simulate the blinding issue using the IEEE 13 bus model, a DG was added on bus 671 with capacity of 1MVA. Three phase and single phase short circuit fault were simulated on bus 680. Due to the contribution of the DG to the fault current, the total amount of fault current increased while the amount of fault current coming from the grid decreased which would impact the OCRs, given that their tripping time depends on the amount of fault current. Therefore, OCRs located between the DG and the main substation will have delayed tripping when there is a DG connected.

Table 4.1 shows the relays tripping times in seconds with and without the DG when there is three phase short circuit fault. Table 4.2 shows the relays tripping times with and without the DG when there is single phase short circuit fault.

Relay number	Tripping time without DG	Tripping time with DG
R671	0.401	0.430
R632	0.774	0.836
R650	1.090	1.178

Table 4. 1: Relays tripping time with and without DG at three-phase fault.

Relay number	Tripping time without DG	Tripping time with DG
R671	0.478	0.530
R632	0.946	1.061
R650	1.333	1.495

Table 4. 2: Relays tripping time with and without DG at single phase fault.

As we see from the tables above, the addition of the DG at bus 671 increased the susceptibility of relays R671, R632, and R650 to the phenomenon of blinding of protection due to excessive reduction of fault current flowing through them. However, the responsiveness of the relays depends on their location from the DG unit. Relays located close to the DG such as R671 tend to have minimal delay compared to relays R632 and R650. In extreme circumstances, the time delay for relays R632 may be too big for effective removal of the fault while R671 may fail to trip. Figures 4.4 and 4.5 show the comparison of tripping time on relay R671 with and without the connection of DG at three-phase and single-phase fault.

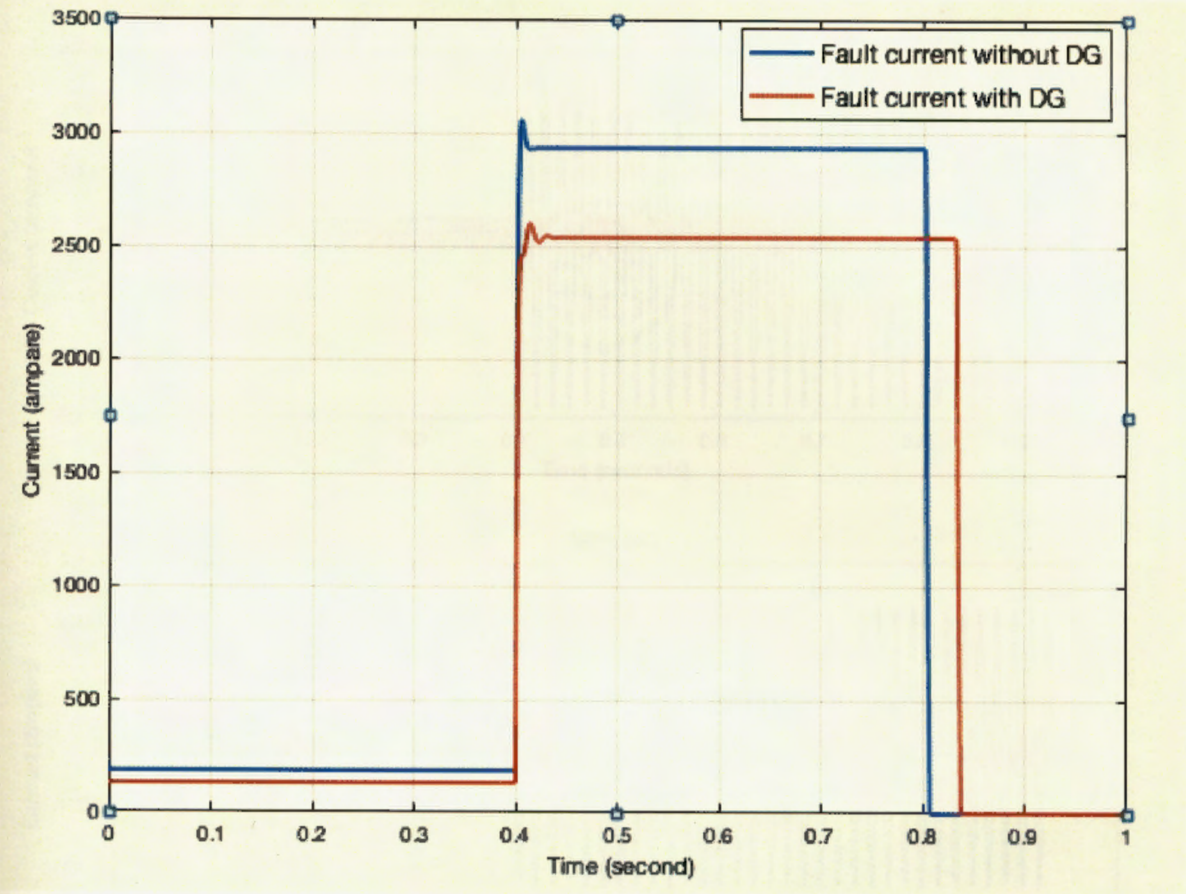

Figure 4. 4: Tripping time of relay R671 at three-phase fault

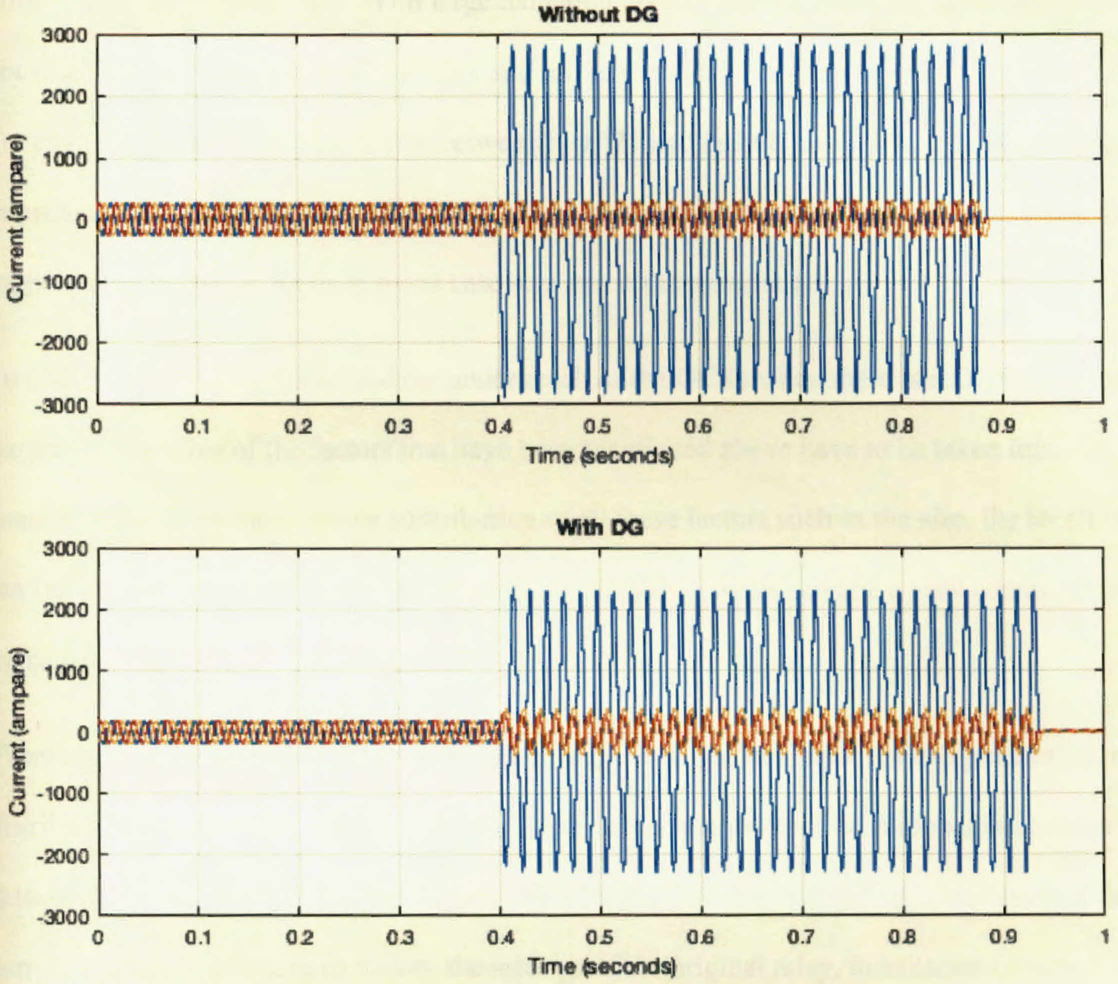

Figure 4. 5: Tripping time of relay R671 at single-phase fault with and without DG

The delay of tripping time for the single-phase fault is larger than for the three-phase fault. This delay could increase more with the factors that have been mentioned in the previous chapter such as the size, topology and the location of the DG. Additionally, the location of the fault is also one of the important factor that has an effect on the blinding issue. In other words, if the fault location is far away from the main substation, the fault current level will decrease which will affect the OCRs tripping time. With large reduction in fault current level, the fault current may not reach the pick-up current of the relay and fail to trip. This is referred to under-reach of relay. For example, if the transmission line between bus 671 and bus 680 is 60 km instead of 6 km, the impedance of the fault will increase and the fault current will decrease which will increase the tripping time of the OCRs or in worst case scenario no tripping at all.

To observe the blinding issue and the under reach of the OCRs when there is a DG connected to the grid, all or most of the factors that have been mentioned above have to be taken into consideration. With the negative contribution of all these factors such as the size, the location of the DG and the type, the location of the fault, the blinding issue would be a very common issue in the network.

There are many solutions that have been proposed to mitigate the impact of DG penetration on distribution and sub-transmission networks, such as disconnection of DGs immediately after the detection of fault, limitation of the capacity of DGs that have been installed, installation of fault current limiters to preserve or restore the settings of the original relay, installation of more breakers to modify the protection scheme, and fault ride through inverter based DGs' control strategy. However, there are certain limitations to all these methods because of high cost or to their being unsuitable for the situation. Disconnection of large DGs immediately after the detection of the fault may lead to severe voltage sags as the DGs' reactive power contribution will be cut-off. The disconnection of DG is also not economically beneficial because most of the faults are temporary and hence, DG will have to be reconnected to the network after the temporary fault is cleared. Also, in the case of high penetration of DGs in the network, there may be stability problems [34].

4.2 False Tripping Simulation

False tripping occurs when there is a fault located between the main grid and the DG. The contribution of the fault current comes from both of the main grid and the DG. The fault contribution coming from the DG causes the bidirectional OCRs to trip which are outside the protective zone. To simulate this issue, a three-phase short circuit fault was simulated on bus 645. There was a contribution fault current coming from the DG causing tripping of the relay R671 which is outside the protection zone of the fault. Table 4.2 shows the false tripping simulation on relay R671.

Relay number	Tripping time without DG	Tripping time with DG
R645	0.151	0.143
R632	0.599	0.615
R650	0.843	0.865
R671	No tripping	0.491

Table 4. 3: False tripping simulation

The possibility of false tripping occurring on relay R671 mainly depends on the amount of fault current coming from the DG. The contribution amount of the fault current by the DG depends on the size, the type and the location of DG. With increasing of the DG units, the relay R671 may trip before the R645 trip and cause an outage of healthy feeder.

The solution that has been presented for this issue is using directional overcurrent relays. However, directional relays are more expensive and have slow operating time than non-directional relays [34,35].

4.3 Increase of fault current level simulation

Inserting a DG into the DN increases the total fault current thus affecting the protection equipment. Every circuit breaker has SCCR (Short Circuit Current Rating) which is the maximum short circuit current that the protection device could withstand. The main purpose of the SCCR is to satisfy safety and insurance requirements. To simulate the increase of fault current level issue, three phase short circuit fault was allocated at bus 675 to compare the level of fault current with and without DG. Figures 4.6 show the difference in fault current level on bus 675 with and without the connection of DG.

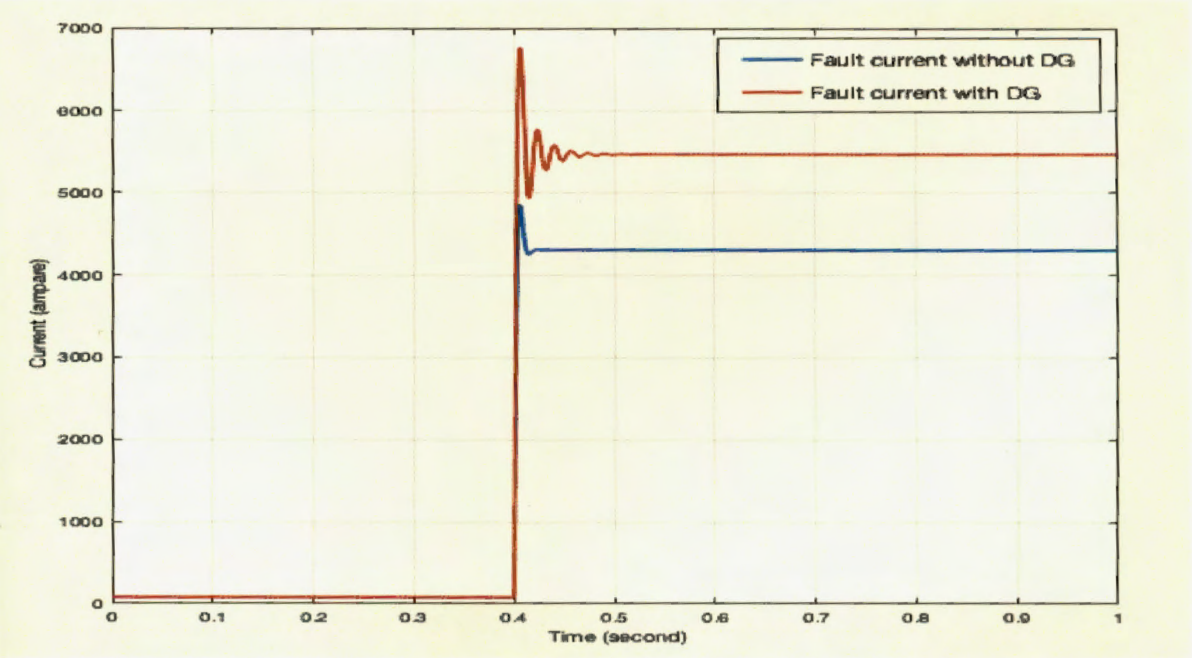

Figure 4. 6: Comparison of fault current level with and without DG

It is clear from the figure above that the fault current significantly increased when there was a DG connected. The increase of the amount of fault current is directly proportional to the size, the location and the type of the DG. With increasing the capacity and the number of the DG units the fault current may exceed the SCCR and jeopardize all the protection equipment. The increase of fault current cause thermal and mechanical damage to the protection equipment and reduce their reliability and selectivity and thus reducing the overall system's reliability.

Chapter 5: Conclusion and future work

The main aim of this thesis was to study of protection issues of a microgrid operating in connected mode. The advantages of using microgrids have been clearly elucidated. The connection of Distributed Generation (DG) to the main network causes changing in power flow direction and fault current level which can cause miscoordination of the Over Current Relays (OCRs).

Blinding of protection, false tripping and increase of fault current level are the main protection issues that have been focused on in this paper. These issues have been discussed and simulated on MATLAB (Simulink) software using IEEE 13 bus model. The seriousness of these issues depends on several factors such as the size, the type, and the location of the DG. Other factors have been discussed also are the type and the location of the fault.

The simulation results show the validation of these issues and how such scenarios can aggravate the seriousness of these issues. It can be concluded from the simulation that blinding of protection, false tripping and increase of fault current issues will be common problems where the number or the size of DGs increase. DGs with low impedance could have more effect on these issues than DGs with high impedance. Several solutions have been presented in the literature [34,35] to overcome these issues. However, some of these solutions are expensive to apply and the other are not applicable.

As the demand for electrical power increases, the number and the capacity of DG units will increase which will raise the probability and the consequences of these issues. These issues can cause power failure and reduce the overall system's reliability which will negate the most common advantages of the microgrids.

The first priority, before expanding the utilization of microgrids and determining the capacity of DGs should be researching suitable solutions for the issues presented in this thesis. The solutions should be economically reasonable and suitable for the different situations. Further research is needed in order to study the lack of standardization in the process of microgrid-protection. The size, topology type and location of the DGs are some of the major aspects that need to be researched further in order to achieve standardization of protection in microgrid.

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