FAULT CURRENT CONTRIBUTION FROM DISTRIBUTED GENERATOR BASED ON INVERTER AND SYNCHRONOUS GENERATION IN A DISTRIBUTION SYSTEM

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OF

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By

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CERTIFICATE

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Abstract

Fault current in the system increases when distribution generators are installed in the distribution system. Protection system designed in a conventional technique may lack coordination with increase in number of distributed generation (DG) units, depending on locations, penetration level, and type of DG's. Circuit breaker and Protective relay settings which were designed before, for the system without distributed generator, may not appropriately and safely coordinate to tackle faults in a system having DG. Analysis of fault current in systems having inverter based generation may not be feasible with conventional tool and technique of fault analysis. In case of low inverter based DG penetration level (like below 5% of system capacity), traditional protection analysis method might be enough. Though for higher penetration level, new methods may be required. Fault current calculation in power system is utilized to find out interrupting capability of circuit breaker. Generally, applying the system *z* bus matrix, the fault current calculation at the system buses is done. A modified *z* bus method for fault current calculation is compatible for analysis of synchronous machine DG implementation at high penetration level. In case of synchronous machine DG the linear equivalent circuit modeling is possible for higher penetration also. But in case of inverter based DG, equivalent circuit designee is not possible for its non linearity. For inverter based generator sources, fault currents are not as severe as synchronous machine sources. Yet with the presence of inverter based DG (IBDG), the fault current calculation by application of *z* bus matrix may be impractical due to difficulty in estimating the transient impendence of inverter based DG. As inverters are nonlinear, to analyze system changes and dynamics in the system fault response with inverter-based DGs, a simulation process has been developed to incorporate an inverter-based DG model. This inverter-based DG model was utilized in illustrative examples of systems with DGs. In this work, voltage, active and reactive power with current control for dual loop inverter based DG is done. In grid connected mode, normally inverter based DG is operated in active reactive power control to give a specific penetration. For island mode it is operated in voltage control mode. Firstly , IBDG is operated with a single load to find the output performance with respect to the voltage and current with load transition. After that IBDG is connected with a part of the grid which is also operated in voltage control mode to give a specific output voltage. A three phase fault is applied to find fault current contribution in the network by IBDG. As tuning of the gain of controller is very difficult for a non linear mode of operation, a time domain analysis is used. Using an optimization tool (genetic algorithm) its tuning is done. Again a MATLB/Simulink model of synchronous based DG (SBDG) has been prepared from its short circuit test data. Finally, a fault analysis has been observed for three cases viz. without DG, with IBDG and with synchronous based DG (SBDG). Comparative analysis of these three events has been done. It is observed that fault current without DG is minimum and for SBDG it is maximum. Effects of connecting IBDG and SBDG simultaneously for fault simulations have been considered also. It is found that IBDG predominates the situation.

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1. Introduction

Previously electric power industries were large and integrated utilities. Now it is privatized and sectionalized. This new evaluated structure is known as deregulated power system. In this deregulated power system, power industries are sectionalized in generation, transmission and distribution companies with an open access policy. Traditionally electrical power system is dominated by centralized power plant. Power is generated at high level (11 KV or 30 KV) and then stepped up through step up transformer at high voltage (66 KV up to 765 KV) [1]. It is then transmitted through high voltage cable or transmission line and stepped down to lower voltage level and distributed to different sections of the society. Demands are passive, not controllable, and connected to distribution networks. Power flow is unidirectional in traditional systems. In deregulated environment, one of the main objectives is to minimize the energy supply costs. Implementation of small scale energy units like fuel cell, PV cell, hydro and wind energy becomes efficient than large units as in traditional systems due to technical innovation. One of the main objectives of electric power industries is to reduce greenhouse gas (GHG) emissions, to secure its future energy supply and to reduce fuel poverty. To solve all these problems DG (distributed generation) becomes an attractive option.

1.1. Distributed generation (DG)

The characteristics which define Distributed Generation technologies are the location and application of the device and the size of the power production of the technology [2]. DG systems are mostly located close to the power demand, preferably on the customer side of the meter or on the distribution network, rather than on the transmission network. A DG connected distribution system is beneficial economically, environmentally and technically [3]. It minimizes transmission loss so it is economically advantageous using DG connected distribution system. It is an eco friendly system as PV cell, wind energy is used as DG, and green house gas emission is almost negligible. It improves voltage profile, reliability so it is technically beneficial [3]. The common characteristics of DG are as follows [2]:

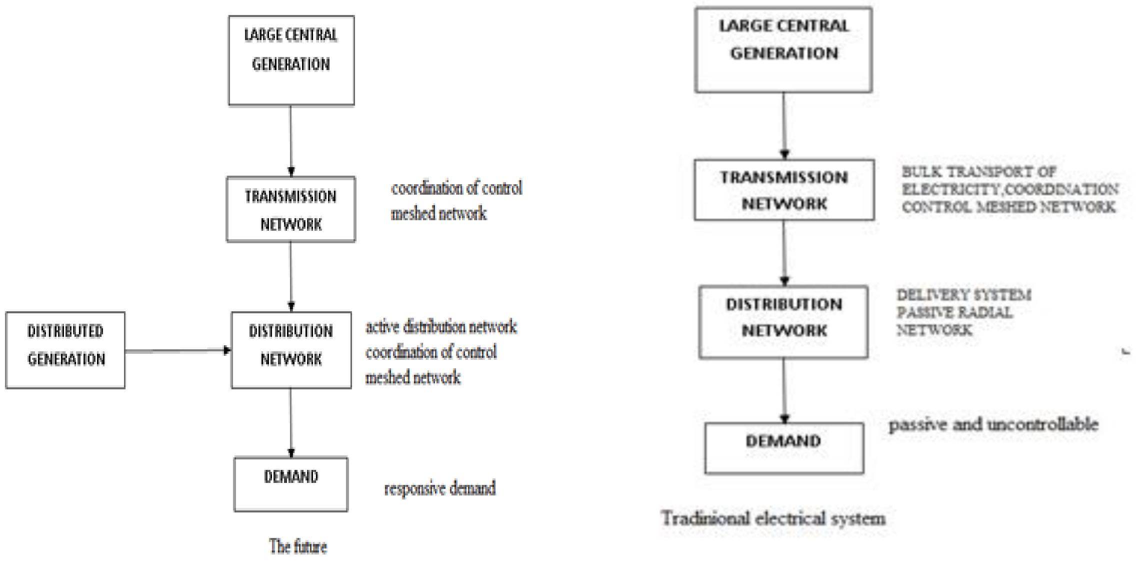
- DG is connected to the utility at low voltage or medium voltage distribution network.
- Rating of the generation will generally be small.
- DGs are many a times privately owned
- DGs are not centrally controlled

- DGs are sometimes based on the co-generation, renewable energy source (solar, wind etc) or waste fuel (biomass, land fuel gas, sewage gas)

These distributed generation sources have become an integral part of the distribution system for efficient performance in the restructured environment.

1.2. Present day distribution system in restructured environment

Nowadays power sector has been going through several challenges. Transmission and distribution loss minimization becomes one of main challenges of distribution system. In cases, where the source is present near the user location, transmission losses are negligible. As a consequence of the deregulation and the application of new technologies in the power sector, a new approach was taken in the sector of power system known as ‘‘distributed generation’’ [4]. In restructured environment, power system combines with distributed generation (DG) units, substantially smaller amounts of energy are created by modular energy conversion units. Figure 1.1(a) and 1.1(b) show the future and traditional structure of distribution system [4]. Both distribution generation and demands are directly connected at same point in the distribution network. This needs a coordinated control and larger interconnections in the network. Distributed generation (DG) units locally respond to demands and storage systems connected to the system.



(a) (b)

Figure1.1. (a) and (b): Future and traditional distribution system [2]

DG can be operated stand alone or interface with the grid [4]. In the last 10 to 15 years, numerous countries have started the liberalization procedure of their electric systems, giving business house access to transmission and distribution grids. This process is supported by a fast growing presence of small generators of different technologies; some of them being renewable energy sources (RESs). Several types of faults are common in distribution system. Due to presence of DG many problems arises in the protection methodology against symmetrical faults, transient faults etc. Hence study of these faults in distribution system with DG becomes necessary.

1.3. Types of faults in distribution system with DG

Fault or fault current in an electric network is defined by abnormality of electric current in network. For example, in short circuit fault current bypasses the normal load. If a circuit is interrupted by some failure, an open circuit fault takes place. Different types of faults are common in distribution network. These are transient fault, persistent fault, symmetrical fault and asymmetric fault as shown in Figure 1.2 [5].

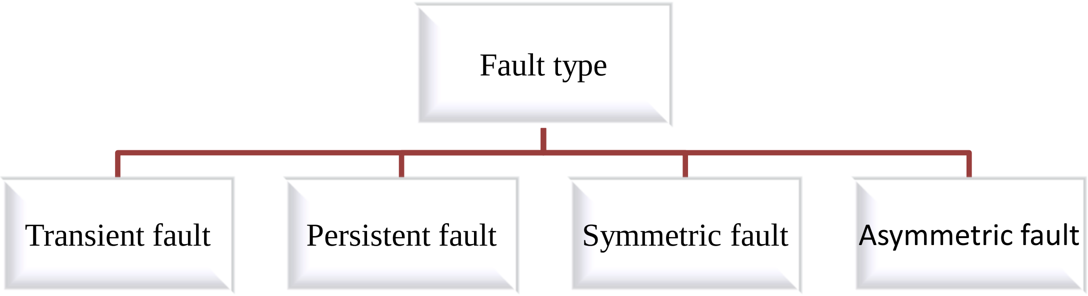


Figure1.2: Types of fault [5]

A transient fault does not persist if a short time power is disconnected and connected once again; or an insulation fault which affects temporarily a device's dielectric properties which are reinstated shortly [5]. A persistent fault does not disappear when power is disconnected. Faults in underground power cables are mostly steady due to mechanical damage to the cable, but may be transient in nature in case of lightning. In three phase systems, fault may happen involving one or more phases and ground. If all three phases are effected by the fault is known as three phase symmetrical fault. It may be three phase line to ground fault (L-L-L-G) where all the current flows to the earth or may be three phase line to line fault (L-L-L) [5]. Line to ground, line to line and line to line to ground faults are known as "asymmetrical fault". These types of faults analysis become often complicated. This is done by symmetrical component analysis [5]. DG source without grounded system may cause over voltages at the time of line to ground faults on the utility system [6]. This condition is specifically dangerous if a generation in island mode takes place and continues to serve a group of customers on a distribution system that is faulty one. On the other hand customers on the non-faulty phases in extreme bad cases could observe their voltage rise to 173% of the pre fault voltage level for an unlimited period. Utility and customer equipment damage is almost certain at this high level [6]. Prompt diagnosis of these faults is of tremendous importance also from business point of view.

1.3.1. Importance of fault diagnosis

From the above discussion it is found that many types of abnormalities may occur in distribution system with DGs. The corresponding protection systems must have an ability to disconnect the faulty section of the power network rapidly and automatically from “healthy” system. In this way protection system ensures the maximum security of supply to users. So fault detection and isolation are very important to give safety to the system. Fault diagnosis is the combination of fault detection or identification and isolation. In case of power system fault, this is achieved by protection device. Fault diagnosis prevents component by restricting the fault current in case of short circuit fault and from over voltage during open circuit fault or transient fault. In this way it provides efficient, reliable and safety the system. Four inter related parameters sensitivity, discrimination, stability and operating time describes the protection system ability.

Ability of the protection system device to select whether to operate or not to operate for the given measured system is called discrimination. Sensitivity is the degree of measuring the ability of protection system device for identification of fault presence or other conditions which are not desired, even though they differ slightly for apparently healthy condition. These two steps help to identify the fault properly. So fault current calculation and its nature is very important to execute this step mainly (discrimination and sensitivity). The main purpose of fault diagnosis is to differentiate permanent fault and temporary fault. Protection relay plays a very important function in case of fault diagnosis in power system which senses the fault current and operates the circuit breaker (CB). Operating time is the time required from onset of the fault to send trip signal by protection relay to the circuit breaker (CB) [7]. CB isolates the faulty section from healthy system. Stability is measuring the ability of the protection system to be in inoperative mode under some specific fault conditions, as the fault is of such a nature that other protection system somewhere is intended to effect tripping. DG interfaces with distributed network through power electronics interface in case of DC source or variable ac source. Switches are a non linear device and which may restrict the fault current and supply harmonics to the system. Beside this for many other purposes like fault current level increase, sympathetic tripping (false tripping of feeder) DG interfaced distribution system becomes more challenging for fault diagnosis purpose.

1.4. Objective of the Thesis

The improvement in the relays’ technology is very much needed to match the growing interest of shifting the conventional power grids into smart grid. The vital quality of this smart grid will be improved penetration of DG at distribution levels [8]. Normally, DG integration has various impacts on distribution systems which have been discussed later and one major challenge is the effect of DG on the protection system [9]. Configuration of traditional distribution system is radial. But presence of DG converts the radial system into mesh network. In radial network, relay recloser fuse CB is the main protective device. In mesh network, due to presence of bidirectional power flow, a bi-directional over current relay is essential. In centralized generation (CG) system, alternator is the main electric source which supplies the fault current and it can be modeled as a linear circuit.

If DG is integrated into the protection system then another impact is observed. There is an increase in short circuit levels in the system strongly depending on the DG type. DG is interfaced with distributed network through power electronics interface in case of DC source or variable source. Switches are a non linear device and which may affect the fault current [10]. Digital microprocessor based over current relays having different constant setting is currently used to give safe and efficient protection with better capabilities than conventional electromechanically run over current relays [11]. So protection system faces different problems which are discussed later. To solve the protection problem, new optimal relay settings needed to be determined. This means fault current calculation becomes essential to reset the relay setting during grid connected mode and island mode. In this study, different types of DG is considered in different modes (grid connected mode and island mode) and its control technologies. The main objective of this study is to determine relay pick up current at different control mode.

1.5. Contribution of the work

The main contribution of the thesis is to identify the relay pickup current that is fault current considering different situation like island mode, grid connected mode considering different type of DG i.e. IBDG and SBDG and their interconnection with utility including their system dynamics. In many literature reviews, fault current relay settings etc are identified with or without DG but actual DG dynamics is not considered. For IBDG this is done here. The aim of the thesis is to first develop the MATLB/Simulink model of synchronous based DG and DG which are inverter based at different control mode and operate at island mode and identify the fault current and then operate them in grid connected mode. Again dual loop voltage control for IBDG has been considered for fault diagnosis. To develop the control operation, Proportional Integral (PI) control and Proportional Resonant control (PR) is considered. To reduce the error between reference signal and actuating signal evolution the value of proportional constant (K_p) and integration control (K_i.), constant optimization technique is used. A MATLAB code is developed which calls the Simulink modeling and evaluates the value of K_p and K_i.

1.6. Outline of the Thesis

This thesis consists of eight chapters as follows.

Chapter one highlights brief descriptions of distribution system in restructure environment, types of fault distribution generation (DG) and the basic importance of fault current diagnosis along with the objective and contribution of the thesis.

Chapter two provides a review on factors affecting different faults in DG based system like DG penetration, DG location and different kind of DG. A briefly discussion on fault current contribution from synchronous based DG and inverter based DG and its effecting features and control technologies are thus provided.

Chapter Three describes the effects of DG on power quality, voltage profile, reliability, losses and power security and also contains discussions on DG limitation its size and type and DG interconnect interface. DG interconnection interface is an important concern of this thesis.

Chapter four provides a review on fault related problems and its solutions.

Chapter Five begins with developing the model of inverter based DG followed by synchronous based DG in simulink and different techniques for selection of the values of different controller Proportional integral (PI) and Proportional Resonant with harmonic controller.

Chapter six introduces the simulink modeling of IEEE 14 bus system with DG and without DG, and island model and simulation technique is used to show the fault current during three phases to ground fault. For simulation MATLB/Simulink is used.

Finally Chapter seven presents a summary of the study, an outline of future scope, and some concluding remarks.

2. Fault in Distributed Generator based system

2.1. Introduction

Interfacing of DG has an adverse effect in respect to the fault. Many factors like DG penetration, DG type depends on the connection interface, DG location and fault location effect in the existing protection scheme. General electrical distribution systems are equipped with radial structure and with a single source, where the protection schemes are dependent on relay, fuses and reclosers. The main feeders are safe in this structure, unlike as in case of temporary fault where they are protected with reclosers. Fuses are placed at the beginning of laterals and sub-laterals to give protection against persistent faults [12]. Problems for recloser fuse mis-coordination may arise due to current contribution of DG. The recloser-fuse coordination is usually operated based on fuse saving principles [13]. In addition to this, the short circuit fault current of the distribution system increases due to DGs contribution. This may be responsible for tripping the healthy line before clearing the faulty lines. As per IEEE standard 1457 recommendation, the DGs should be disconnected when the system abnormality takes place [14]. To establish the proper coordination in protection device, effect of DGs on fault current is evaluated. Effects of DG penetration level, DG location, types of effects on faults are discussed below.

2.2. Effect of DG penetration level on faults

If the penetration level of DG is increased, short circuit current level of system exceeds the previous existing limit of the relay fuse recloser. Existing protection scheme may be hampered when false tripping of feeder takes place [15]. So in many literature reviews it has been suggested to limit the penetration level in order to keep the existing protection scheme intact. In a research work, a single DG has been considered in the distribution system. Two or more DGs have been considered in separate nodes at second stage [16]. DG capacity could not be found out to limit the fault current level ultimately. In another work, determination of DG location and power is a multi objective function created considering fault current level, power loss reduction and voltage enhancement and GA (genetic algorithm) is used for optimization [17]. On the other hand a new index, known as “protection coordination index” (PCI) is suggested, in which higher PCI would point towards the fact that DG penetration level may be increased [18]. It can provide an efficient measure for the development of the protection with DG based system. To find out the PCI, two-phase non-linear programming (NLP) optimization problem is formed. By varying the maximum DG penetration level, PCI is calculated optimally with changes in the protection coordination time interval. The calculation of optimal size of DG is done using optimal power flow (OPF), and with consideration of recloser-fuse coordination in [19]. The determination of maximum capacity of DG at each node of distribution system is done with consideration of protection coordination. From the above discussion it is found out that all of above schemes are developed to minimize the fault current level by restricting the DG penetration level. Presence of DG is also responsible for reverse power flow during fault.

2.3. Reverse power flow during fault

Classical protection system has been developed considering the unidirectional power flow of traditional network. But use of DG, traditional network becomes mesh network from radial. Reverse direction power can flow during upstream fault. Classical protection scheme can’t be utilized to protect the system [13]. So use of directional over current relay becomes essential. Fault current may be provided in faulty feeder from healthy feeder DG which may cause tripping healthy feeder. This phenomenon is known as sympathetic tripping [20]. In [21], a different protection scheme operation is discussed after DG is connected to the distributed system. The DGs effect on protective device coordination is analyzed with various schemes such as fuse-recloser, fuse-fuse, and relay-relay arrangements. Along with this the effect of DGs on protection coordination and operation of distribution network s explored in [22]. The study contained the rise of fault current level, protection devices malfunction and protection coordination. The evaluation of the performance of directional recloser is done with the use of real time power system simulator [23]. Bi directional over current relays are also used to protect the system. DG location is also important for fault current as it is dependent on the distance between the fault and the placement of DG.

2.4. Effect of DG location on faults

Protection coordinate index is a computing tool proposed to identify the best location of DG owned by utility [18]. Additionally, the PCI can also assist in determining the level up to which the customer owned DG effects on system protection coordination. This leads to identification of any requirements for adjusting the relay settings. Finally, the results showed that a fixed capacity of DG located at a certain position can be responsible for either increasing or decreasing the PCI value at other locations [18]. It is shown in previous works that the number and capacity of DG and its location, both are considered to determine the fault current for protection purpose [24]. With DGs presence, the fault current value is larger than the value when DGs are absent. With the increase in penetration level, fault current slowly increases. Hence, it is shown that fault current value decreases with the distance between the fault location and the DG increases [24]. The kinds of DG used in system also contributed to the fault current level variation.

2.5. Different kinds of DG

DG inter connection interface and its control strategies also give an effect on fault current. Depending on the interconnection and controls, DGs are different types. The effects of different kind of DG are discussed below.

2.5.1. DG as an active reactive power source

Coffele et al. considered four types of DG depending on active reactive power injection [25]. Type 1 DG consumes both active and reactive power while type 2 DG is capable of injecting real power but consuming reactive power. Type 3 is injecting only the active power. Type 4 DG only injecting the reactive power. A study is done on different types of distributed generators which affect the fault current and voltage profile in radial distribution networks [25]. Various cases for mis-coordination problems caused by DG have been analyzed. An enquiry on DGs impacts on voltage profile has been introduced and explored. Besides, the performance of the interconnected DG distribution network regarding voltage profile during the fault has been explained. In many cases a comparison is done considering the different types, locations and sizes of interconnected DGs. To get the maximum advantage compared to the installation cost a complete investigation must be done before incorporating the DG sources in a distribution network and an optimal solution must be searched. But in this analysis an evaluation is done comparing the DG without considering their DG dynamics and control strategy. DG is only described as active reactive power source [25].

2.5.2. Interconnection interface and their effects

In another research work, short circuit levels of DG are analyzed by DG inter connection interface. Energy resource is connected to the distributed network through synchronous machine, induction machine or power electronics interface defined as asynchronous machine.

Fault current supply by asynchronous machines is 100 to 400% of rated current [26]. In case of synchronous machines, it may be at 500-1000% for the first few cycles and then it decays up to 200-400% [26]. In case of induction machines, fault current level increase up to 500-1000% during first few cycles and then decreases to an insignificant amount in 10 cycles [26]. For asynchronous machines, the fault contributions will be controlled by the response of current limiter of machine manufacturer's depend on the current level and duration up to when power electronics device can tolerate. The current contribution from synchronous machines may be influenced by the pre fault voltage and exciter characteristics. Induction machines can supply fault current as long as excitation is given by any residual voltage in the feeder [26].

In another wok, first simulation of different type of DG source is done to investigate the fault current characteristics and an analysis is done to know the impacts on over current [27]. PMSG interfaced wind turbine or PV generation's gives a little effect on OCPs. The addition of distributed SCIG or DFIG to the distribution network becomes a source of the inaccurate operation of OCP. When fault occurs after the DG connection point, the increased level of fault current may cause mal-operation of OCP [27]. Secondly, the comprehensive analysis is done considering the source capacity, the fault location, the DG location, the transmission line length and the reliability coefficient in the distribution system model. Specially, by varying capacity of the renewable energy source, the correlation among the fault current flowing through the protection and the short-circuit capacity ratio at the integration point is investigated. [27]

A preliminary study regarding short-circuit current parameterization of DFIG-WT, in order to establish a mathematical model to describe short-circuit current contribution has been done elsewhere. Therefore, a simple network was used to simulate short-circuit current of DFIG and SG under two types of short-circuit as defined by IEC-60909, as a standard reference of DFIG and SG [28]. Different nature between DFIG and SG is known by observing the simulation result. Difference in physical construction and controller behavior is responsible for this. Besides this the simulation results show that the IEC-60909 short circuit definition are not suitable for DFIG and the current definitions should be upgraded or improved to be sufficient for it. In contrast to SG, the short-circuit quantities of the DFIG cannot be directly calculated from analyzing the machine parameters as reaction of the controller and the MSC (machine side converter) is fast [29]. Besides this, controller behavior is not standard as different types of controllers with different control strategies are available in the market. So it is hard to make a standard mathematical model for DFIG short-circuit current contribution [29].

A complete analysis is done considering different type of DG like PV cell, induction generator, DFIG, SG, PMSG etc [30] for impact determination. The impact of DG units is analyzed when a downstream fault occurs. Grid contributes less fault current compared to the total fault current leading to a blinding of protection. A complete analysis is done to find how DG units actually influence the sensitivity of the protective device [30].

In another review, from the viewpoint of increase in the fault contribution a discussion and comparison study was performed with respect to the effect of DG installation in the distribution systems [31]. To show the steady state and transient effect of fault current caused by DG units and also to explore the effect of interconnection and type of distributed generation unit on the fault current contribution of the distributed systems, a study was done based on two indices. Simulation results shows that fault current increase is frequently greater in synchronous and induction machine implementation against a comparable inverter based design. [31].

2.5.2. Inter connection interface with control strategy

A complete comprehensive analysis between synchronous and induction machine for distributed generation applications is presented elsewhere [32]. The effects of these generators on the performance of distribution network are derived and compared by use of computational simulations. Electrical power loss, voltage stability, voltage sags during unbalanced faults, transient stability, steady-state voltage profile and short-circuit currents are the technical factors that are analyzed here. The result shows that network characteristics are responsible for best technical choice, which is a main factor that may control the penetration level of distributed generation to a certain level [32]. Different current responses are observed from each generator. Initially magnitude of current is high for induction generator, but they decrease rapidly as the machine is incapable to provide sustained short-circuit currents. Being no external excitation source present for the generator, generator becomes unable to produce voltage [33]. On theoretical basis this fact causes the detection of faults by protection systems based on over-current relays harder. Though voltage based relays could be used in this case. For synchronous generators, it can be seen that the using excitation system as a voltage regulator allows that the generator supplies bear short-circuit current. In spite of that, if the excitation system is used as a power factor regulator, fault current is decreased [32].

A detailed analysis had been carried out systematically on IIDG and DFIG to study the dynamic behaviors [34]. A review is done on IIDG and DFIG considering the control model. Then the electromagnetic transient response of DFIG and IIDG are quantitatively investigated and an analogy is drawn between them. In a word, it can be said that DG fault transient characteristic is mostly depended on its operating principle, associated controller and topology. The fault responses of DFIG and IIDG are distinct from synchronous generator [34]. The fault currents may carry large numbers of harmonics .Effects of this harmonics is also discussed above. For protection purpose the power electronic devices of IIDG its fault current is restricted. For this the fault current provided to the feeder by IIDGs is not clear [34].

A full analysis of DFIG is done where a vector control method for DFIG was shown, and when the DFIG was connected to the test system and a fault occurs in the system which leads to a loss of excitation [35]. As per the simulation results, different conclusions were drawn from this review. The active power may rise for a short time when the system node voltage and the DFIG in the PLOE (partial loss of excitation) fault increases simultaneously. Following the fault, violent fluctuation of the active and reactive power takes place when the converter reconnects to the grid which could effect in the impulse on the microgrid [35]. With the CLOE (complete loss of excitation) fault, the machine is operating into an asynchronous state, the active power will decrease and absorb reactive power and the voltage may be reduced [35]. If the rate of penetration of DFIG is low, stabilization of the voltage takes place with the reactive power compensation. If the penetration rate is high, WGs are suggested to be disconnected from the grid [36]. In case of the short circuit of the rotor winding, along with the increase of the turn of the rotor winding (short circuit), the difference between the average node voltage and normal active power increases, and the difference of the active power is larger than the voltage’s when 10% of the rotor winding is short circuited [37]. So, these types of the faults generally have an impact on active power balance of the system.

From above discussion it can be found out that a complete models of DGs have been widely studied, the short circuit current level differ [38], and DG units are normally replicated as an ideal voltage sources without considering their dynamics [39]. The simulation becomes fast and simple by considering the DG as ideal source but the results are got with inaccuracy. An ideal source represents by a source with impedance. So short circuit currents depend on the fault impedance and short circuit power of DGs. It is only possible for rotating machine. Use of ideal DG source becomes more tangible when between DG and the grid; power electronic is used as an interface. For renewable energy based DG interface with power electronics device limits fault current. The generated fault current is then not more than 2 or 2.5 times of the converter rated current.[19] On Practical basis the fault current duration and its transient behaviour is dependent on the type of generator, how it is interfacing with the grid and also depends on the used control strategy. So investigate the effect of different factor IBDG a detailed analysis must be done. Different effecting factor in case of IBDG is discussed below.

2.6. Different factors in case of IBDG

2.6.1. Effect on insulated gate bipolar transistor (IGBT) in case of IBDG faults

Mostly in research works, DG is considered as an ideal source. But from actual modeling it is found that fault current from inverter based DG is less than other types of D. In a certain work, the DG is modeled without the control system being considered [30]. Only simple voltage source inverter (VSI) is considered connecting with DC source and IGBT is used as switching device. And it is found that fault current is only 2 times of rated current. It is only possible when switching device limits the current [40]. It actually happens to protect the IGBT from over current. Power electronic switches (solid state devices like IGBT) usually have relatively low thermal inertia and over current sensitivity. Thus switches need to be protected from overheating. For this limitation of current is necessary above the maximum rating. A number of approaches are taken to limit this current. It is done actively by limiting the filter inductor [41] or provides a fast over current sensors to keep away from self destruct of the power bridge due to the first abnormal situation [42].

2.6.2. Harmonics and their effects

Full control of both active and reactive power can be properly designed with acceptable total harmonic distortion in grid current [43]. In case of IIDG, power converters uses with switching frequencies in the range of 1–20 kHz cause of harmonics injection to the network. Due to this harmonics, protection devices such as circuit breaker, relay may be triggered [44] without any fault. When a nonlinear source like power electronics interfaced source supply distorted (non-sinusoidal) current to the grid. This distorted current flow through all impedances connecting between the power source and the load. The harmonic currents associate with fundamental current following through the impedance. Due to this voltage drops for every harmonic frequency is different. Voltage drops is calculated by Ohm’s Law shown in Eq. 5.1 [45]

$$V_h = Z_h \times I_h \tag{5.1}$$

Where Z_h = Impedance at frequency of harmonic (e.g., for 5th harmonic, $5\times 50 = 250\,\text{Hz}$ if fundamental frequency is 50 Hz) V_h = h th harmonic voltage (e.g. 5th) I_h = Harmonic current at hth harmonic (e.g. 5th) The total voltage distortion is the vector sum of all the individual voltage drops. The magnitude of voltage drops can be controlled by available system current levels and present harmonic currents at each harmonic frequency and the system impedance. So during fault, fault current is increased when distribution system impedance and distortion become low and Harmonic current is drawn from the source is high and fault current is low when increased when distribution system impedance and distortion become high and Harmonic current is drawn from the source is low. So harmonics reduction is one of the important factors in case of fault [45].

2.6.3. Design of LCL filters and effect on faults

Harmonics can be mitigated by the use of an output filter between the grid and the power converter. LCL (inductor-capacitor-inductor) filter is one of the most important solutions to eliminate the harmonics problem because it introduces higher attenuation with small sized passive elements. Thus IEE 519-1992 standards are met with relatively low switching frequency converters [46]. An LCL filter provides better dynamics, when compared to a simple L- filter. Control design challenges are introduced by the third order nature of LCL filter due to hindrance related to filter resonance occurrence and corresponding stability constraints [47, 48]. Hence, the engaged control system will notably affect the overall system behavior throughout healthy and abnormal conditions. The DG connection onto medium and low voltage electronic supply networks can contribute to higher fault a current level which leads to increased stress on network components. This matter has been recognized as a potential limit to the level of installed DG which may be merged into existing networks. FCL (Fault Current Limiting Devices) offers way to manage this issue without the requirement for extensive network reinforcement [49, 50].

2.6.4. Different control technologies

A number of attempts for characterization of inverter faults have been published in the technical literature. Many types of control technique are used to represent DG as a constant PQ source or PV source. For grid connected operation, normally active reactive power control with current control loop is done to give a specific power and during island operation PV (active power and voltage) control or active power frequency and reactive power voltage droop control(P-f &Q-V control) etc are done. Depending on the control loop it may be dual loop or single loop control.

Depend on control technologies fault current may be changed. These control technologies are as follows [51]

- Active reactive power control with voltage or current control loop
- Current control:
    - Single loop current control
    - Dual loop current control
- Voltage control

2.6.4.1. Active reactive power control (PQ control) with voltage or current control mode

The investigation on the effect of PQ controlled inverters on fault level is done by full time domain simulations where current limiting is done by instantaneous limits on the inductor current mentioned in this control system [52]. It can be given as conclusion that the low fault-current contribution of IBDG with comparison to standard generators allows a greater amount of DG to be connected to a feeder. However no step has been taken to add in the IBDG into a traditional fault analysis technique that can be applicable to larger networks [52].

In another review a comparison is made between fault responses of PQ controlled IIDGs which may use inner voltage or an inner current control loop [53]. A differentiation is done between the transient and sub transient components of the fault response of the above mentioned cases. On the basis of analysis of the time-domain and control system simulation results, an equivalent fault model developed analytically of the PQ source IIDG having an inner voltage control loop for utilizing in systematic fault studies that was proposed [53]. The representation of IIDG is done as a constant voltage source in series with the filter inductor. To obtain an approximate fault response this representation can be used for both time domain simulations and in analytical fault studies. The adaptation of magnitude and phase of the voltage source is done every time in order to take into account controller dynamics. When certain over current threshold are exceeded, the inverter is presumed to be disconnected and no current limiting was performed. The verification of analysis and proposed method is done by time domain simulation. [53]

The short circuit behavior of grid connected photovoltaic Inverters was scrutinized with an assumption that they will be disconnected when an over current threshold exceeds and a conclusion was drawn that inverter fault current contribution was insignificant [54]. No attempts were made to specify inverter fault behavior or examine the need for inverters to possibly ride through a fault if significant share of the generation mix is represented by IBDG. A time domain simulations result supported this discussion [54].

A fault response of commercial inverter was found through experimentation [55]. Though, any details about the factors which are responsible for inverter's fault response or how this fault response may help the fault ride through of a distribution system which contains IIDG were not given. An experimental verification of the inverter fault models based on present fault analysis techniques is mentioned here [55]. Some other researchers proposed a method for modeling an IIDG based on the inverter control system transfer function and output filter components [56]. This method is used for experimental verification and development of fault models of standalone voltage inverters in [57].

A new technique was implemented in grid connected inverters and how the calculation is done of the fault responses of multiple inverters [58]. The present available technical literature gives emphasis on describing the fault response of inverters by giving description of example inverters or with time domain simulations. None of the above methods is acceptable for use of protection studies, which are logical calculations. So it is necessary to understand the factor which controls inverters fault response as to determine a logical fault model which can be verified against experiment. The main modeling tasks are to find the effect of the control system and the process of current limiting on the formulation of the fault current. [58]

2.6.4.2. Current control

Current control technologies are mainly used when DG connects to the grid. Its output voltage is controlled by the grid and a specific current output control technologies is used. It may be single loop controlled or dual loop controlled [59].

- **Single loop controller**

In this literature, Single loop PR (proportion + resonant control) current control strategy is used [1703]. The resonance rejection, stability and dynamic response of the system gives higher gain at lower frequencies. Thus it is expected to get the response faster. In this case the contribution of the inverter to the fault may be large. The current reaching 4 times of rated value, leads to improper activation of nearby protection devices [59]

- **Dual Loop Current Controller**

Inverter output current may be controlled by using multi loop control to overcome the sluggish response problems and stability related with single loop control [60]. This controller comprises of inner and outer control loops. The inner loop is responsible for fast dynamics and improved stability, while the outer one provides steady state reference current tracking [43]. In this works, explanation is given the experiment outcomes for the system using the extra loop during a low impedance fault. When comparison with single loop results is made, it can be concluded that introduction of the additional loop to the control system minimizes the current overshoot magnitude and duration at the time of faulty condition of controller proportional gain (kp) in a single loop system is increased, this would result in the reduction of the current overshoot value to be nearest to the results .It leads to a marginally stable and unsafe operation [61].

2.6.4.3. Voltage control

A study to analysis the fault response of inverter-interfaced distributed generators in stand-alone networks was carried out [62]. The fault response is dominated by the different inverter control strategy with different control reference frame. The active current limiting method also controls the fault response. Control reverence frame is two types such as SynRF and NatRF. The main differences between control in the NatRF and in the SynRF are that NatRF controller has ability to regulate the voltage of each phase separately and there is a possibility to limit the inductor phase currents separately. Particularly in case of unbalanced faults, the fault response varies. Conventional fault analysis method of islanded microgrid can directly use this proposed fault model. The model is developed in PSCAD time domain simulations is done for result analysis [62]

2.7. Effecting factors in case of synchronous based DG (SBDG)

As it is known to us that a alternator (SBDG) short circuit current divided into three state: Sub transient (first few cycle and current decay very rapidly), transient (few cycle after sub transient period with slower amplitude rate), and steady-state (the current amplitude reach to a constant value). The sub transient and transient periods depend on sub transient, transient time constants and sub transient, transient reactance. The equations 4.1 to 4.4 show the sub transient and transient time periods along *d* and *q* axis. [63]

$$T_d^{'} = \frac{X_d^{'}}{X_d} T_{d0}^{'} \tag{4.1}$$

$$T_d^{''} = \frac{X_d^{''}}{X_d^{'}} T_{d0}^{'} \tag{4.2}$$

$$T_q^{'} = \frac{X_q^{'}}{X_q} T_{q0}^{'} \tag{4.3}$$

$$T_q^{''} = \frac{X_q^{''}}{X_q^{'}} T_{q0}^{'} \tag{4.4}$$

Where T_d', T_d'', T_q', T_q'' , $T_{d0}''$and T_{q0}'' are direct axis transient time periods , direct axis sub transient time periods, quadrature axis transient time periods, quadrature axis sub transient time periods, direct axis open circuit time constant, quadrature axis open circuit time constant respectively X_d', X_d'', $X_q'$and X_q'' direct axis transient reactance, direct axis sub transient reactance, quadrature axis reactance, quadrature axis sub transient reactance respectively. This equation is independent of control technologies. Impacts of control technologies on fault current are given bellow [63].

2.7.1. Control technologies

Normally alternator used constant active power and constant voltage with reactive power is variable. But when it is used as DG there are two separate methods for controlling the distributed system generator excitation system. One method targets to maintain the constant terminal voltage (voltage control mode) [64] and other one tries to maintain uniform power factor (power factor control mode) [65]. This decision is dependent on the utility adopted operational rules. In fact, it is essential to figure out the impact of various excitation system control modes on factors which can potentially bound the number of synchronous generators attached to a typical distribution system, i.e. the highest allowable penetration level of distributed synchronous generators [66]. In order to know the effects of different types of excitation control methods on the permissible penetration level of distributed generation, dynamical simulation analysis is applied. It consists of signal processing and measurement circuits. An exciter and a regulator, is the general structure of an excitation system. Comparing the reference value with the measured signal, a determined error signal is obtained is provided for the regulator. Adjustment of the excited field voltage is made on the regulator output. The regulator generally contains over and under excitation limiters that limit the maximum reactive power consumed or injected by the generator [67]. In many research works how short circuit current varies with control strategies is discussed. Effects different control modes are discussed below.

2.7.1.1. Comparing the constant voltage, unity power factor, capacitive power factor and inductive power factor

In a research work, SBDG is operated with constant voltage, unity power factor, capacitive power factor, inductive power factor respectively [68] Simulink modeling is done for every mode of control. Short circuit is applied for 300 ms. it can be noticed that the current responses are distinct depending on the adopted control method. The observation can be made that the highest values of peak current takes place when capacitive power factor control is chosen. On the contrary, the lowest values are acquired when inductive power factor control mode is adopted. When a pre fault value of the terminal voltage is considered, this fact can be explained [68]. The more will be the value of pre fault terminal voltage, the larger will be the maximum value of the stator current. The value of the pre fault terminal voltage is elementary to get the highest value of short circuit current. Terminal voltage is dependent on the power factor and inductive capacitive power factor [65]. In capacitive power factor mode terminal voltage is greater than inductive mode, though the sustained response is determined by the dynamic behavior of the field voltage. Similar fact can be confirmed by examining the RMS value of the short circuit current alongside the time. It can be observed that after 12 cycles of the fault application, the maximum value of short circuit current is obtained in the voltage control mode [68]. For the case of inductive power factor, the generator is practically not able to provide sustained short circuit currents. This happens because inductive power factor mode armature current producing field have demagnetizing effect which minimizes the effect of field. This is a significant fact as in this case, the generator protection system might not be able to find the fault in network. [68]

In another review, fault current comparison between constant power factor control and constant voltage is analyzed [69]. It is concluded that the using constant power factor synchronous generators may be considered as the poorest alternative. However, other factors must be taken into account to decide which the best option is globally, for example, economical and political sides. [69]

2.7.1.2. Fault current transient nature analysis

In another work, voltage sag is shown during single phase to ground fault [70]. It is shown that presence of generator minimizes the voltage sag. The generators' installation aggravates the problem of voltage sag. It occurs because the generators increase the system short-circuits level. From the analysis, the voltage sag magnitude is larger for constant voltage synchronous generator, and no difference between constant power factor synchronous generators and without generator. It was show that voltage constant synchronous generator give better dynamic performance of voltage at installation point [70].

2.7.2. Effect on voltage sag during unbalanced fault

A comparison is done on the reactive power injection during fault between the constant voltage synchronous generator and constant power factor [71].This gives an impact on the generator transient stability response. Generator injects reactive power during fault because the excitation system response slowly. After the fault clearance the excitation system operates at unitary power factor operation, it gives an adverse effect on transient stability of synchronous generator. In case of voltage constant power is injected during and after fault which gives a positive impact on transient stability. [71] In another work transient nature is analyzed by rotor speed. During short circuits, usually, synchronous generators accelerate, so that they may become unstable due to loss of synchronism. The stability of synchronous generators can be determined by analyzing the dynamic response of the rotor angle [72].

2.8. Comparison between fault current from synchronous based DG and Inverter based DG

In another review a short circuit fault is applied in a sub transmission system with presence of IBDG, SBDG and without DG [73] .The impact of installation of DGs (i.e., synchronous machine DGs as well as inverter based DGs) is discussed on coordination of protection devices. The presentation of this paper contains sections on the model of an inverter based DG with combined controls, the simulation blue print, case studies and outcomes from the simulation model, and a consultation on the effect of DG's protection coordination. It is found that fault current level is high for synchronous based DG. In this paper voltage controlled inverter is used. But different current limiting factor is not considered. In case of SBDG, its control mode is not described [73].

2.9. Calculation of fault current

Fault current calculation is important to know the circuit breaker (CB) relay settings to interrupt the line during fault. Normally Z bus matrix is used to calculate the fault current for conventional fault analysis method [73]. In the experiment, a simple linear equivalent model represents the fault response of a generator. By winding impedances and machine excitation, parameters of the model have been calculated [74]. Transient nature of fault response is taken into account by using different parameters, which depends on the time period under study. For presence of multiple generators in power system, each of the generators is represented in the similar way, irrespective of the fault type and distance from it [59]. Difficulty in estimating the impedance of the electronic inverter results in complications while performing the fault current calculation using the conventional matrix. An IIDG’s (Inverter interfaced distributed generator) fault response depends physical on its control system more than its parameters. For inverter based DG IGBT (insulated gate bipolar transistor), harmonics, LCL filter, and its control technology affect the fault current. So simulation modeling of the distribution generation becomes important.

2.10. Conclusion

Maximum renewable sources like solar, wind, fuel cell, micro turbine, DFIG etc are interfaced with grid through IBDG and synchronous generator is used for diesel generator combustion engine. Renewable sources are natural based. Its output is not predicted. So, non renewable sources are required to give the system a better sustainability and performance. For protection purpose fault analysis is important. Fault current is maximum for three phases to ground fault. So for this, in this work, short circuit current supplied by SBDG and IBDG during three phase faults are investigated. Different control factors which affect the fault current in case of IBDG and SBDG have been discussed. But in previous researches, all the affecting factors have not been considered. Calculation of equivalent circuit is also not possible for IBDG. If effects of the control strategy are considered then in case SBDG existing circuit model is not enough for the linear model of SBDG. In all of the above discussions it is also found that DG location, type, penetration level affects the fault current. But all the things are not considered at same time or comparison is not made. In maximum cases DG control technology are not considered to investigate the effect of penetration level and location. In another review DG control technology is considered but the penetration level is neglected. For same network depend on load demand or other purpose DG may be operated as island mode or grid connected mode. In this work considering both type of DG with same control mode which are interfaced with same system network fault behaviors are studied. Considering Grid connected mode and island mode, DG penetration level and DG types based fault currents are observed. Here a complete simulation model of IBDG and SBDG are made for fault analysis. IEEE 14 bus is considered as mesh distribution network for fault analysis purpose and comparison is made between SBDG and IBDG based fault currents.

3. Distributed generation and its impact

3.1. Introduction

In deregulated power system Distributed generation (DG) has become more attractive and economic. Distributed generation (DG) is defined over the world in different way however there is no consistency. U.S. Department of Energy (DOE) says that DG is the modular electric generation or storage with control technologies which is connected near the point of use. Distributed generation systems may be renewable like biomass-based generators, thermal solar power and photovoltaic systems, fuel cells, micro turbines, wind turbines, and storage systems or non renewable like combustion engines/generator sets. Distributed resources can connect with grid or work island mode depending on the requirement [75]. The grid connected DG are typically connected with the distribution system. As per the IEEE Standard 1547-2003, definition of DG is Electric generation facilities joined to an area operator of Electric power System (EPS), with a common coupling point (PCC), which is a subset of distributed resource. (DR)[76].

In another research work it has been defined that distributed resources are resources that connect demand and supply side which can be extended throughout an electric distribution system to fulfill the energy and reliability needs of the customers. Installation of distributed resources can be done on the customer side or at utility side of the meter [DD28]. The distributed generation is used in different name all over the world like ‘embedded generation’ by Anglo-American countries, ‘dispersed generation’ by North American countries, ‘decentralised generation’ by Europe and parts of Asia etc. The application of DGs in the power systems is based on the size of the DG to be implemented along with its impact and limitations [77].

3.2. DG Size

DG is defined according to the size in all over the world. There are massive ranges of DG’s from few KW to 50 MW which has been defined by Electric power research Institute [78]. Preston and Rastler defined this range as few KW to 100 MW [79] while Cordell defined it from 500 KW and 1 MW. The definition of DG given as per International conference on Large High Voltage electric systems is ‘smaller than 50-100MW’[80].

The defined range of the DGs varies from country to country depending upon the different government regulations. For example, in the English and Welsh market, the plants accumulating the DG with less than 100MW capacity are not centrally dispatched. The power output need not be traded in the wholesale market if the capacity is less than 50MW. DG plants with a capacity of less than 100 MW are not centrally dispatched and if the capacity is less than 50 MW, the power output does not have to be traded via the wholesale market [81]. According to Swedish legislation, they provide special consideration to DG capacity up to 1500 kW [82, 83]. A wind farm with one hundred 1500 kW wind turbines is considered as DG under Swedish law while for hydro units, in comparison the total rating of the power station is relevant. [84]. Depending on size and application, DGs are classified in four types as shown in Table3.1. [85]

Table 3.1: DG size [85]

DG type depend on size	**Size**
Micro distributed generation	1 W - 5 kW
Small distributed generation	5 kW - 5 MW
Medium distributed generation	5 MW - 50 MW
Large distributed generation	50 MW -300MW.

3.3. DG Types

Different applications and technologies are required as per the load requirements (thermal needs, size, power quality requirements , stand-alone or grid-connected electrical power, and environmental issues in the site, etc.). Few of these applications are remote and rural applications(standalone), stand by sources to provide power for sensitive loads during grid failures, combined heat and power (CHP) with introduction of power into the network when the DG capacity is greater than its local loads, peak-loads phasing, utility owned DGs, to supply part of the major required power and aid the grid by enhancing the system voltage profile, minimizing the power losses, and enhancing the system power quality, connection of grid to trade the electrical energy.[86] To get high efficiency DG can be used to fulfill peak load demand (Emergency power) parallel with grid or it can operate at island condition (prime power).It may be conventional or non conventional. [87] Depending on various factors it can be classified as shown in Figure 3.1 [86, 87].

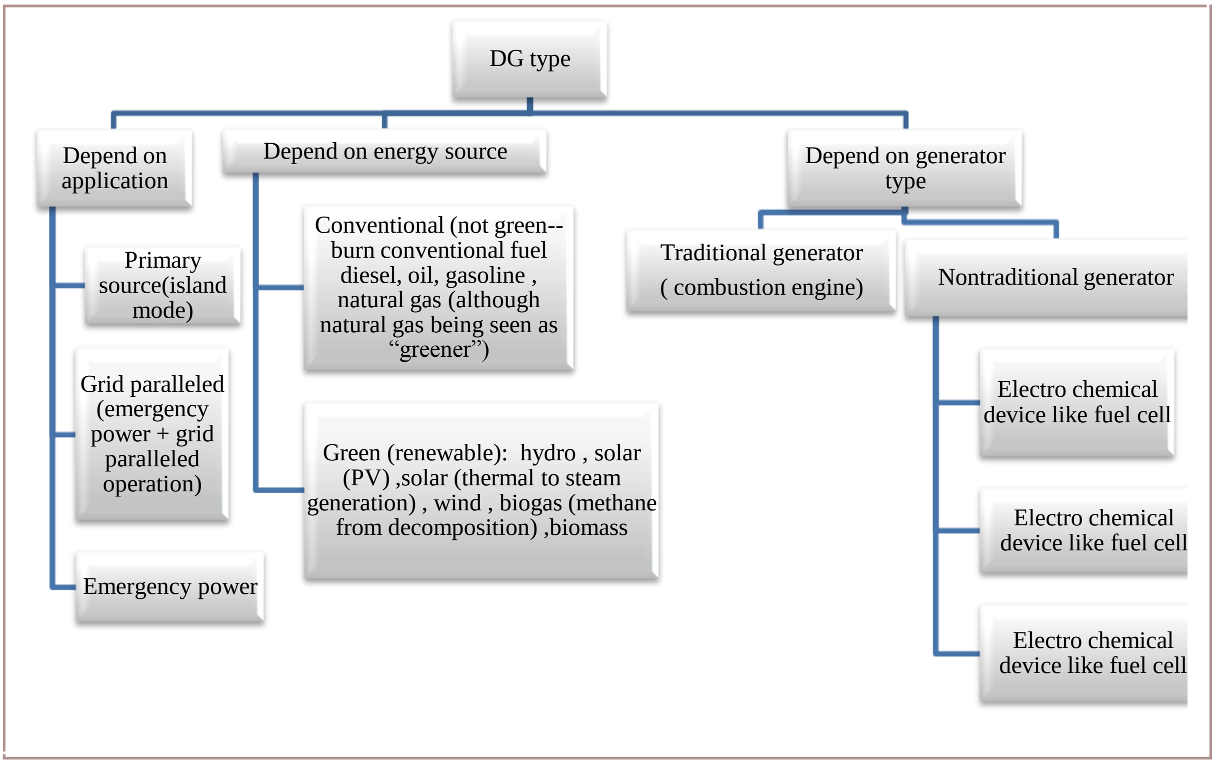


Figure 3.1: DG type [86, 87]

3.4. Distributed Generation interconnection interfaces

Depending on DG source it can generate AC from Synchronous or induction generator and DC. If DC or variable AC is generated it can't connect directly to the AC distribution system .It connects through power electronics interface.

- Synchronous Generator

Most reciprocating engines and most high power turbines (gas, steam, and hydro) connect with Synchronous generators which generate power more efficiently. It injects both active and reactive power [88].

- Induction Generator

Wind turbines, some low-head hydro power connect to the induction generator to generate power. Induction generator can be classified in to two types as per rotor design cage-rotor and wound-rotor. The cage-rotor induction generator is normally used because it is more chief then a synchronous generator, but synchronous generator controls reactive power inherently. Induction generators consume reactive power. It absorbs Var. VARs is provided externally from capacitors or from power electronic-based reactive Compensator. Otherwise it absorbs VAR from grid. The doubly fed induction generator (DFIG) has some additional advantages. But it is more costly [88].

- Power Electronic Interfaced DG Units

Power electronic (PE) devices has a capability to convert almost any form of electrical energy to a more desirable and usable form. PE coveter has another advantage that it has extremely fast response times [89]. It improves the power quality. Application of PE-based inverters is as follows.

- Micro turbines generators (MTG),
- Fuel cells (FC),
- Photovoltaic (PV)
- Energy storage system like battery,
- Some wind turbines

It has another applications due to high response time of inverter such as the operation of intentional islands (micro grids) for high-reliability applications and reducing fault level currents of distributed generation [89].The PE interface can also contain protective functions for both the distributed energy system and the local electric power system that allow paralleling and disconnection from the electric power system. These functions would typically meet the IEEE Std. 1547 interconnection requirements [90].

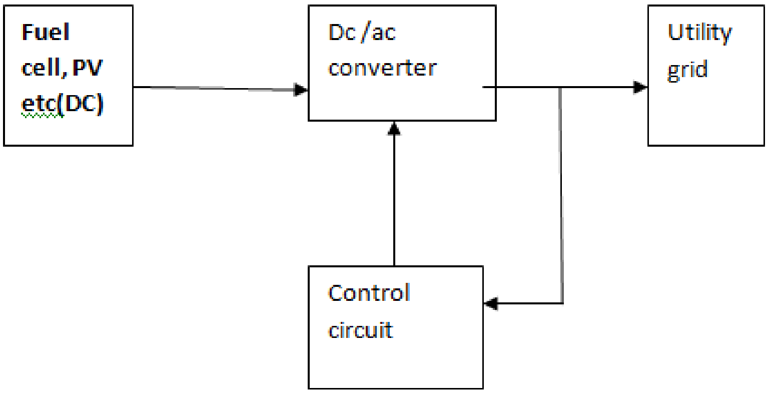


Figure3.2: DG circuit model with power electronics interface [89]

3.5. DG model

Depending on DG operation mode, types and network connection method DG units can be modeled as PV or PQ bus [91]. DG type and connection method to the grid are discussed below in Table 3.2.

Table 3.2: DG model [91]

DG	Electric machine	Utility interface	Control circuit
Photovoltaic		Inverter	Control circuit of the converter controls independently P and V Control circuit of the converter controls independently P and Q
Wind	DFIG, Asynchronous generator, permanent magnet, synchronous generator	Rectifier plus Inverter	Control circuit of the converter controls independently P and V Control circuit of the converter controls independently P and Q
Fuel cell		Inverter	Control circuit of the converter controls independently P and V Control circuit of the converter controls independently P and Q
Micro turbine	Permanent magnet or synchronous generator	Rectifier + Inverter/ ac-ac converter	Control circuit of the converter controls independently P and V Control circuit of the converter controls independently P and Q
Internal combustion engines	Synchronous generator	Directly	Regulating excitation voltage in power factor control mode Fixed excitation voltage Regulating in excitation voltage Voltage control mode
Gas turbine	Synchronous generator	Directly	Regulating excitation voltage in power factor control mode Fixed excitation voltage Regulating in excitation voltage Voltage control mode

The type of modeling of inverter-based DG units is determined by the convertor control method, while machine operation mode regulates the type of modeling of machine-based DG units. DG units give a particular value of active power with constant power factor to the network which can be modeled as P an Q source.[91] and DG units are modeled as a variable Q generator with a specific voltage and active power output operator like constant PV source. [91].

3.6. Impact of distributed generator

In early days Central Generation or CG system there was a centrally stationed power plant that used to generate bulk power to be transmitted through transmission and distributed line [92]. But in DG connected system power is generated near consumer site. Therefore, reverse power flow may be occurred from generators or DG's output may be varied on the grid. There are chances of effect on total distribution system in terms of voltage profile, power quality, reliability, power losses, protection and safety. Here potential impact of DG has been further described as per the literature works [92].

3.6.1. Power losses

In CG system power, generated in the power station, is transmitted through a complex network like transformer over head line, cables to reach the user end. In DG connected distribution system power is generated at the load centre due to which transmission loss minimization can be possible with proper allocation of DG [93]. Like capacitor allocation DG location can be identified properly by different optimized technique for minimum loss. Optimum location of DG is that location where the presence of DG losses is minimum compared to the presence of DG at other location. Only difference between capacitor and DG that Capacitor serves only reactive power where DG has impact both on active and reactive power. For feeders which have high losses, a small amount of DG allocations with proper planning (10–20% of the feeder load) can cause a significant reduction of losses [94].

3.6.2. Voltage Profile

The distribution systems are operated a standard voltage level which can be regulated through tap changing at substation transformers. Voltage regulators and capacitors, FACTS device are used on the feeders. Power flows from the substation to the loads in this type of voltage regulation. Capacitor supplying reactive powers is absorbed by the loads and tap changing transformer regulates the voltage changing the trans ratio of the transformer. DG supply both active and reactive power at the load centre which reduce the I^2R loss and improve voltage profile by supplying reactive power. Power flows may be reverse which can interfere the regulation procedure above mentioned [94]. Radial power flows is important for control of voltage regulation, for this DG allocation has become more important otherwise voltages of the network are low or over. DG can supply or absorb reactive power from the network that is voltage control possible by reactive power compensation technique. [95]. But under voltage and over voltage conditions are the main problems of distribution network with DG for radial power flows of voltage regulation purpose [96].

3.6.3. Power system Security

During short circuit for DG connected distributed network fault current is supplied from utility grid as well as DG to the fault point [97] If the total fault current crosses the capacity of the feeder’s circuit breaker, the faulty section cannot be disconnected from the system, and it may become dangerous. During the fault, fault currents may flow downstream as well as upstream in the faulty section. Fault detection due to miss coordination of CB, relay, fuse becomes more challenging task. Fault current level or direction may be changed depending on size of DG, type of DG (inverter base DG or synchronous machine) and location of DG. Fault current increase causes some problems to the existing over current protection devices. Due to increase of DG’s penetration, the protection systems cannot identify the fault because it unnecessarily removes a non faulty section or cannot remove the faulty section. This situation is known as sympathetic tripping and blind tripping respectively [98].

3.6.4. Power Quality

Power quality of a electrical network or grid describes the ability to produce power up to which it’s characteristics can align with the ideal sinusoidal current and voltage waveform, with current and voltage in balance [99]. To protect the system from power quality degradation, it is very much important for network operators to ensure a specified minimum short circuit capacity [100]. The relation between power quality and distributed generation is not clearly explained anywhere. Many authors have said that distributed generation can mitigate power quality problems. For example, in areas where proper voltage support can’t be provided easily, distributed generation can compensate these areas because rise in voltage in the network can be obtained by connecting distributed generation [101]. For voltage support and power factor corrections, potentially positive effects of DG have also been mentioned. Excess voltage and Voltage fluctuation are the defining elements of power quality.[102]

3.6.4.1. Excess voltage

Programmed timer or line drop compensator (LDC) controls the voltage of the distribution line [103]. Generally several feeder lines are connected to a single distribution transformer and a single control unit regulates the voltage profile of these lines. Additionally, the voltage of middle of the line is compensated by Static VAR Reactor (SVR) in case of heavy power-flow line or long transmission lines. Each feeder load should be proportionally balanced for utilization of these voltage control systems. If DG concentration is high in a specific line, the power cannot flow among feeder lines and hence the gap of power flow becomes wider because of power back-flow due to presence of DG. The voltage profile of feeder lines may deviate from the standard range due to this non uniformity in power flow [103].

3.6.4.2. Voltage fluctuation

Voltage fluctuation is one of the main problems for DG connected distribution system because voltage of local line fluctuates due to change of the output voltage of DG. Under or over voltage at consumer receiving point would be caused by this fluctuation [104]. These becomes the main concern for natural dependent generating source like wind power (depend on wind speed), solar photovoltaic generators, tidal power etc when connected to the local load. The target of a power system is to provide its customers electricity which will be economical and reliable.[105] Planning and maintaining reliable power systems is very much essential as interruption cost and power black outs can have extreme effect on the consumers and utility [106]. Generally reliability analysis and evaluation processes for natural generating sources are far underdeveloped at the generation level than the existing sources. Since distribution interruptions occur mostly on local basis and is not as much costly as generation or transmission black outs. It has been concluded from outage of utilities of customer that distribution failure mostly contributes for unavailability of supply. Integration of DG to the distribution system is needed to boost reliability of the power supply [DI58]. DG can be simultaneously used as backup system or main supply. Additional charges can be avoided by using DG at peak load periods. The impact of distributed generation makes this an attractive option in case of power generation. However, applications of DGs in the power system infrastructure have some limitations in implementation.

3.7. Limitation

When significant penetration is done by DG, it affects the system dynamics. Thus DG interconnection exploration is complex, particularly taking into account extensive variety of technologies which have been designed for unidirectional power flow when large scale DG operation will be done researchers will face these challenges [107]. These are—

- Reverse Power Flow: During upstream fault, fault power from DG is in the opposite direction with respect to the utility grid, is known as reverse power flow. As a consequence of DG connection in the system, protection circuit malfunction occurs as per their present configuration.
- Reactive Power: Many DG technologies like wind generator uses asynchronous generators which absorb reactive power instead of supplying it. For DFIG(Double Fed Induction Generator)it may be controlled
- System Frequency: Supply and demand unbalance causes deviation from nominal frequency of the system. System frequency is affected by the rise in the penetration level of distribution generation. The control process becomes more complicated due to free riding capability of the generator.
- Protection Schemes: Due to configuration in radial form and split rings, unidirectional flow pattern is observed in most of the distribution network. So the protection system is designed as per this conditions keeping in mind. The installation of DG causes change of flow to bi directional. So new safety equipments are installed and resize is done for same purpose. Resizing of the network includes grounding, breaking capacity, supervisory control and Data Acquisition (SCADA), short circuit etc.
- Asynchronous DG sources like wind generator or dc source like storage system or photo-voltaic system which connect through inverters with system inject harmonics
- Fault currents level is increased which depends on the position of DG units.
- Financial cost/kW of generation is high if the source is renewable energy because these technologies are still developing.
- Power quality also becomes a problem for renewable source. Power electronics application is used to control the SPV wind energy technologies [108,109].

3.8. Conclusion

In this chapter DG type, size and its application, DG model, DG inter connection interface and its impact are discussed. DG interconnection and its modeling are very important. DG is used as island mode or grid connection mode depending on its application. If DG operates on island mode it must be operated as constant PV source otherwise consumer voltage will fluctuate. If it is operated in grid connected it may be operated as PV or PQ mode. From above discussion it is found that DG has adverse effect mainly on protection system. In next chapter effect of DG in protection system is briefly discussed. Different protection system risk and its solution are also highlighted

4. Protection system risks due to DG in distribution system

4.1. Introduction

Like many other technologies, DG also has its demerits with benefits. Integration of DG in the network changes the radial configuration and it is converted into a mesh network. Its integration also leads to the loss of co-ordination of network which exists between the protection devices [110]. DG size, DG type, location of DG affects the protection coordination up to some extent sometimes protection coordination completely lost or coordination range demonizes. Many researchers have worked on how DG integration influences the protection of the distribution network and also how this problem can be solved [111].

As per literatures, some problems arise after connecting DG for protection purpose and some remedies have been stated [112].

4.2. Protection system risks

Type of DG is the main concern for fault related problems. The type 1(synchronous generator) and type 2 (induction generator) DGs are identified by high short circuit current contribution reaching up to 10 per unit (pu) of the current rating, depending on the generator and connecting transformer [113]. For type 2 DGs, the currents deteriorate quickly and may go below rated current, as asynchronous DGs lack independent excitation system of their own. This fact makes it harder for a relay to detect a fault. The DFIG (type 3) generally consists of a crowbar scheme for rotor circuit protection, with activation of the crowbar, rotor becomes short circuited and the DFIG behaves like the standard synchronous generator [113], with a high initial current that decays quickly. The type 4(inverter interfaced) DGs are distinguished by short circuit currents up to 1.1 to 2 pu of rated current which is a limited contribution. The quick response of the inverter control makes it sure that this current level is rapidly reduced to below standard level [113]. The effects of DG connection in the network during fault are as follows:

- Affecting short circuit levels
- False tripping of feeders (sympathetic tripping) & unwanted islanding

- Prohibition of automatic reclosing
- Blinding of protection
- Un synchronised reclosing
- Relay miss coordination

4.2.1. Protection system risk due to inverter based DG

- **Prohibition of automatic reclosing**

When a temporary fault occurs on a line, permanent tripping of relay or CB is not required [114]. During fault the re-closer automatically is disconnected and it is automatically reclosed after a short period of time when arc extinguishing is complete. Repetition of the process is done for a certain number of times, after that the line is disconnected permanently if the fault still persists. However, with IBDG installed, the inverter may continue to energize the fault by developing arc, which may change the temporary fault to a permanent one even with the re-closer open. Hence, line is unnecessarily disconnected [114].

4.2.2. Protection system risk due to synchronous based DG

- **OVER CURRENT RELAY MISS-CO-ORDINATION**

It has been observed that synchronous based DG’s fault current generation is higher than inverter based DG, so it effects have much more intense impact on the protection systems, where as inverter based DG impacts on the distribution system protection at minimum level, since fault current of inverter based DG ranges from 1 to 2 p.u. miss-coordination of relay gives a negative impact for DG addition and usually it is of meshed, dynamic nature. The bi directional power of the distribution system makes relay co-ordination more difficult [73].

4.2.3. Protection system risk due to both types of DG

Protection related problem arises due to presence of any type of DG.

4.2.3.1. Short circuit current level

Penetration level of DG units increases day by day in distribution network. In maximum cases it may lead to increase in the fault current level depending on DG location, types of DG. In some cases in some parts of the grid this increase can be of significant magnitude [115]. If many DGs are connected to the distributed network during fault total impedance becomes low than central grid connected system. So fault current may be high which may lead to increase of short circuit level. In case IBDG it may be reduced. DG type is one of the main important issues for short circuit level.

4.2.3.2. False tripping feeder (sympathetic tripping)

Protection device like fuse, relay, recloser, Circuit Breaker (CB) etc operate to protect the system during fault. Integration of DG to the system may cause of miss co-ordination problem. The relay, CB may operate unnecessarily in healthy feeder.

- **Case1: Sympathetic tripping due to upstream fault**

As shown in the figure 4.1 fault occurs at point F at feeder 1. Fault current is supplied from both DG and substation. Any CB & relay cannot realize the total fault current. Fault current $I_F = I_S + I_{DG}$. Removal of faulty section is only possible by operating fuse 1. But R2, CB2 may experience over current which leads the relay to operate before operation of fuse F1 [116].

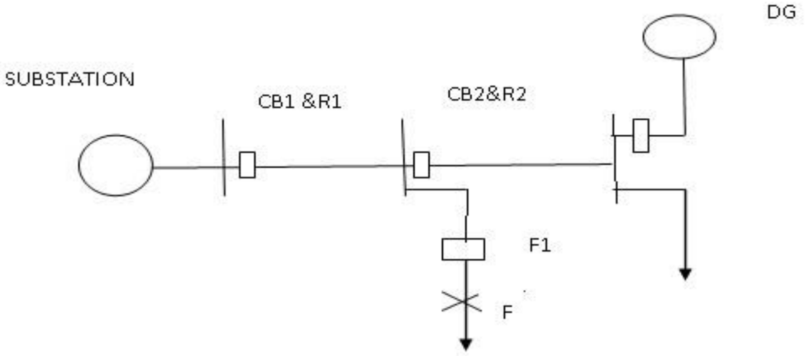


Figure 4.1: Sympathetic tripping due to upstream fault (at point F) [116]

- **Case 2: Sympathetic tripping due to fault in adjacent feeder**

If fault occurs adjacent of feeder of DG connected feeders which get supply from same substation, DG unit also supply fault current to the faulty feeder along with substation. Over current relay of healthy feeder may operate if fault current supplied by DG exceed the limits of pick level of relay. As shown in figure 4.2 if fault occurs at feeder 1, DG supplies fault current and CB3, CB1, CB2 may be operate before clearance of fault. So it is an example of false tripping of feeder [117].

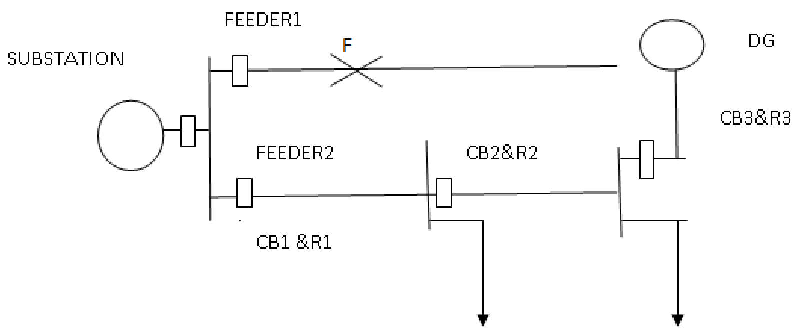


Figure 4.2**:** Sympathetic tripping due to fault in adjacent feeder (feeder 1) [117]

4.2.3.3. Unsynchronized reclosing

DG contribute fault current which can significantly change the short circuit levels and which is the source of the errors in fuse–recloser, fuse–fuse, or relay–relay miss coordination. In case of recloser and fuse coordination, recloser normally gives protection from temporary faults and fuse operates during permanent faults. During temporary fault, the reclosers will operate.

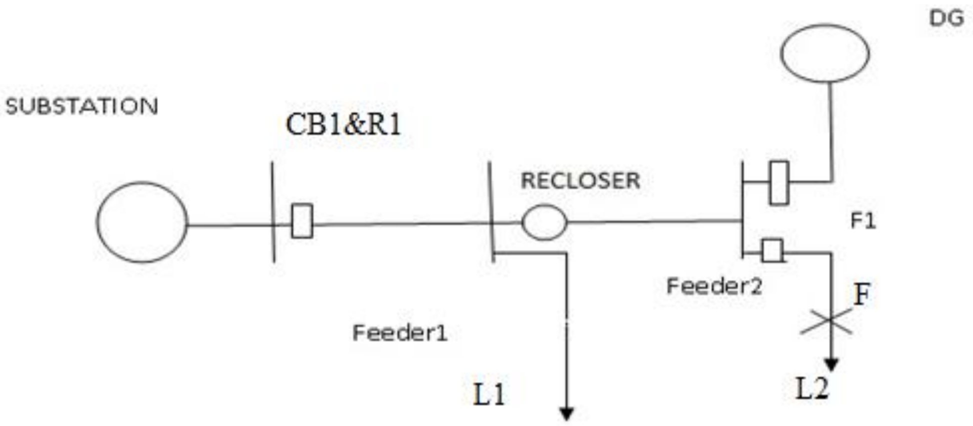


Figure 4.3**:** Fuse recloser miss-coordination [118]

It successfully recloses after clearance of fault without disconnecting the load feeder. Among all faults 70–80% of faults are temporary faults which occur in the distribution network. As shown in Figure 4.3 DG is placed at the end of feeder. Fault takes place at feeder 2 at point F. The fault current passing through recloser is supplied by only substation not DG, current passing through the fuse is the total current supplied by both substation and DG. It is clear that the fault current through fuse 1 is greater than the fault current through recloser. If the fault current through fuse 1 is higher than $I_{f(max)}$, the fuse will blow before the recloser operates. During any temporary fault permanent interruption will occur [118].

4.2.3.4. Blinding protection

The blinding of protection happens when fault occurs at downstream. In these situations, the fault current is contributed by both the DG unit and the grid. Thus Grid contribution is less than previous system [117]. This problem mainly is noticed in distribution grids at rural areas. In case of central grid system, grid contributes high short circuit current. Thus impedance of the grid is low. In case of DG connected system, fault current is contributed by grid. It mainly depends on DG location and capacity of DG and types of DG. If DG is present near the substation or capacity of DG is small grid contributes high short circuit power. For rural distribution grid, grid impedance is high enough compared to the DG unit (if single unit). Hence it can't be neglected. So less fault current contributing by DG may be leading towards blind protection.

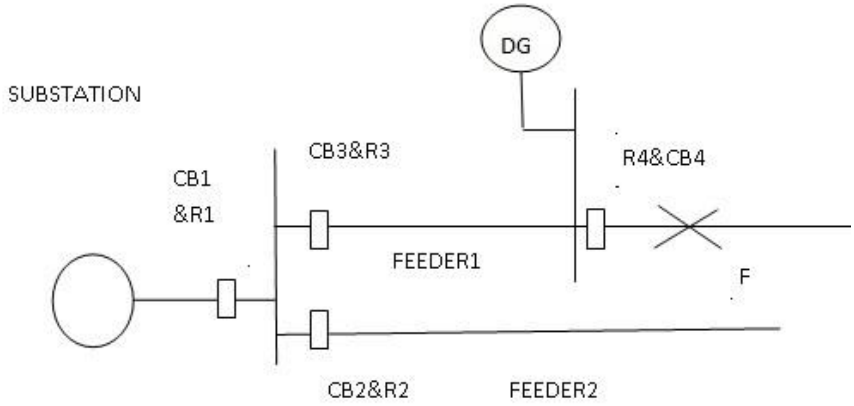


Figure 4.4: Blinding protection at Feeder 1 [117]

It may happen that fault current can't reach the relay's pick up current and relay can't identify the faulty feeder. It is also found that if DG contribution increases relay miss co-ordination may take place. As shown in figure 4.4 a DG unit is connected to bus and faults of 200 ms are applied to the downstream feeder 1. DG is adjusted to change the value of output power from 1 MVA to 3 MVA and the fault can be sequentially applied to 20, 40, 60, 80 and 100% of feeder. Pickup current of Relay3 is 0.15 KA and pickup current of relay4 is 0.2KA [117] Photo voltaic cell is connected with inverter used as a DG. Figure 4.5 shows the fault current which varies with DG location and DG size. Short circuit current (RMS value) sensed by relay 4 and relay 3 for single phase fault are shown in figure 4.5 (a) and figure 4.5 (b) respectively and 3 for three phase fault are shown in figure 4.5. (c) and figure 4.5 (d). It is shown that for both types of faults (single phase and three phases) relay3 operates before relay4. That is relay miss co-ordination is happened [117].

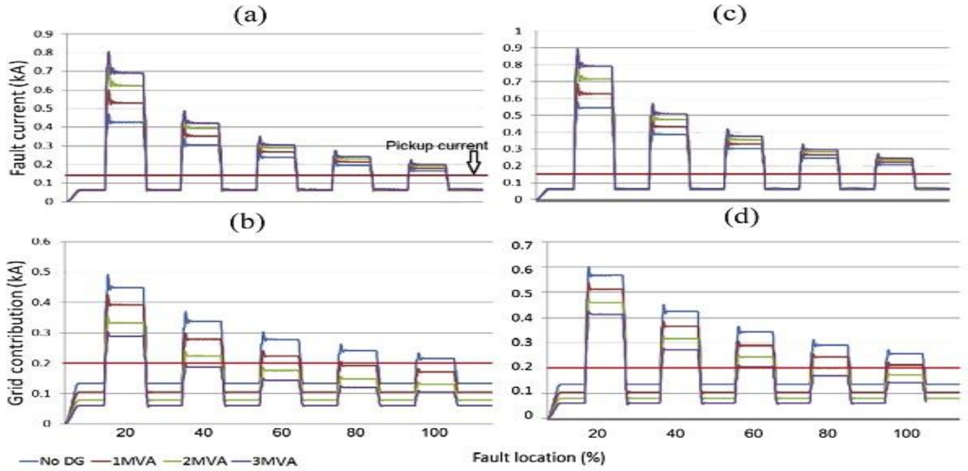


Figure 4.5**:** Short circuit current (RMS value) sensed by relay 4 and relay 3 for single phase fault are shown in figure (a) and figure (b) respectively and three phase fault are shown in figure (c) and figure (d) [117]

4.3. Different protection scheme

4.3.1. Adaptive centralized protection scheme

A new advancement in the field of distribution network protection in presence of DG's has been discussed in this [119] paper .A distributed network is divided in many zones; each of

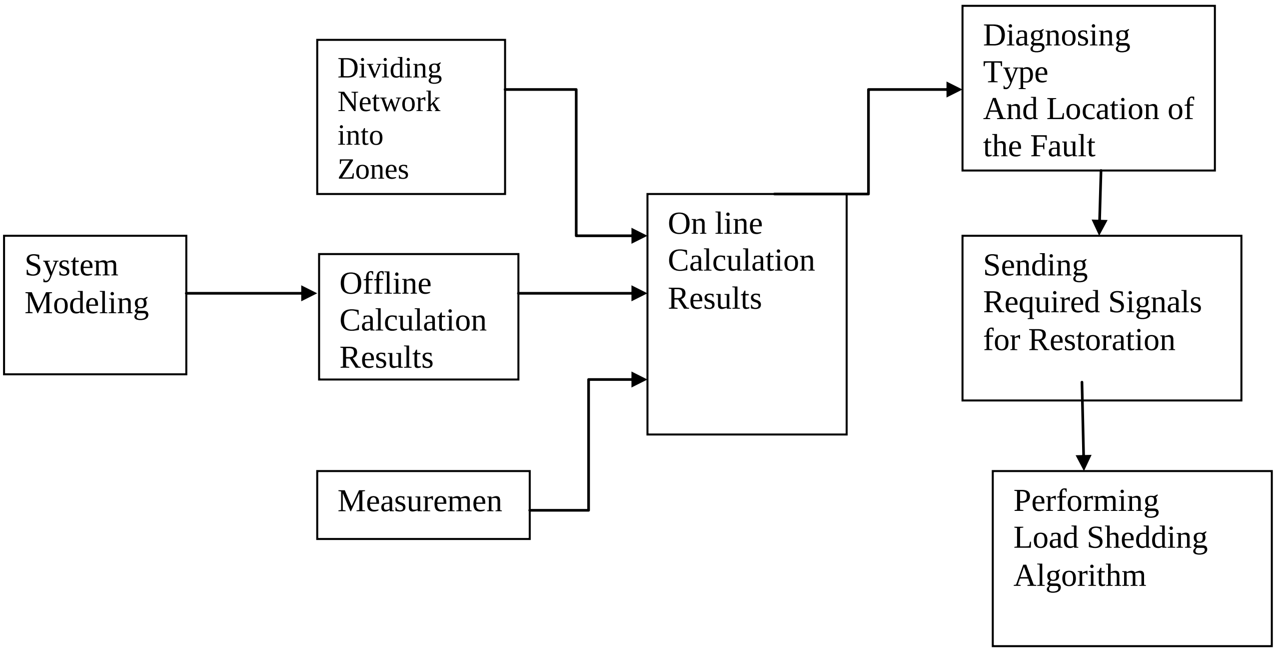


Figure 4.6: Flow chart of centralize protection scheme [120]

the zones is proficient in island operation. Optimal placement of the protective devices is done, thus risk analysis is useful to optimize the protection zone. Fault determination is done by Multilayer perceptions (MLPs) neutral network. The suggested scheme has been applied on a selected area of an actual distribution network of a big city and a MATLAB based software which has been developed to use for the implementation of the proposed algorithm on the actual network data [120]. As shown in figure 4.6 that system is divided into different zones. The calculation of different parameter is done offline that what is the possible value of voltage and current and networks parameters are measured. Then these parameters are compared through online calculation type and location of fault identified and relay is tripped and circuit breaker operates according to this result [119].

4.3.2. New Coordination Strategy for setting of Directional Inverse Time Over-Current Relays

Generally radial distribution networks will be changed into meshed and looped structure having bi directional power flow, which leads to increasing dependence on directional inverse time over current relays (DOCRs) in distribution systems. For modern distribution system DOCR is a popular and attractive option. These relays are optimally coordinated to lower the overall time of operation of all relays [121]. As a result of DG addition miss coordination occurs. To overcome this, new optimal relay with new settings is required that take into account DG's presence. Various optimization methods, which comprises of conventional and heuristic techniques are applied to decide optimum time dial and pickup current settings of the relays that assure co ordination and minimum total relay operating times [122]. Digital DOCR's is capable to improve protection system performance especially in existence of DG, either using dissimilar of modified groups of relay settings and characteristics [123] or by utilizing the communication in digital relays [124], thus other protection coordination technique take advantages.

The relay time-current characteristic can be expressed as given in equation 4.1[121]

$$T_i = TDS_i\left(\frac{A}{M_i^c - 1} + B\right) \tag{4.1}$$

Where $M_i^c = \dfrac{I_{fi}}{I_{pi}}$

For standard IEEE relay curves, the following constants for *A*, *B*, and *C* are respectively 0.0515, 0.114, and 0.02 [125].

Where, I_{fi} = relay short circuit current

I_{pi} = relay pickup current

Generally pickup current and time multiplier setting (*TDS* and *Ip*) adjustment are responsible to achieve co ordination between relays operating times within meshed system. Digital inverse time over current relay operation equation has two constants. [126]

i. Constant for relay characteristics (*A*)
ii. The inverse time type (*B*)

The suggested coordination strategy takes the constants as continuous variable settings that is adjustable. These A and B values are optimally chosen in addition to (TDS and Ip) coordination achievement. The coordination problem is prepared as a non linear programming problem is prepared as a non-linear programming with main purpose to minimize overall time of relay operation, at the time of primary and back up operation taking into account faults at various locations [127].

4.3.3. Optimal allocation of fault current limiters

Fault current limiter (FCL) installation is a new process to control or limit the fault current produced by DG. Fault current level will be limited and circuit breakers and fuses change will not be necessary when FCL is installed at the utility system. Various configurations of FCL are available to minimize the effect of DG on Distributed Protected System. [128]It is necessary to develop the process to determine less number of FCL with optimal locations and size, as FCL's are costly. The optimal location and sizes are obtained Genetic Algorithm (GA). This algorithm was for allocation of DG's recloses and other devices for which Genetic Algorithm has been used before. [129].

4.3.4. Protection scheme using inverter current control strategy

An alternative way to minimize the DG impact on the protection system is to find the fault and also trip all the converters in the specified protection zone [130]. However converters cannot distinguish between short term disturbances (like load switching) and fault conditions. Therefore unwanted power delivery interruptions may take place due to converter tripping in all abnormal conditions. As shown in table 4.1, it is a way to ride through short term disturbances and as well as avoid excessive nuisance tripping is by introducing allowed time delay. If the abnormal condition persists after the delay, as per IEEE standard1547 [131], the converters tripping and reconnection should be done after 5 minutes of the system returning of normal condition. These days fast automatic reclosers open and recloses in less than 6 cycles subsequent to fault occurrence, so the above time delays may be ineffective, i.e. during the reclosing, DG still contributes to the arching fault. Apart from this minimization of these delays may result havoc nuisance tripping due to short term disturbances. One method to solve the ride through short term disturbances and miss coordination problem in parallel is to minimize the converter current as per the seriousness of the irregularity instead of completely blocking the converter. Converters which are nearest to the fault, will have greatest impact on the protection system, they also experience the largest voltage fluctuation from normal boundaries and should notably decrease their contribution. On the other side, DG units which are distant, they have minor effect on the protection system, they can continue power supply. For implementation of above mentioned current control strategy as per DG terminal voltage, the DG's reference current can be calculated as following flow chart [132]. As shown in flow chart figure 4.8, voltage is measured at the point of coupling($V_{pcc(p.u)}$). If it is greater than 0.88 P.U reference current is measured by equation 4.2. If $V_{pcc(p.u)}$ less than 0.88, current references is measured by the equation 4.3

$$I_{ref} = \frac{P_{Desired}}{V_{pcc}} \qquad \text{When } V_{pcc} > 0.88\,\text{P.U} \qquad (4.2)$$

$$I_{ref} = K.V_{pcc}^{n}.P_{Desired} \qquad \text{When } V_{pcc} < 0.88\ \text{P.U} \qquad (4.3)$$

Where $P_{Desired}$= desired output power,

$V_{pcc(p.u)}$ = coupling point voltage, *n* and *K* are constant here *n*=3

Table 4.1: IEEE STD 1547 required response to abnormal voltage conditions [131]

Voltage at PCC	Maximum tripping time(sec)
V<50%	0.16
50%<V<88%	2
88%<*V*<110%	Normal operation
110%<V<120%	1
137%<V	0.16

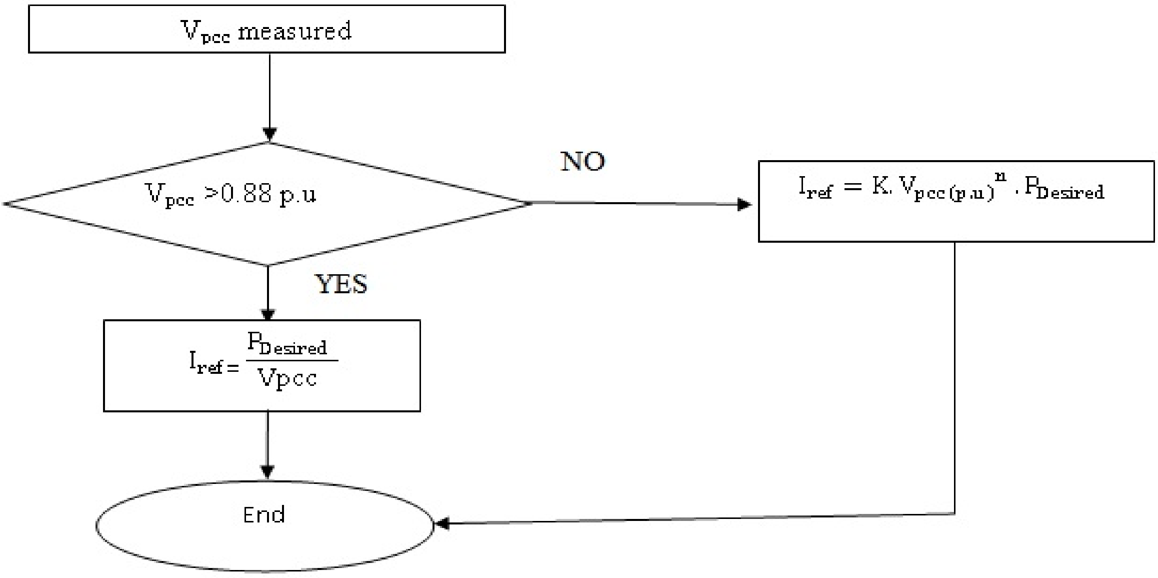


Figure 4.7: Protection scheme using inverter current control strategy [132]

4.4. Conclusion

In this section, problems due to DG in protection purpose and its control schemes are discussed. In the protection schemes as discussed in section 4.4.1, 4.4.2, 4.4.3, DG dynamic characteristics are not considered. Here DG is considered as an ideal source. Inverter based DG fault current is neglected but if penetration level of inverter based DG is greater than relay fuse miss co-ordination or other problem may arise[133]. In the protection scheme in section 4.4.4, this problem has been tried to solve by controlling the DG output current. But in this case identification of the value of constant '*n*' is difficult. Usually the value of '*n*' governs the sensitivity of the control scheme to a change in voltage. When the value of '*n*' is larger it leads to more evident output current reduction with voltage sag. However, too large value of '*n*' will be responsible for the control scheme to be over sensitive to a small voltage disturbance also. This scheme is only possible for current control inverter based DG. There are many other control technologies which may affect the fault current contribution from it. If the control strategy changes, fault current contribution may change. In chapter 2 , the effects of DG element and its control strategy are discussed. To know the effect of control system and its dynamics during fault inverter based DG and synchronous based DG, modeling is done in MATLAB/Simulink in next chapter. IEEE 14 bus is considered there.

5. Distributed Generator system modeling

5.1.Inverter based DG modeling

For conventional systems normally primary power is converted into electric energy via a rotating AC machine and directly connected to the utility grid system. But some non conventional resources like solar, wind, micro turbine etc are not connected directly to the grid via ac rotating machine. Power electronic devices are used as a utility connection. In case of wind power stations first electrical energy is generated with variable frequency which is not possible to be fed directly to the grid that's why first variable frequency ac power is converted into dc and then converted into ac through power electronics devices and connected to the utility grid through a transformer. Micro turbines are usually driven by a synchronous machine at very high speed to give better efficiency. The high frequency has to be transformed to the nominal utility frequency. So it is got by cycle converter or first converted it into DC then converted into AC. Photovoltaic panels and fuel cells create DC power which has to be transformed in to AC. The main benefit of power electronic converters is that its control is possible to get desired output. A converter has an ability to give required power, voltage, current and frequency which is suitable for utility grid.

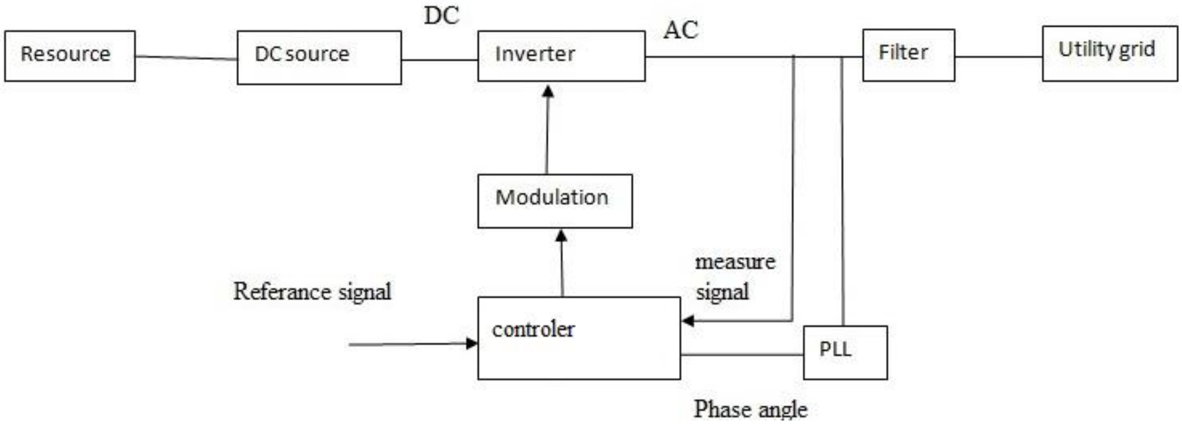


Figure 5.1**:** Modelling of inverter based DG [134]

Figure 5.1 shows the simplified diagram of the Inverter based DG model. Production of DC takes place from the energy sources that have been discussed before. This DC is converted into AC by inverter filter and is used to reduce the harmonics. Phase lock loop (PLL) is utilized to mark the phase angle. Controller generates modulating signal by comparing the reference and measure signal and controller (PI or PR). Different modulation techniques are utilized to generate triggering pulse for the thyristor bridge.

5.1.1 Inverter

Inverter usually consists of semiconductor switches and it converts the DC voltage or current into the desired AC voltage and current depending on the modulating signal received from the modulation block. Inverter is mainly two types. These are Voltage source inverter (VSI) and current source inverter(CSI) . If a DC voltage source is connected with inverter through a negligible reatance known as VSI and if a DC source is connected with inverter through a large inductor to fed continious value current known as CSI. Output of the CSI is not varied with load. In this work, voltage source inverter is considered . As shown in figure 5.2, the inverter consists of six IGBT with anti parallel diode and a gate pulse is generated to trigger the IGBT's. Modulation techniques are most normally used to control the output voltage of inverters. Gate pulse $g_{1,}$ $g_{2,}$ $g_{3,}$ $g_{4,}$ g_5 and g_6 are triggered by the IGBT T1,T4,T3,T6,T5andT2 respectively.

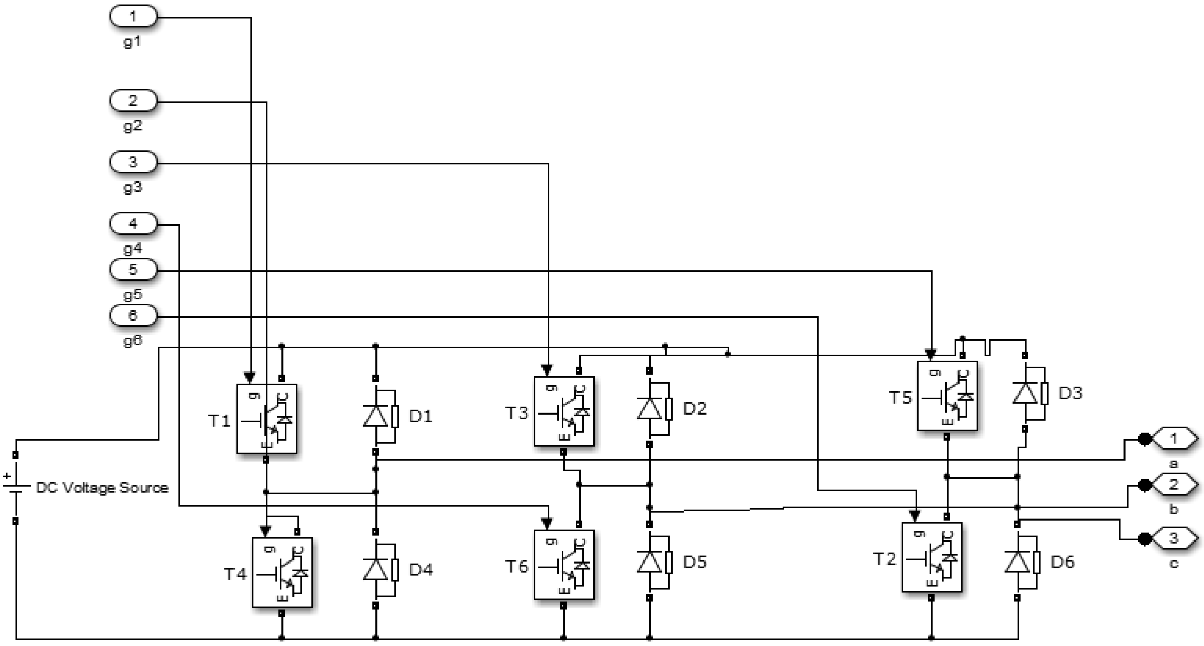


Figure 5.2: Inverter

5.1.2.Modulation

In modulation block modulating signal changes into tiggering pulse to tigger the inverter's switching device to restrain the out put voltage of the inverter. Pulse width modulation is very important technique. In this technique a controlled ac output voltage is obtained by regulating the on and off periods of the inverter switches although input of the inverter is fixed dc voltage. A Sinusoidal Pulse Width Modulation is most popular modulation technique in which the switching instant of inverter switch determined by making a comparison between high frequency triangular carrier wave and the sinusoidal reference wave. Modulating index determines the value of output voltage. It is defined as the ratio of peak magnitudes of the modulating waveform to the carrier waveform.

If $A_m \sin wt$ is the modulating signal and magnitude of the triangular carrier signal alters between the peak magnitudes of +A_c and -A_c. Then the modulation index is described as

$$m = \frac{A_m}{A_C} \tag{5.1}$$

The output voltage of the inverter is

$$V_{ai} = 0.5V_{dc}(m\sin \omega t) \qquad \text{When } m < 1 \tag{5.2}$$

$$V_{ai} = \frac{1}{2\sqrt{2}}V_{dc}(m\sin \omega t) \qquad \text{When } m=1 \tag{5.3}$$

When over modulation technique is used output voltage is as equation 5.3 up to some extent. Over modulation is not favorable due to the introduction of lower frequency harmonics in the output waveform and the load current is distorted.

5.1.3.Filter

Filter is normally used to mitigate the impact of harmonics in the ac output current from inverter. The inverter bridge is generally connected to the AC grid or load through an output filter . L, LC and LCL are the most common configurations of filters with addition to this, a grid interfacing transformer can be used in between the filter and the AC grid or load for the cause of DC injection preventation, change of voltage level, or isolation. Design parameters of converter side converter(L1) ,total capacitance(C1),gridside inductor (L2) is described below.

Design of the Converter Side Inductor L1: To design L1 it is assumed that allowable THD of converter-side inductor current is limited to10%. L1 can be calculated as follows [135]

$$L_1 = \frac{1}{3\sqrt{2}} \frac{E^2}{100.P} \frac{f_0}{f_{SW}} \frac{1}{THD} \sqrt{\left(\frac{3}{2} - \frac{4\sqrt{3}}{\pi} + \frac{9m^2}{8}\right)} \qquad (5.4)$$

Where THD= total harmonic distortion $= \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1}$, f_{SW} = switching frequecy of PWM ,f_0 = fundamental frequency,*E*= the out put voltage, *P*= rated power, *m*= modulating index,

Design of the total capacitance C_1:The value of total filter capacitance $C_1$is designed to restrain the reactive power to 2.5% of rated power .the value of C_1 can be desined by the equation 5.5

$$C_1 = \frac{2.5\%P}{100\pi E^2} \qquad (5.5)$$

Design of the grid Side Inductor L2: To design L2The first resonant frequency ω_1 is set to 0.3 times ωsw(switching frequency of PWM) according to the requirement of control bandwidth, the value of L_2 can be designed by the equation 5.6

$$L_2 = \frac{L_1}{L_1 C \omega^2 - 1} \qquad (5.6)$$

5.1.4. Controller circuit

To generate modulating signal comparison of referance signal with measured signal is made and an error is generated which is reduced by PR or PI or other type control is used.Current regulated voltage -source inverters (CR-VSI) which are Current regulated, normally used for parallel operation of VSI-to-grid and VSI-to-VSI. And voltage regulated voltage source inverter is used for standalone mode to give constant voltage. Active reactive power control is used to generate reference current. An essential component of this block is PLL, *abc* to *dq* conversation and *dq* to *abc* conversion.

5.1.4.1. Park's transformation (*abc* to *dq* and vice versa)

The dq transformation is responsible for converting of the three-phase stationary coordinate system to the two phase rotating coordinate system. This transformation is done in two steps:

- In first step the three-phase stationary coordinate system transforms (abc) in to the two-phase stationary coordinate system ($\alpha\beta$), is known as abc to $\alpha\beta$ transformation. If u_a, u_b, u_c are the three phase signal and $u_\alpha u_\beta$ are the two phase signal stationary reference frame then it is calculate as equation 5.7

$$\begin{pmatrix} u_\alpha \\ u_\beta \\ u_0 \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} \tag{5.7}$$

- In second step two phase stationary coordinate system ($\alpha\beta$) transforms in to the rotating coordinate system *(dq)*. This transformation known as αβ to dq transformation. If u_α, u_β are two phase signal and u_d, u_q are two phase signal are in rotating frame , the relationship between two phase stationary frame to rotating frame is expressed by the equation 5.8

$$\begin{pmatrix} u_d \\ u_q \\ u_0 \end{pmatrix} = \begin{pmatrix} cos\,\theta & sin\,\theta & 0 \\ -sin\,\theta & cos\,\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_\alpha \\ u_\beta \\ u_0 \end{pmatrix} \tag{5.8}$$

The relation that transforms the abc to dq frame is as follows

$$\begin{pmatrix} u_d \\ u_q \\ u_0 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} u_\alpha \\ u_\beta \\ u_0 \end{pmatrix} \tag{5.9}$$

5.1.4.2. Phase lock loop (PLL)

A phase-locked loop or phase lock loop (PLL) is a control system where input and output signal phase are related to each other. To detect the phase or angular position this technique is most of the time used [136]. For three phase system, Synchronous Frame PLL (SF-PLL) is most commonly used .The block diagram of SF-PLL is demonstrated in Figure 5.3. SF-PLL detects the instantaneous phase angle by synchronizing the rotating reference frame to the utility voltage vector at stationary frame. The direct (V_d) or quadrature axis (V_q) reference voltage is set to zero by PI controller, that is responsible for locking of the reference to the vector phase angle In addition, PLL gives the voltage frequency f and amplitude V_m as outputs. A fast and specific detection of the phase and amplitude of the utility voltage vector can be possible by SF-PLL with a high bandwidth if the utility voltage is balanced and harmonics distortion is not present. Under distorted utility voltage with high order harmonics, the SF-PLL can still operate if its bandwidth is reduced. To minimise the effect of harmonics, PLL must reject or cancel out the harmonics. Due to this PLL response speed reduces. But in case of unbalanced condition, reduction of the PLL bandwidth is not an acceptable solution [136]. SRF-PLL gives the information about phase amplitude and frequency of the voltage in average. For individual-phase it is not possible. SRF-PLL may not be applicable for single phase systems in a straightforward manner. If orthogonal component of the single phase input signal is produced, it gives a useful structure for single-phase PLLs [137].

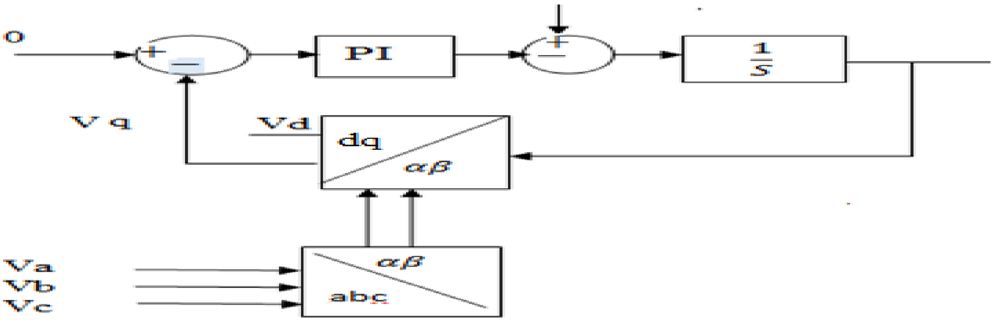


Figure 5.3: phase lock loop [136]

5.1.4.3. Active reactive power control with current control

In case of grid-connected inverters, the magnitude and angle of their output current controlled by adjusting their DC-link voltage (active rectifier) or real and reactive power flows (PQ source). To achieve the control of real and reactive power, several approaches have been existed. The discussed approach in [138] has been selected because it is simple and it has high inductor current quality. As shown in figure 5. Active reactive power control consists of a three-phase three-leg inverter bridge, multi-loop control system and an LCL-filter. Power controller current controllers are the main control loop.

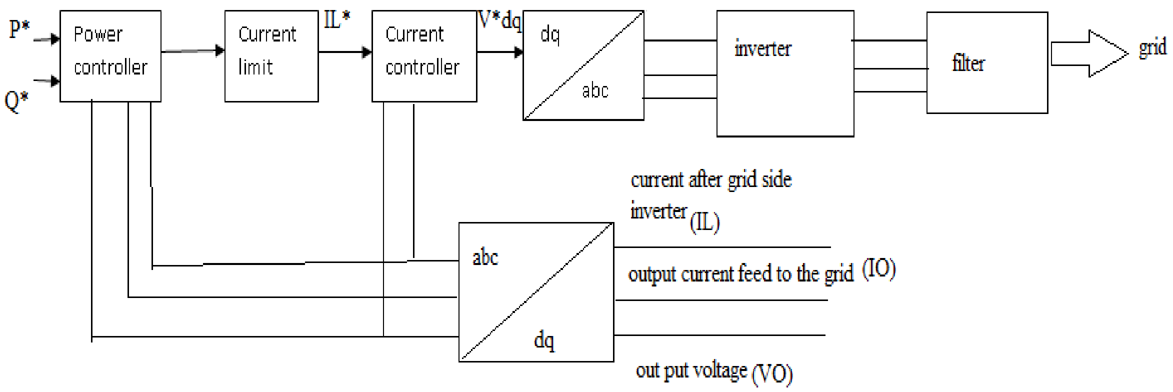


Figure 5.4: Active and reactive power controller [138]

- Power controller: The outer power control loop shown in Fig.5.4 was used to determine the output current references which are required to track the complex power set point $S^* = P^* + jQ^*$ for a given output voltage . This output voltage is normally voltage at point of coupling to the grid. It is determined by executing an inverse instantaneous power theory operation in the dq reference frame which is synchronously rotating.

$$\begin{pmatrix} i_{od}^* \\ i_{oq}^* \end{pmatrix} = \frac{1}{V_{od}^2 + V_{oq}^2} \begin{pmatrix} V_{od} & V_{oq} \\ V_{oq} & -V_{oq} \end{pmatrix} \begin{pmatrix} P^* \\ Q^* \end{pmatrix} \tag{5.10}$$

In power control, first generate output current reference (i_{od}^*, i_{oq}^*) by the equation5.10 which is subtract from output current (i_o)feed to the grid or load and then add to the current pass through the inverter side inductor $(i_l)$and low pass filter and generate reference inverter output current(i_l^*) as shown in equation 5.11

$$i_{l,dq}^* = i_{o,dq}^* - i_{o,dq} + i_{l,dq} \tag{5.11}$$

- Current regulator: This reference signal is $(i_{l,dq}^*)$ compared with inverter output current $(i_{l,dq})$ thus an error signal is generated which is given to PI or PR controller. A reference output voltage $(v_{o,dq}^*)$ is generated from the output of the controller which is compared with output voltage $(v_{o,dq})$ and passed to PI or PR controller and produces modulating signal at dq reference frame (v_{dq}^*) as shown in figure 5.5 and converted into abc frame (v_{abc}^*) by using equation and fed to the PWM modulator.

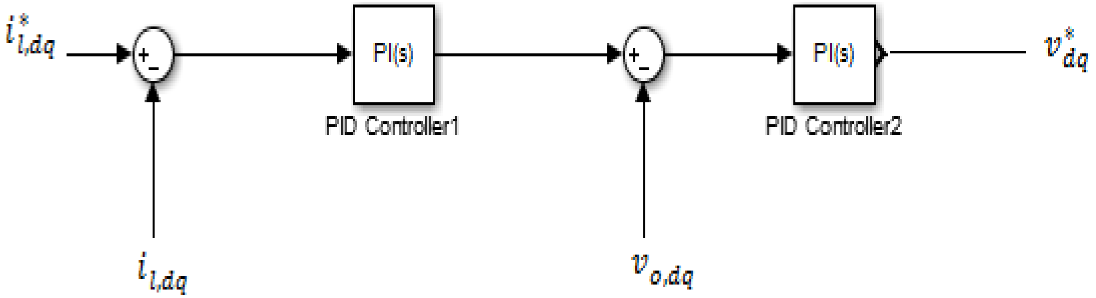


Figure 5.5: Current controller [138]

5.1.4.4. Voltage controller

In the Voltage regulated voltage source inverter based DG units, the direct control of amplitude and frequency of output AC voltage is done by a linear voltage regulator organized either as a single-loop or a dual-loop feedback controller [139].

- Single-loop voltage regulator

Figure 5.6 demonstrates the block diagram of the single-loop voltage regulator. First DG output voltage is measured and compared against the reference voltage command with a desired magnitude and frequency. This error is tracked and passed on to a linear compensator (Proportional (P), Proportional +Integral (PI), or Proportional +Resonant (PR)) to create a modulation command for the PWM modulator which regulates the on off of VSI switches. At the fundamental frequency usually a PR compensator give better tracking accuracy.

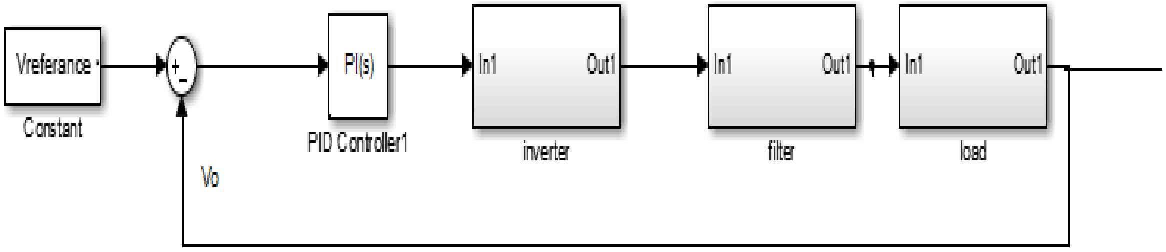


Figure 5.6**:** single loop voltage regulator [139]

A dual-loop regulator consists of an inner current control loop and an outer voltage control loop. To improve the stability of a single-loop voltage controller it is often used. As shown in Figure 5.7 First a reference voltage V_{ref} compares with output voltage and generates an error signal then it passes through a controller block and generates a current reference. Controller block may be PI or PR type. After that it is compared with the output current of the inverter, generating a error signal and pass through the PI/PR controller and generate a modulating signal which converts into abc reference frame and fed to the PWM. Whole system operated in dq reference frame if PI controller is used. Otherwise it is done in $\alpha\beta$ reference frame for PR controller. To make the system stable, the inner current loop must be tuned faster than the outer voltage control loop [140].

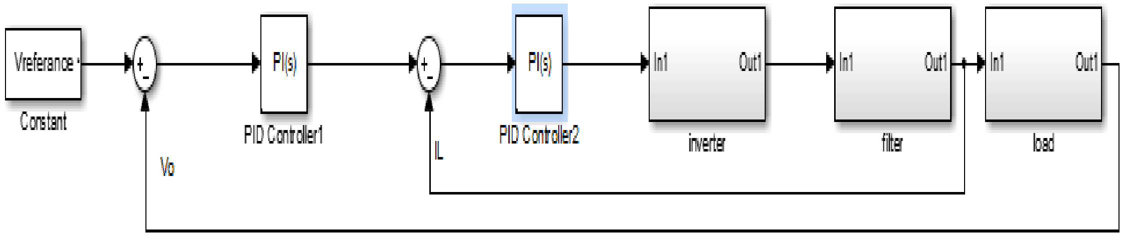


Figure 5.7**:** Dual loop voltage regulator [140]

5.1.4.5. Droop control

Generation the same amount of active and reactive power is preferable for DG units in an islanded microgrid. Overloading of the DG units is prevented by this controller, due to this flowing of the transient power uniformly distributed among DG units. Flowing of any circulating current is also reduced between DG units, since this current can exceed the DG ratings if not properly controlled. Fig. 5.8 demonstrates the block diagram of a typical droop controller. The output active and reactive powers are computed at each computational cycle and then passed onto the droop function block to generate a reference voltage magnitude and frequency. This voltage reference is supplied to the DG voltage regulator, generally works as a dual loop voltage controller. The Active Power-voltage and Reactive power frequency droop controller relationship for low voltage microgrid, with almost resistive distribution lines, can be given as [141].

In droop control consists of a voltage controller in addition a reference voltage is generated from droop controller. The droop controller adjusts the magnitude and phase angle of reference voltage corresponding to the active and reactive power flow. The equation of the droop control can be given as follows.

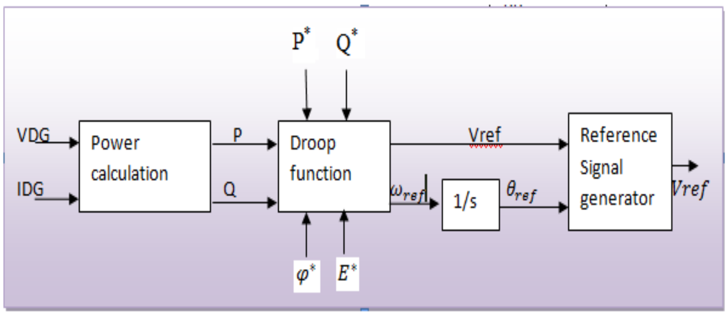


Figure 5.8: Droop control [141]

$$\varphi = \varphi^* - G_p(s)(P - P^*) \tag{5.12}$$

$$E = E^* - G_Q(s)(Q - Q^*) \tag{5.13}$$

Where

P^*, Q^*= active reactive power reference normally it is set to zero.

$\varphi^* = \omega^* \int dt = \omega^* t$= reference phase angle

And φ and E are the phase and magnitude of V_{ref} respectively.

$$G_P(S) = K_{PP} + \frac{K_{IP}}{S} \tag{5.14}$$

$$G_Q(S) = K_{PQ} \tag{5.15}$$

With K_{IP} and K_{PQ} is the static droop coefficients whereas K_{PP} can be regarded as a virtual inertia of the system, also called transient droop term. The static droop coefficients K_{IP} and K_{PQ} can be selected keeping in mind the following relationships $k_{IP} = \frac{\Delta f}{\Delta P}$ (maximum frequency deviation/nominal active power) and $k_{PQ} = \frac{\Delta V}{\Delta Q}$ (maximum amplitude deviation/nominal reactive power).

5.1.4.6. Proportional Integral (PI) Controller

Proportional Integral controller (PI) is used extensively and simultaneously along with dq control, but its employment in *abc* frame is also possible as described in [142]. The transfer function of the controller in this case becomes (3), Additional disadvantage related with the PI controllers is the possibility of distorting the line current caused by background harmonics initiated along the feed forward path if the grid voltage is distorted. This distortion can successively trigger LC resonance especially when an LCL filter is used at the converter AC output for filtering switching current ripple [142]

$$PI = K_p + \frac{K_i}{S} \tag{5.17}$$

Where K_p and K_i are the proportional and integral constant respectively

5.1.4.7. Proportional Resonant Controller

These control loops contains proportional resonant (PR) terms adjusted at the fundamental frequency, fifth, seventh, and eleventh harmonics. Not only current control loop but also voltage control loop includes current harmonic tracking so that to supply nonlinear currents to nonlinear loads, since it is necessary to suppress voltage harmonics produced by this kind of loads [143]. Large gain can be provided by the conventional PI controller for the dc signal attributed to a pole at the origin, which is quite appropriate for the voltage magnitude control. Though for current decoupling control purpose, the sinusoidal current tracking control would be problematic in α−β axes when PI controller is used, as at the grid frequency control gain is limited, this problem arises. So to get proper sinusoidal current tracking at grid frequency a controller with large gain will make the control loop design easier and improve the system performance.[143]

$$PR = k_p + \frac{k_i . s}{s^2+\omega^2} + \sum_{h=5,7,11} \frac{k_{vh} . s}{s^2+(h\omega)^2} \quad . \tag{5.18}$$

Where K_p , K_i and K_v are the constant and ω is the fundamental frequency.

5.2. Modeling of synchronous generation based DG

Various methods of synchronous modeling have been suggested. As the cost of detailed prototype of electrical machine modeling is raising day by day, mathematical modeling and computer simulation of the prototype has become compulsory. Early works [see 144] have described the paramount importance of a good model of synchronous machine taking into account dampers and other components which are sometimes disregarded or neglected in simplified modeling. In this paper, a brand new method of synchronous generator modeling with consideration of an inside infinite resistance will be presented [145]. The particularity of such a modeling method is to make the performing of tests, usually used to confirm or identify the machine, easy: short circuit test, load impact test, shedding test, etc. Once the synchronous machine has been made, manufacturers use programs based on different parameters (e.g., reactance and times constants) which are been graphically estimated to check the finest structural details of this one. To be in the same way with manufacturer's methods, link between transient and sub transient quantities on one side and the modeling parameters such as mutual and main inductances on the other side, will be presented [145].

5.2.1. Synchronous generator equivalent circuit modeling

A schematic diagram of a synchronous generator winding with dampers at the rotor is shown in Figure 5.9 d-axis and q-axis dampers are represented by the D and Q respectively. Three phases of the synchronous generator is represented by a, b and c. θ_e is electrical angle.

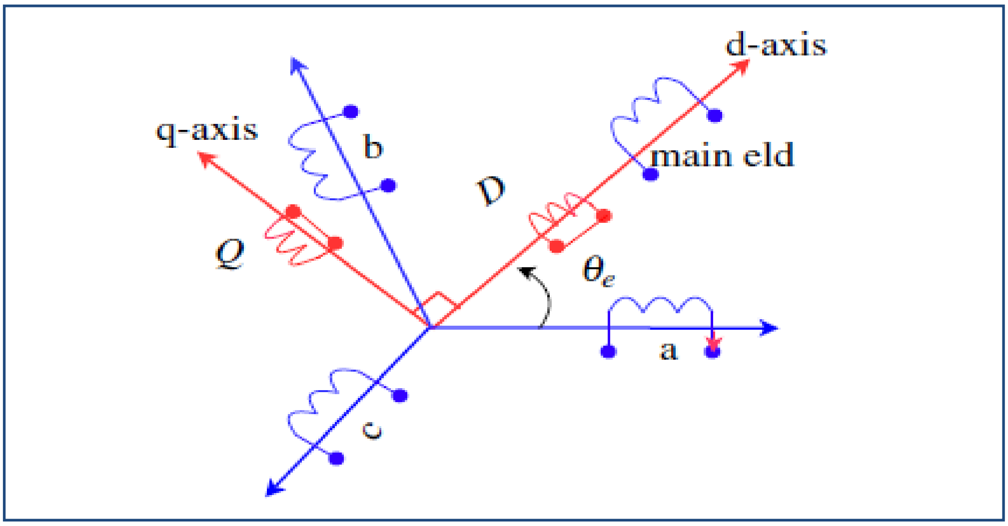


Figure 5.9: Synchronous generator windings with dampers [144].

Synchronous generator electrical equivalent circuit

As we can see on the figure above, dampers are synthesized by short circuited inductances. From this figure and adopting generator convention, we can write machine equations in three axes frame as follows:

$$V_{abc} = -r_s i_{abc} + \frac{d\varphi_{abc}}{dt} \tag{5.19}$$

$$V_f = r_f i_f + \frac{d\varphi_f}{dt} \tag{5.20}$$

$$0 = r_D i_D + \frac{d\varphi_D}{dt} \tag{5.21}$$

$$0 = r_Q i_Q + \frac{d\varphi_Q}{dt} \tag{5.22}$$

Where φ_{abc} is stator total flux, $\varphi_f$is the main field total flux. r_s is the stator resistance, r_f is the main field resistance, r_D and r_Q are the dampers resistances. i_D and i_Q are the direct and transverse dampers' currents, φ_D and φ_Q are the direct and transverse dampers' total flux,

From park's transformation three phase stationary frame transform in to rotating reference

$$\begin{pmatrix} V_d \\ V_q \\ V_0 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ -\sin\theta_e & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{5.23}$$

Where electrical angle of the machine is θ_e

Then, the global equation of the machine becomes Voltage equation:

$$V_d = -r_s i_d - \omega_e \varphi_q + \frac{d\varphi_d}{dt} \tag{5.24}$$

$$V_q = -r_s i_q + \omega_e \varphi_d + \frac{d\varphi_q}{dt} \tag{5.25}$$

$$V_f = r_f i_f + \frac{d\varphi_f}{dt} \tag{5.26}$$

$$0 = r_D i_D + \frac{d\varphi_D}{dt} \tag{5.27}$$

$$0 = r_Q i_Q + \frac{d\varphi_Q}{dt} \tag{5.28}$$

$$J\frac{d\omega_e}{dt} = T_e - T_r \tag{5.29}$$

Torque equation: T_e is the electromechanical torque depending on machine current and given by

$$T_e = \frac{3}{2}P\left(\varphi_d i_q - \varphi_q i_d\right) \tag{5.30}$$

T_r is resistant torque depending on the external load .*P* is the machine's poles number and J is the machine inertia. To make the simulations following our future experimental conditions, the electrical speed is assumed to be constant. Indeed, in the test bench which is being attained for confirming the algorithms and control laws that we developed, the synchronous generator is involved by a DC motor. This last one mentioned is controlled by a motor drive: VNTC4075 from Alstom Company. Then, the state space equation of the machine will be given by using this presumption. In order find out synchronous generator equivalent circuit, a two salient poles machine will be considered. The scheme of this one is given in Fig. 5.10where$\varphi_{\sigma D}$ and $\varphi_{\sigma Q}$are the direct and transverse dampers leakage flux, $\varphi_{\sigma sd}$ and $\varphi_{\sigma sq}$ are the direct and transverse stator leakage flux, $\varphi_{\sigma dD}$ is the linkage flux between direct axis and direct dampers, $\varphi_{\sigma fD}$ linkage flux between main field and direct dampers, φ_{ad} and φ_{aq} are the direct and transverse main flux but implicitly omitted in Fig. 5.10 The effect of main field on the stator $\varphi_{\sigma fs}$ is neglected, then the following relationships can be written [146].

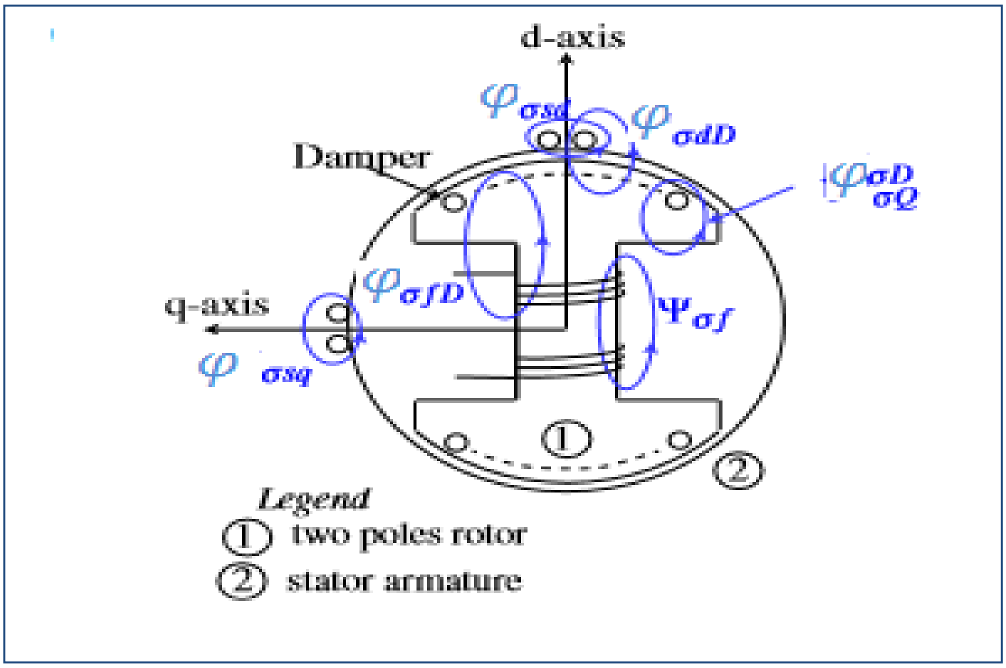


Figure 5.10: Synchronous generator leakage and linkage flux.

Flux linkage equation:

$$\varphi_d = \varphi_{ad} + \varphi_{\sigma sd} + \varphi_{\sigma dD} = l_{ad}\left(-i_d + i_D + i_f\right) - l_{\sigma sd} i_d + l_{\sigma dD}(i_D - i_d)$$

$$= -L_d i_d + M_{sf} i_f + M_{sd} i_D \qquad (5.31)$$

$$\varphi_q = \varphi_{aq} + \varphi_{\sigma sq} = l_{aq}\left(-i_q + i_Q\right) - l_{\sigma sq} i_q = -L_q i_q + M_{sQ} i_Q \qquad (5.32)$$

$$\varphi_f = \varphi_{ad} + \varphi_{\sigma f} + \varphi_{\sigma fD} = l_{ad}\left(-i_d + i_D + i_f\right) + l_{\sigma f} i_f + l_{\sigma fD}\left(i_D + i_f\right)$$

$$= L_f i_f + M_{fD} i_D + M_{sf} i_d \qquad (5.33)$$

$$\varphi_D = \varphi_{ad} + \varphi_{\sigma fD} + \varphi_{\sigma Dd} + \varphi_{\sigma D} = l_{ad}\left(-i_d + i_D + i_f\right) + l_{\sigma dD}(i_D - i_d) + l_{\sigma fD}\left(i_D + i_f\right) + l_{\sigma D} i_D = L_D i_D + M_{fD} i_f - M_{sD} i_d \qquad (5.34)$$

$$\varphi_Q = \varphi_{aq} + \varphi_{\sigma Q} = l_{aq}\left(-i_q + i_Q\right) + l_{\sigma Q} i_Q = -L_Q i_Q + M_{sq} i_q \qquad (5.35)$$

Where $l_{\sigma sd}$ and $l_{\sigma sq}$ are the direct and transverse stator leakage inductances, $l_{\sigma f}$ is the main field leakage inductance, l_{ad} and l_{aq} are the direct and transverse stator main inductances, $l_{\sigma dD}$ is the linkage inductance between stator d-axis and the direct damper, $l_{\sigma fD}$ is the linkage inductance between rotor and the direct damper, $l_{\sigma D}$ and $l_{\sigma Q}$ are dampers leakage inductances.

$$l_d = l_{ad} + l_{\sigma sd} + l_{\sigma dD} \qquad (5.36)$$

$$l_D = l_{ad} + l_{\sigma sd} + l_{\sigma dD} + l_{\sigma D} \qquad (5.37)$$

$$l_f = l_{ad} + l_{\sigma f} + l_{\sigma fD} \qquad (5.38)$$

$$l_q = l_{aq} + l_{\sigma sq} \qquad (5.39)$$

$$l_Q = l_{aq} + l_{\sigma Q} \qquad (5.40)$$

$$x_{ad} = l_{ad}\omega_e \qquad (5.41)$$

$$x_{aq} = l_{aq}\omega_e \qquad (5.42)$$

5.2.2. Synchronous generator parameter design using short circuit test data

The relations between main reactance and machines parameters are as follows [146]

$$x_{ad} = \sqrt{T_{d0}^{'}\omega_e r_f\left(x_d - x_d^{'}\right)} \qquad (5.43)$$

$$x_{aq} = \sqrt{x_q\omega_e r_Q\left(T_{q0}^{''} - T_q^{'\prime}\right)} \qquad (5.44)$$

Where x_d is steady state reactance, $x_d = l_d\omega_e$, $x_d^{'}$ is the direct transient reactance , $x_d^{''}$ is the direct sub transient reactance $x_q^{''}$ is the transverse sub transient q-reactance, $T_d^{'}$ is the direct transient time constant, $T_d^{'\prime}$ is the direct sub transient time constant, $T_q^{'\prime}$ is the transverse sub transient time constant, $T_{d0}^{'}$ is the open direct transient time constant, $T_{q0}^{'\prime}$ is the open transverse sub transient time constant, and ω_e is the machine electrical speed corresponding to the time derivative of he.

Thus, from the expressions in (5.43) to (5.44), the machine can be represented by reactance and time constants and fluent relationships between parameters usually used in industry [146].

5.2.3. State space modeling

The model used in this discussion is given by Figure.5.11. Here in this modeling, a star connected infinite resistance in (10^6) is combined. This allows ones to generate three phase voltage and then to make terminals A, B and C on which a three-phase load can be joined. On Fig. 5.11, V_f and the output currents are used in the input vector. For this, inside currents i_a, i_b and i_c are transformed into id and iq on one side and load currents i_{sa}, i_{sb} andi_{sc} into i_{dl} and i_{ql} on the other side. Hence, the output voltage in Park's frame work can be expressed as

$$V_d = r_{in}\left(i_d - i_{ql}\right)$$

(5.45)

$$V_q = r_{in}\left(i_q - i_{dl}\right)$$

(5.46)

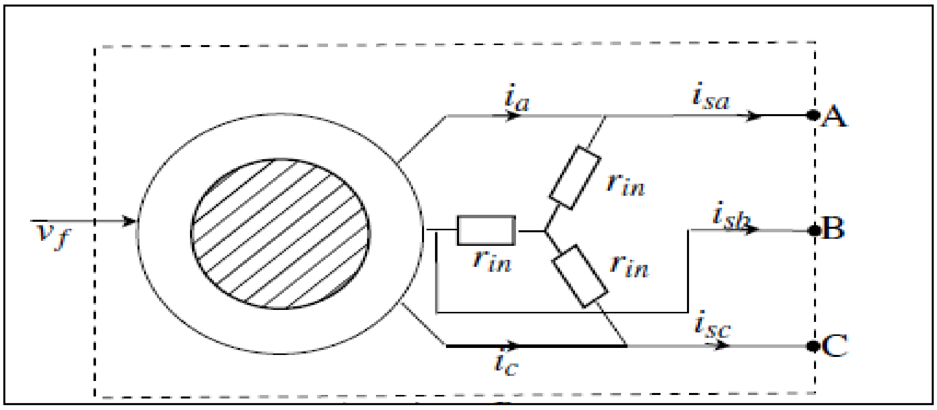


Figure 5.11: Synchronous generator with infinite inside load.

$$\begin{pmatrix} i_{dl} \\ i_{ql} \end{pmatrix} = \left(P(\theta_e)\right) \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix} \tag{5.47}$$

$$\begin{pmatrix} -r_{in} i_{dl} \\ -r_{in} i_{dl} \\ v_f \\ 0 \\ 0 \end{pmatrix} = R \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{pmatrix} + M_a \frac{d}{dt} \begin{pmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{pmatrix} \tag{5.48}$$

Where,

$$R = \begin{pmatrix} -r_s - r_{in} & l_q \omega_e & 0 & 0 & \omega_e m_{sQ} \\ -l_d \omega_e & -r_s - r_{in} & \omega_e m_{sf} & \omega_e m_{sD} & 0 \\ 0 & 0 & r_f & 0 & 0 \\ 0 & 0 & 0 & r_D & 0 \\ 0 & 0 & 0 & 0 & r_Q \end{pmatrix} \tag{5.49}$$

$$M_a = \begin{pmatrix} -l_d & 0 & m_{sf} & m_{sD} & 0 \\ 0 & -l_q & 0 & 0 & m_{sQ} \\ -m_{sf} & 0 & l_f & m_{fD} & 0 \\ -m_{sD} & 0 & m_{fD} & l_D & 0 \\ 0 & m_{sQ} & 0 & 0 & l_Q \end{pmatrix} \tag{5.50}$$

Then, the synchronous generator state-space equation is given by

$$\dot{x} = Ax + Bu \tag{5.51}$$

$$y = Cx + Du \tag{5.52}$$

Where state transition matrix is $A = -M_a^{-1}R$, and the observation matrix is $B = M_a^{-1}$,

$C = \begin{pmatrix} r_{in} & 0 & 0 & 0 & 0 \\ 0 & r_{in} & 0 & 0 & 0 \end{pmatrix}$, $D = \begin{pmatrix} -r_{in} & 0 & 0 & 0 & 0 \\ 0 & -r_{in} & 0 & 0 & 0 \end{pmatrix}$ the state vector is

$x = (\, i_d \quad i_q \quad i_f \quad i_D \quad i_Q)$,

The input vector is $u = (\, i_{dl} \quad i_{ql} \quad v_f \quad 0 \quad 0)^T$

The output vector is $V = (V_d \quad V_q)^T$

5.2.4. Excitation system

In synchronous generator a fixed excitation or regulated excitation is given. Regulated excitation is preferable for synchronous machine to get better performance. The general structure of an excitation system is presented in Figure 5.12, which consists of measurement and signal processing circuits, a regulator and an exciter. A determined error signal, obtained comparing the reference value (X_{ref}) with the measured signal (X) is provided for the regulator. Then, the exciter field voltage is adjusted based on the regulator output. The regulator is normally equipped with over and under excitation limiters, which limit the maximum reactive power injected or consumed by the generator [147], [148]. To type of regulator is used for synchronous generator. These are voltage regulator and power factor regulator.

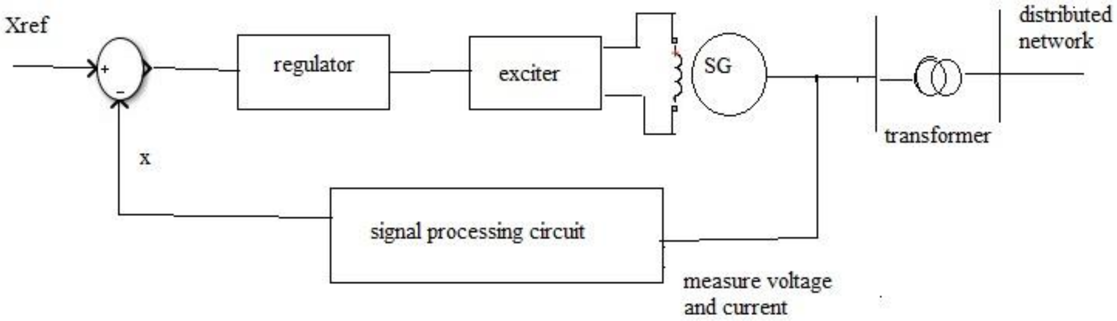


Figure 5.12: excitation systems [147].

5.2.4.1. Excitation system with voltage Regulator

This type of control strategy is adopted for output voltage of the synchronous generator to remain constant In this case, of the measured signal X is given by equation 5.53, V_T is the terminal voltage phasor, I_T is the terminal current phasor, X_C is the compensation reactance.

Reactive droop compensation (positive) is adopted to share the reactive current among generators connected to the same bus. Line drop compensation (negative) is used to regulate the voltage at a remote bus, usually the transformer high-voltage bus. In this work, the reactive current compensation was neglected. That is $X_C=0$ and $X = |V_T|$.In this case, the terminal voltage is directly compared with the voltage reference X_{ref}. The usage of reactive current compensation should not be confused with power factor regulators [149]

$$X = |V_T - j\, I_T\, X_C| \tag{5.53}$$

5.2.4.2. Excitation system with power Factor controller

In this case, synchronous generate operate as a constant active reactive power source. The measured signal(X) is the power factor as shown by equation 5.54. The field voltage is adjusted to maintain constant this power factor. Such type of regulator is often used for excitation control of synchronous motors [149]. In consequence, unitary or capacitive power factor operations adopted. Otherwise, such strategy of control may also be required by regulatory agencies to minimize the steady-state voltage rise in the presence of distributed generators [150]. In this situation, inductive power factor operation is required. Thus, the generator can operate in unitary, inductive or capacitive power factor, depending on the regulatory operating rules. Therefore, in this study, the following different values of power factor reference were simulated: unitary power factor, 0.95 inductive power factors and 0.95 capacitive power factors.

$$X = \frac{real\ (V_T I_T^*)}{V_T I_T^*} \tag{5.54}$$

Where V_T = terminal voltage phasor, I_T = terminal current phasor,

5.3. Time domain based design of PID controller

Parameters of PI or PR controller can be design in both frequency domain and time domain. Controller gain tuning is one of the main important parts of this work. For linear system bode plot Ziegler Nichols methods mainly used for controller designing. But for nonlinear system it is not possible. To apply these methods non linear system first converts into equivalent linear system. Then the value of PID controller is used. This method is simple but not efficient some time design of equivalent linear model cannot be possible. Time domain analysis solves this problem.

Time domain PI/PR controller can be formulated as a single objective optimization problem which depends on time domain indices integral. The objective function is made to focus on the steady state error minimization in this work [151]. Different type of algorithm is used for this purpose. In this work Genetic algorithm is used for PI and PR controller tuning in time domain.

5.3.1. Genetic algorithm

Genetic algorithm is a probabilistic optimization method, dependent on the principles of evolution. First this thought comes into view in 1967 in J. D. Bagley’s thesis “The Behavior of Adaptive Systems Which Employ Genetic and Correlative Algorithms” [152]. J. H. Holland strongly influences by the theory and applicability. Then first basic concepts of Genetic algorithms (GA) were developed by John Holland(1975) who is known as the pioneer of genetic algorithms [152], after that how GA is used for solving complex problems was established by David Goldberg (1989). This algorithm based on the principles of natural genetics based on Darwin’s evolution theory. It is used to solve non-trivial multimodal optimization problems.

The above algorithm consists of four basic components for the transition from one generation to the next:

Selection

The method is used to determine which solutions are to be conserved and approved to reproduce and others to be eliminated while keeping the population size constant. The main objective of this step is “Selects the best, discards the rest’’. These selecting individuals (strings) are used as parent’s string for reproduction according to their objective function value.

Crossover

In this method, the genetic information of two individuals is merged to produce new solution. If the coding is properly chosen, good children may be produced by two good parents’.

Mutation

Erroneous reproduction or other deformations of genes like gamma radiation changes the genetic material randomly in genetic algorithms. Mutation can be recognized by deforming the strings randomly with a certain probability in genetic algorithms. The genetic diversity is preserved and gives a positive effect. Local maxima can be avoided.

Steps

1. The algorithm starts by generating a random initial population.
2. The algorithm then produces a series of new populations. At each step, the individuals in the current generation are used to create the next population. The algorithm executes the following steps to form the new population.
    a. Evaluate the fitness function (objective function value) for each of the current.
    b. Identify the good fitness function value to change them into more usable values.
    c. Perform the selection step to identify the best population known as parents depend on their fitness.
    d. Creates children from the parent's string. They are produced either by creating random changes on a single parent then performs mutation or by combining the pair of parents string then performs crossover, and mutation simultaneously.
    e. Substitutes the current population by the children or next population.
3. Evaluate current population using objective function
4. Repeat the steps from 2 to3.
5. The algorithm terminates after the he converse of the criteria or one of the stopping criteria is reached.

5.3.2. Objective function

The objective function for minimize the steady state error in time domain analysis is express as equation 5.55 [151]

$$J = \min \int_{t=0}^{\infty} t(e(t))^2 dt \qquad (5.55)$$

$$= \min \sum_{t-0}^{\infty} nT(e(nT))^2 \qquad (5.56)$$

Where t=nT (in discrete domain), $e\ (t)$ is steady state error, evaluated from simulink model. First randomly gain of the controller chose and after completes the simulation technique this objective function value is calculated. Figure 5.11 shows the flow chart for find the value of K_p K_i using genetic algorithm. For this first a random value has been chosen for K_p and K_i then the objective function as in equation (5.56) is evaluated and follows the step of 2 to 4. Finally the best value of Kp , K_i for minimum value of objective function is found out.

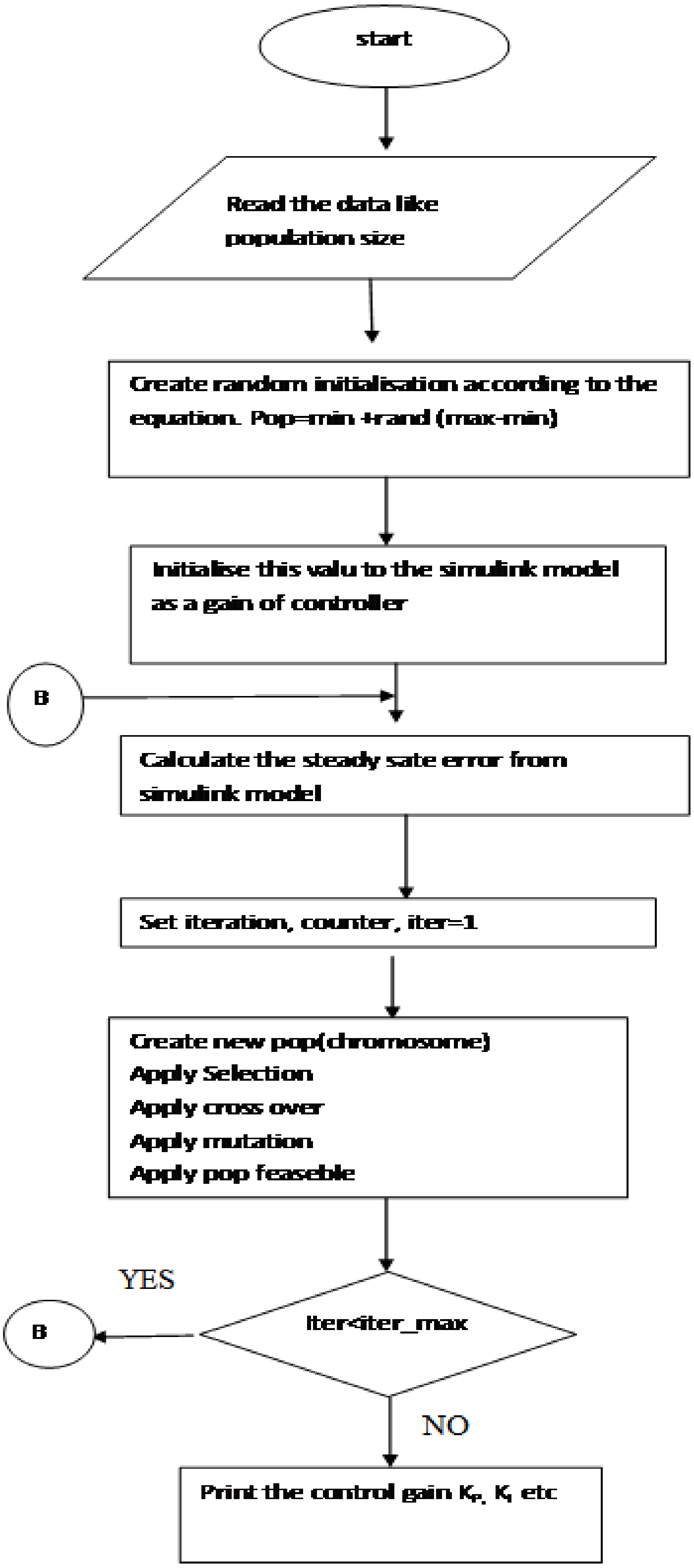


Figure 5.13: Flow chart

6. Modeling of faults in DG based distribution systems: Result and discussion

6.1. Introduction

Planning of protection system is an essential part of an electric power system design. Fault level analysis, voltage level at pre fault condition and post fault condition are necessary to select interruption devices and protective relays. Their settings and coordination is also necessary. The fault current is increased throughout the system due to installation of DG. There are many technologies present for distributed resources other than conventional synchronous based DGs (SBDG). Some DGs like PV cell fuel cell micro turbine etc which produce DC voltage which is further interfaced with an AC system through an inverter interface. This type of DG is known as inverter based DG (IBDG). Fault current of DG based system is varying with the DG change. In this work how DG current vary with DG operated at island mode or grid connected mode has been studied. For this first IBDG model is designed from the equation of previous chapter and operated with single load which is varying type. The value of controller gain is found out by genetic algorithm. SBDG model is also designed. Fault analysis is done for island mode with inverter based DG and for grid connected mode both type of DG (SBDG and IBDG) are considered. Here dual loop voltage control with active power control is used and for SBDG voltage control with active power control is used. Finally a comparison is made. For grid connected application an IEEE 14 bus is considered.

6.2. IEEE 14 BUS system

If DG connects to the distributed network system, the system become mesh network, for this IEEE 14 bus system is considered. The single line diagram of an IEEE-14 bus system is shown in Figure 6.1. The line data, bus data are given in Tables 6.1 and 6.2 respectively. Here two generators are present in the system at bus no 1 and 2 and three synchronous condensers are present at bus 3, 6 and 8 respectably. The synchronous condenser data and transformers tap settings are given in Table 6.3 and 6.4 respectively. The data is on 100 MVA base. The system data is taken from reference [153]. For island mode operation a part of IEEE 14 bus is considered and grid connected mode IEEE 14 bus is considered. DG is connected by replacing the synchronous condenser of bus no 8. As shown in Figure 6.1 the highlighted area has been considered for island mode of operation. It consists of 8 to 14 buses. DG is present in bus no 8. For grid connected mode of operation whole IEEE 14 bus is considered.

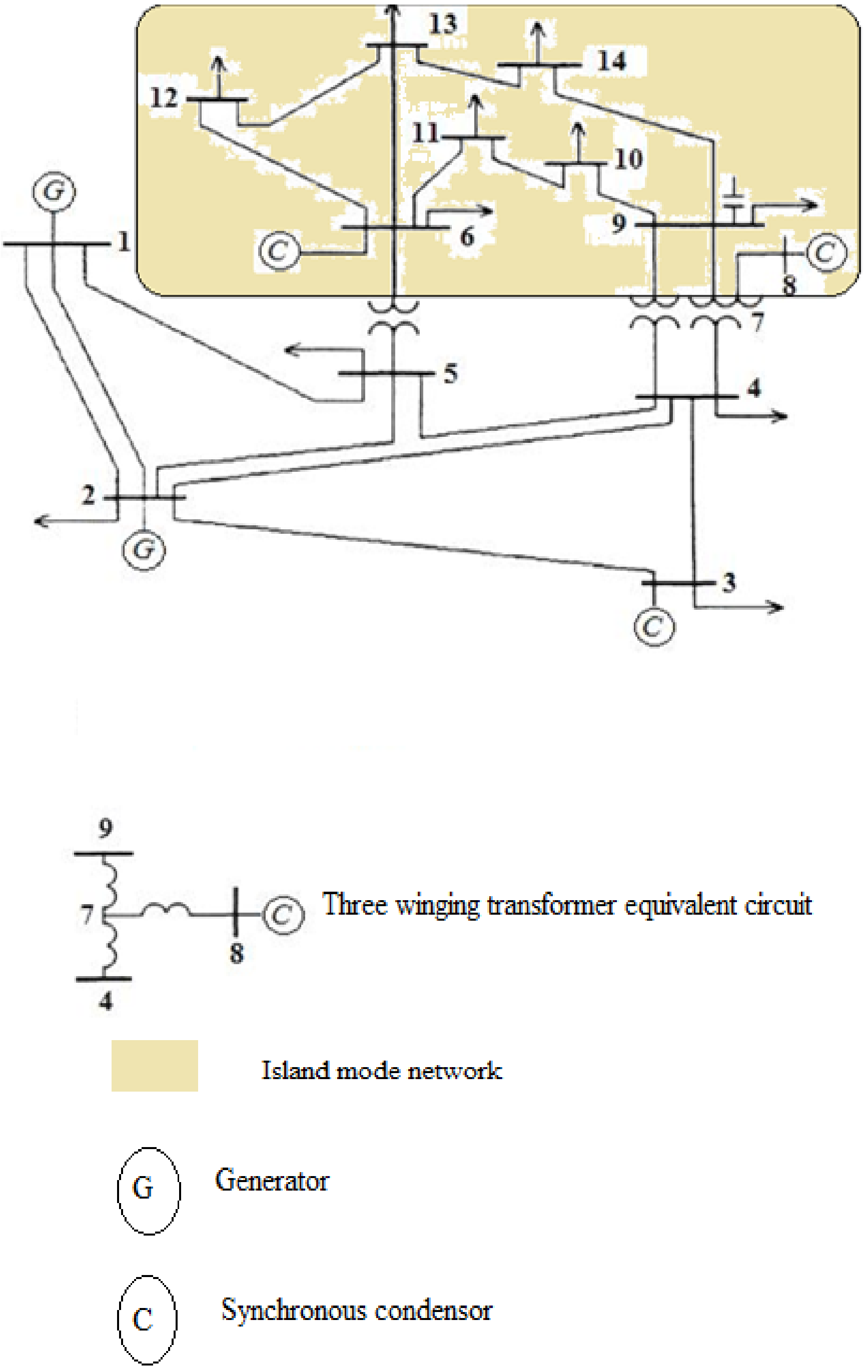


Figure 6.1: One Line Diagram of IEEE-14 Bus System [153]

Table 6.1**:** Line Data of IEEE-14 Bus System

Line no	From bus	To bus	Resistance	Inductance	Half line charging susceptance
1	1	2	0.01938	0.05917	0.02640
2	2	3	0.04699	0.19797	0.02190
3	2	4	0.05811	0.17632	0.01870
4	1	5	0.05403	0.22304	0.02460
5	2	5	0.05695	0.17388	0.01700
6	3	4	0.06701	0.17103	0.01730
7	4	5	0.01335	0.04211	0.00640
8	5	6	0.00000	0.25202	0
9	4	7	0.00000	0.20912	0
10	7	8	0.00000	0.17615	0
11	4	9	0.00000	0.55618	0
12	7	9	0.00000	0.11001	0
13	9	10	0.03181	0.08450	0
14	6	11	0.09498	0.19890	0
15	6	12	0.12291	0.25581	0
16	6	13	0.06615	0.13027	0
17	9	14	0.12711	0.27038	0
18	10	11	0.08205	0.19207	0
19	12	13	0.22092	0.19988	0
20	13	14	0.17093	0.34802	0

Table 6.2**:** Bus Data of IEEE-14 Bus System

Bus No.	Bus Voltage		Generation		Load		Reactive Power Limits	
	Magnitude (P.U)	Phase Angle (degree)	Real Power (P.U.)	Reactive Power (P.U)	Real Power (P.U)	Reactive Power (P.U)	Q min (P.U)	Q max (P.U)
1	1.060	0.000	2.324	-0.169	0.000	0.000	-	-
2	1.045	0.000	0.400	0.000	0.217	0.127	-0.40	0.50
3	1.010	0.000	0.000	0.000	0.942	0.191	0	0.40
4	1.000	0.000	0.000	0.000	0.478	0.039	-	-
5	1.000	0.000	0.000	0.000	0.076	0.016	-	-
6	1.070	0.000	0.000	0.000	0.112	0.075	-0.06	0.24
7	1.000	0.000	0.000	0.000	0.000	0.000	-	-
8	1.090	0.000	0.000	0.000	0.000	0.000	-0.06	0.24
9	1.000	0.000	0.000	0.000	0.295	0.166	-	-
10	1.000	0.000	0.000	0.000	0.090	0.058	-	-
11	1.000	0.000	0.000	0.000	0.035	0.018	-	-
12	1.000	0.000	0.000	0.000	0.061	0.016	-	-
13	1.000	0.000	0.000	0.000	0.135	0.058	-	-
14	1.000	0.000	0.000	0.000	0.149	0.050	-	-

Table 6.3: Synchronous condenser

Bus no	Susceptance (P.U)
3	0.19
6	0.138
8	0.19

Table 6.4: Tap setting of transformer

From Bus	To Bus	Tap Setting Value (P.U.)
4	7	0.978
4	9	0.969
5	6	0.932

The inverter behaves as a constant active reactive power source or constant voltage source with constant power. The inverter behavior is seen by the network is determined by the controls of that inverter and electronic topology. So a complete model of inverter design is very important. For fault analysis of a grid connected network, the model of inverter based DG is done under the speculation that the input voltage is driven by constant DC sources. The pulse width modulation modulates the signal developed by a close loop feedback controlled inverter (PWM)

6.3. System modelling using MATLAB/Simulink

For analyzing the operation of complex ac-dc systems that is a real power system, a simulation resource is required which can operate accurately for system transient, dynamics and steady state. In past, transient phenomena of power systems has been realized by simulation technique using the electromagnetic transients program (EMTP) [154] or electromagnetic transients for dc (EMTDC), or the alternative transient program (ATP) These simulation are all done by the trapezoidal integration rule using nodal approach and fixed-step algorithms. Fixed step algorithm had given excellent results for power systems free from discontinuous operation which are caused by the switching devices like power electronics device. After that SPICE is a general-purpose circuit simulation program which was developed at the University of California, Berkeley [155] SPICE uses the nodal approach with a variable-time-step integration algorithm. Due to this it can correctly simulate the circuit containing switching device like power electronic device. In PSPICE A/D (a commercial version of SPICE by MicroSim) has an analog behavioral modeling (ABM) blocks but there is no specific models for power systems elements, electrical machines, surge arresters, thyristors and circuit breakers etc. To simulate a power system, models are done by SPICE primitives and basic elements, so the simulation setup can take very much time for simulation purpose. After that a new software package the Power System Block set (PSB) in simulink is launched depending on variable step integration algorithms. It gives very accurate simulation for nonlinear, robust, stiff, and discontinuous dynamic systems [156]. It is a suitable tool to simulate electrical circuits containing power electronic devices because it can identify very accurately switching operation and discontinuity and can be easily integrated with control systems implemented with Simulink blocks directly in a diagram built with the PSB. In MATLAB/Simulink Simscape Power Systems™ gives component libraries for perfect analysis by modeling and simulating electrical power systems. It contains models of electrical power components that include electric drives, three-phase machines, and components required for applications such as flexible AC transmission systems (FACTS) and renewable energy systems. For investigating the design performance calculation of total harmonic distortion (THD), harmonic analysis, load flow, and other key electrical power system analyses are automated that helps a lot in this regard. In a nutshell it can be said that Simulink, a MATLAB software package consists of SimPowerSystem, to model and simulate power-electronics circuits and represent performance of power circuits. It has a special library of component blocks, Powerlib, is used in SimPowerSystem. For perfect analysis of faults in a network, a model of IBDG and SBDG and an IEEE 14 bus system network is designed in MATLAB/Simulink [157].

6.4. Design of inverter based DG with single load

Inverter based DG operates as controlled voltage sources, connected to the load through a step up transformer. The zero sequence component form the inverter to the grid is eliminated by the step up transformer with delta connection .Figure 6.2 shows the connection. In the case of the stand alone operation, the inverter must be controlled with voltage at the reference point .First, a simulation model is done for a local load connected inverter based DG which is disconnected from the grid system. The main purpose of the simulation in Case 1 is to explain the transient response of the inverter based DG due to the change of load. The output power varies depending on the load. The inverter based DG parameters is used in the simulation are shown in Table 6.5.

Table 6.5: IBDG specification

DG characteristics	Parameters
DC voltage	2.5 V
Output ac voltage	1V
L	5.44×10^{-5} H
C	0.343×10^{-3} F
L	0.1×10^{-5} H
OUTPUT ACTIVE POWER	0.4-0.7 W
OUT REACTIVE POWER	0-0.17 Var
Harmonic	1.33%

6.4.1. Model of IBDG

Figure 6.2 shows the inverter circuit and 6.3 shows the control circuit.

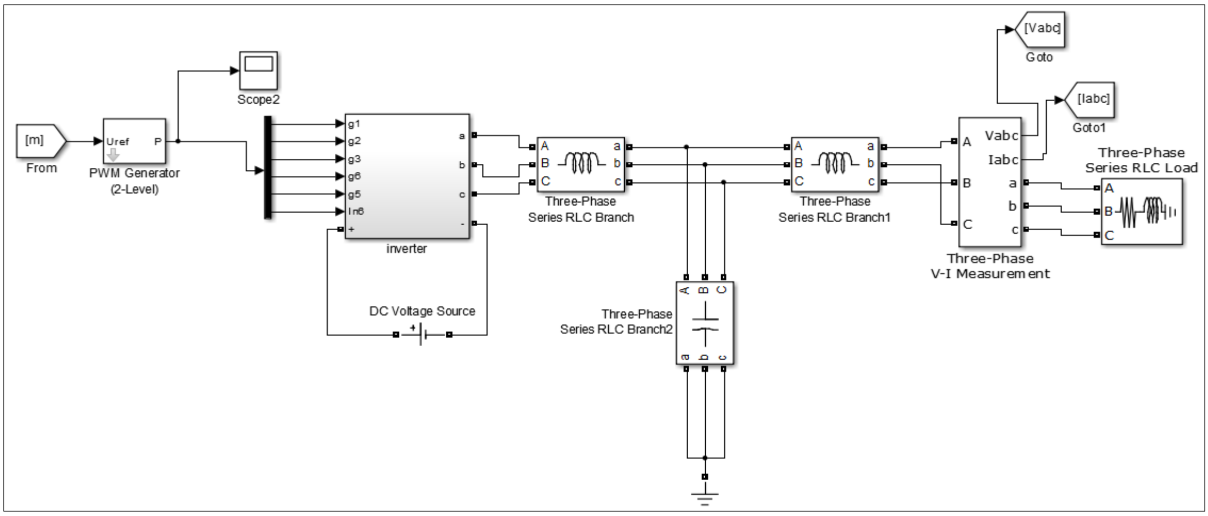


Figure 6.2: Inverter based DG connection model

Inverter based DG consists of a DC source which converts into ac by inverter and feed to the LCL filter. The harmonics from the inverter are filtered by an LCL low pass filter. The cut off frequency f_c should be set low so that to pass the fundamental power signal, but it should be high enough so that it can provide attenuation of harmonics of the inverter voltage. The output voltage and current from LCL filter fed to the controller. As shown in Figure 6.2 V_{abc} and I_{abc} are feed to the controller circuit.

This control circuit generates the modulating signal. This modulating signal generates to give the pulse to inverter. As shown figure signal *m* is coming from controller circuit. SPWM modulation technique is used for this purpose. The controller consists of dual loop voltage amplitude controller. In these model two control loop one is voltage control loop others is current control loop. Outer loop is voltage control loop and inner loop is current control loop. By using this two loops system becomes more efficient. This provides the modulating signal to the PWM signal generator. Here the output voltage of DG is transformed through a time dependent *abc* to *dq0* transformation. The equitation 5.7, 5.8 and 5.9 is used for *abc* to *dq0* transformation. The input of transformation is the power frequency of the grid system which is found by a phase locked loop (PLL). The time domain variables $V_{an}(t)$, $V_{bn}(t)$ and $V_{cn}(t)$ mainly consists of power frequency 50 Hz components. The dq0 transformation is time varying with dc and power frequency components. Therefore $V_d(t)$, $V_q(t)$ and $V_o(t)$ generally include dc, 50 Hz, and 100 Hz components. If a low pass filter is applied to the vector $[V_d(t), V_q(t), V_0(t)]^T$, then $[V_d, V_q, V_0]$ vector is generated, nearly dc for near balanced sinusoidal steady state conditions.

The value of V_d, V_q, are given bellow for a balance sinusoidal wave.

$$V_d = V_m$$

$$V_q = 0$$

When $V_a(t) = V_m \sin(\omega t)$, $V_b(t) = V_m \sin(\omega t - \frac{2\pi}{3})$, and $V_c(t) = V_m \sin(\omega t + \frac{2\pi}{3})$

So for voltage amplitude control, compare V_d, V_q, with reference V_d, V_q and generate an error signal which is minimized by proportional resonant (PR) controller or proportional integral (PI) controller. PR tuning is done using the optimization tool like genetic algorithm. The objective function is discussed in chapter 5.

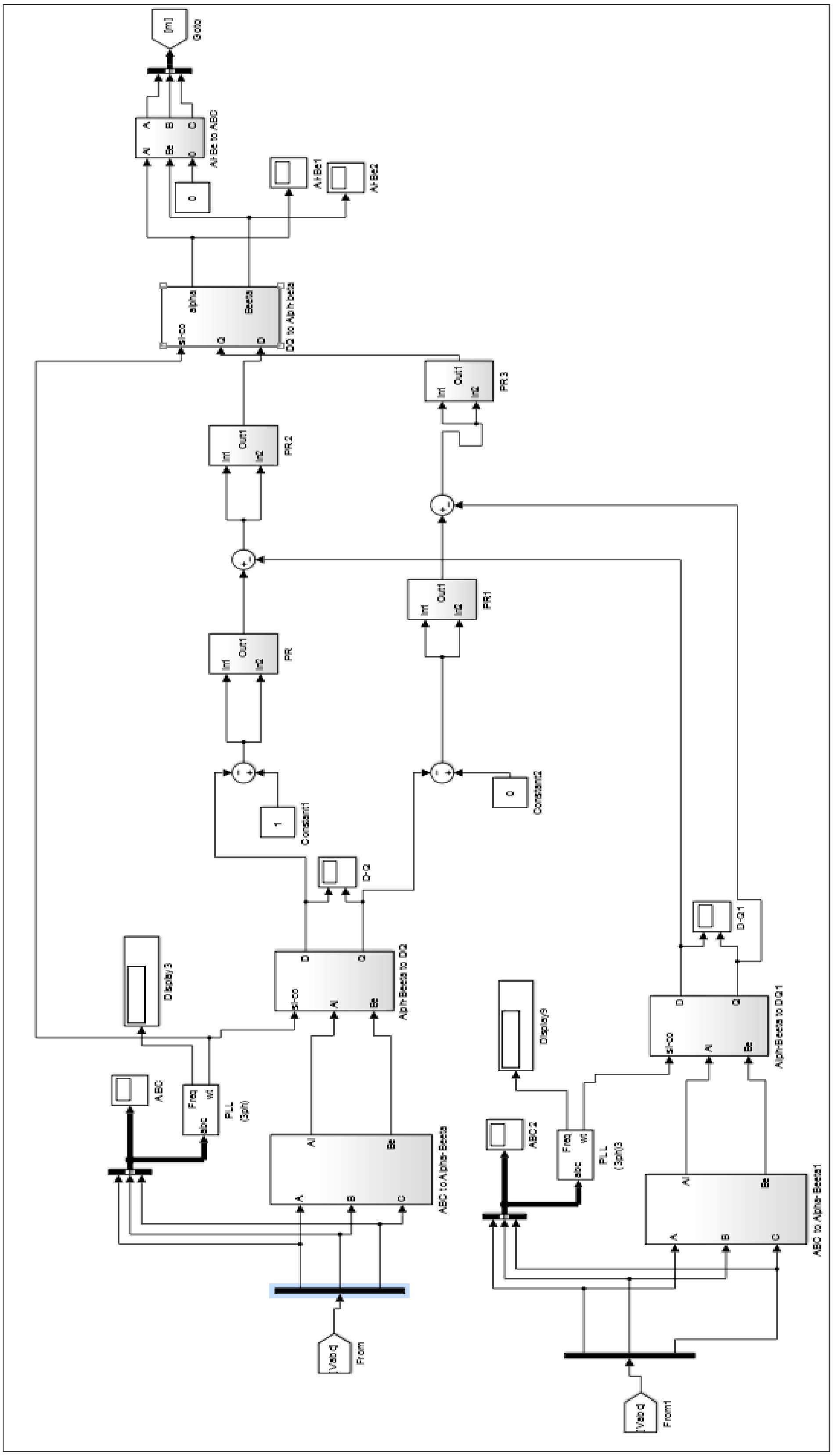


Figure 6.3: Control circuit

Proportional resonant (PR) controller is used to reduce the harmonic. The voltage error signal passes through a PI or PR controller block and generates reference current and which compared with an output current of inverter and generates a current error which has been passed through another PI or PR controller and generate modulating signal in dq reference frame which is transformed into three phase signal. This signal is used as modulating signal of SPWM.

One of the main important parameter is controller design here resonant controller is used. Resonant controller consists of proportion constant (K_p) and resonance constant gains (K_i and K_v) where K_i is tuning with fundamental and K_v tunes with other harmonics. K_p=10, K_i=10, K_v=13.76 which are found by using optimisation technique which is previously demonstrated .for optimization first range of $K_{p,}$ and K_i are chosen between 1 to 20 and the value of K_V is chosen between 1 to 30. If PI controller is used then best output is got at K_p =10 and K_i =1.986. Genetic algorithm is used for optimization tool. The three phase output voltage is at 1 V or 1 P.U. as the reference output voltage set at 1V. The main purpose of the simulation in first is to explain the transient response of the inverter based DG due to the change of load that is explained the dynamics of inverter.

The dynamic performance is demonstrated by changing the load from 0.47 W/ 0.16 VAR to 0.6 W / 0.1 VAR. Figures 6.4 and 6.5 are voltage and current waveform. After load transition occurs, figure 6.6 and 6.7 shows the output voltage and current respectively.

6.4.2. Observation on DG dynamics

It is shown that voltage remains almost constant and current transition occurs from 0.44 to 0.56. Current transition occurs to respond to the load variation. Scope captured wave from are shown bellow. From these figures it can be concluded that voltage control is more useful for a single load or island mode operation to minimize the voltage fluctuation. Harmonic is also reduced by using of PR controller up to 1.33%.

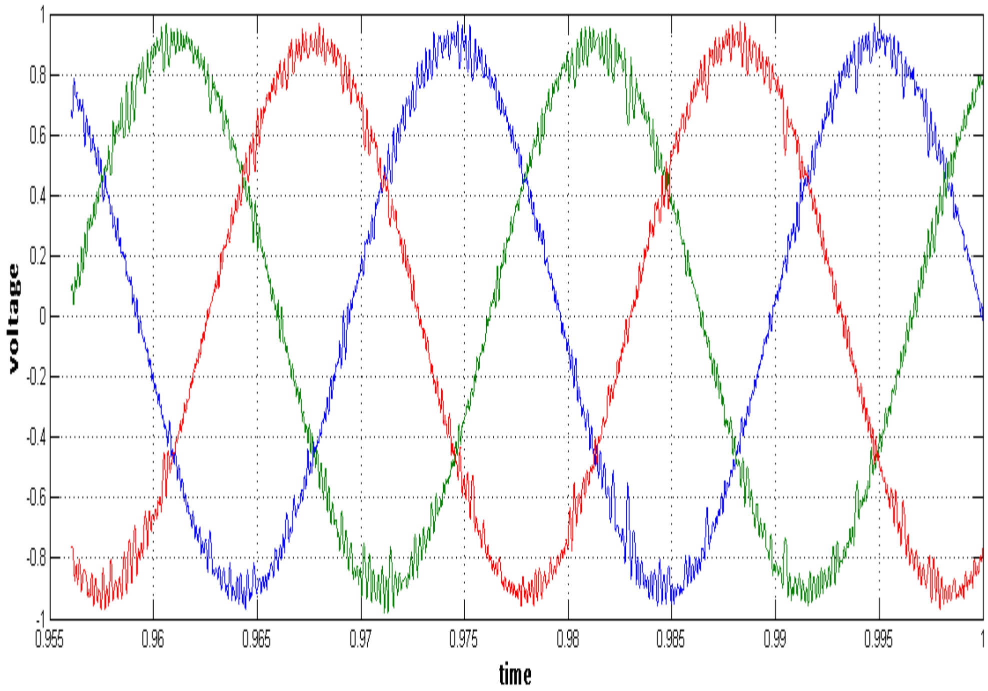


Figure 6.4: Voltage (V) wave from when load is 0.47W (time in sec)

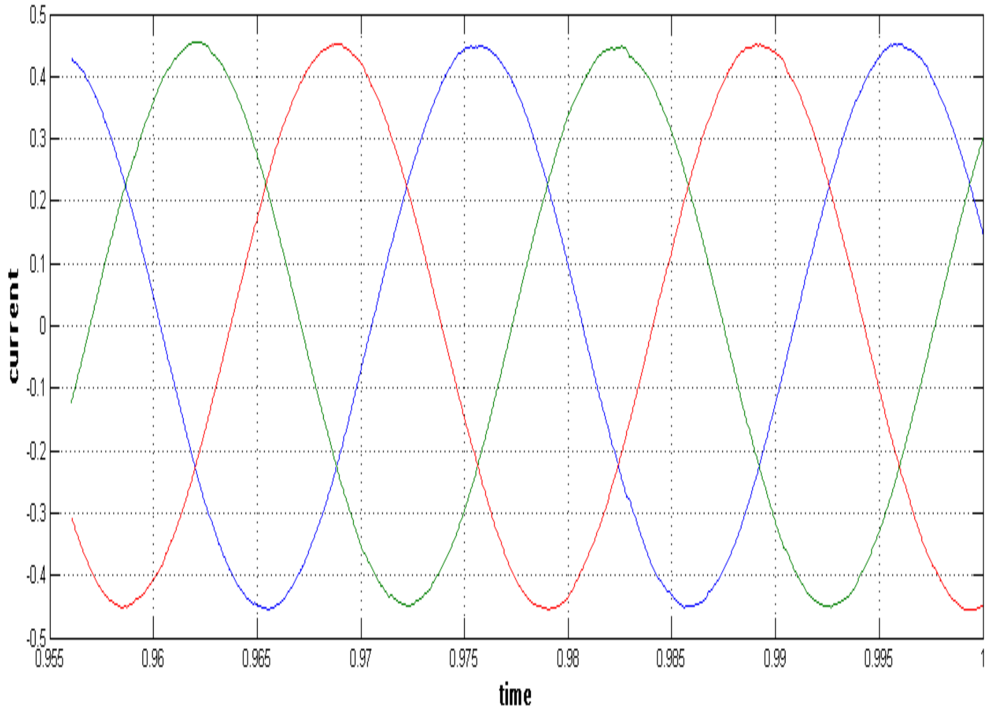


Figure 6.5: Current (A) wave from when load is 0.47W (time in sec)

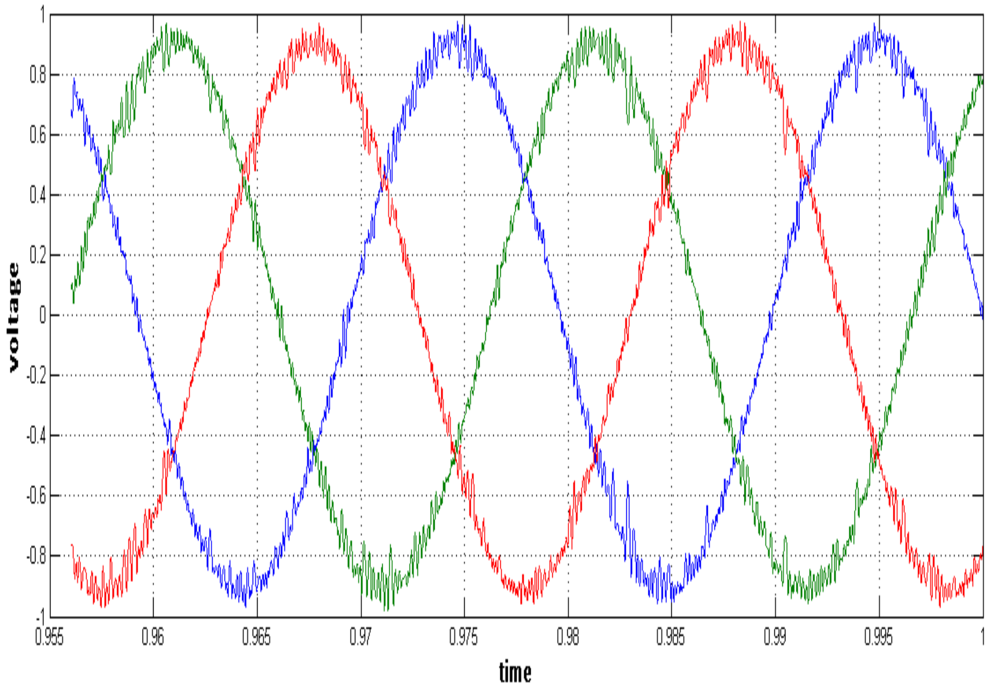


Figure 6.6: Voltage (V) wave from when load is 0.6W(time in sec)

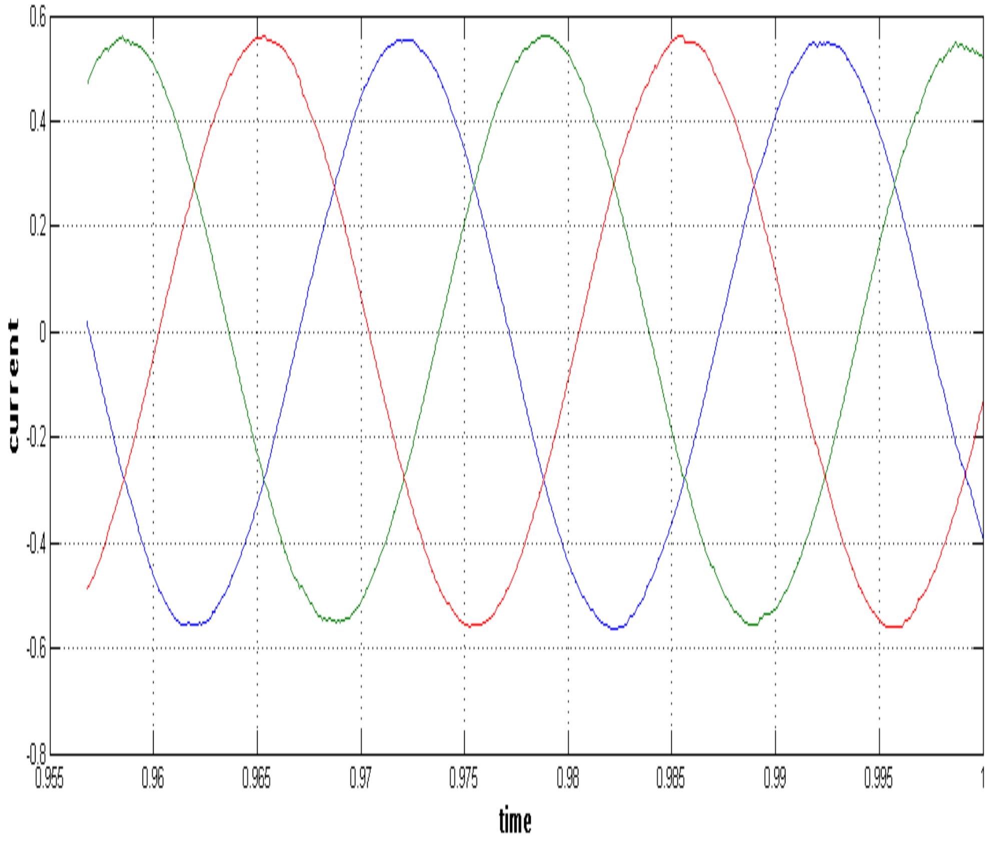


Figure 6.7: Current (A) wave from when load is 0.6W

6.5. Faults in island mode system with IBDG

Sometimes in remote area or minimized the green house gas emission or availability of renewable energy source the DG are supplied the local load in island mode. Due for this fault analysis has become important for island mode also.

Now the inverter is connected to the part of the grid as shown in figure 6.1. To supply the required power input grid voltage increased up to10 P.U where base voltage is 25 KV, base MVA is 100 MVA output power of the DG is 0.8 P.U that is 80 MW. All the specification of IBDG is given below in Table 6.6

Table 6.6: Specification of IBDG in island mode

DG characteristics	Parameters
DC voltage	10 pu
Output ac voltage	1.05 pu
L	5.44×10^{-5} pu
C	0.343×10^{-3} pu
L	0.1×10^{-5} pu
OUTPUT ACTIVE POWER	0.8 pu
OUT REACTIVE POWER	-
Harmonic	1.33%

By using optimization technique K_p , K_i and K_v value will be found. To get appropriate value the range of the gain value set between1 to 20.

K_p =19.9781

K_i =9.636243

K_v=2.78774

It is also shown that the steady sate error value is decreased up to 0.01. That is error is reduced almost up to1%. So this technique gives very nice method for optimization. Figure

6.8 shows the objective function versus iteration graph which shows convergence of the algorithm.

From the overall observation it can be stated that steady state error minimization is possible properly and THD (total harmonic distortion) minimization is also possible. That is it can also be stated that a perfect controller designing is possible by the optimization method in time domain.

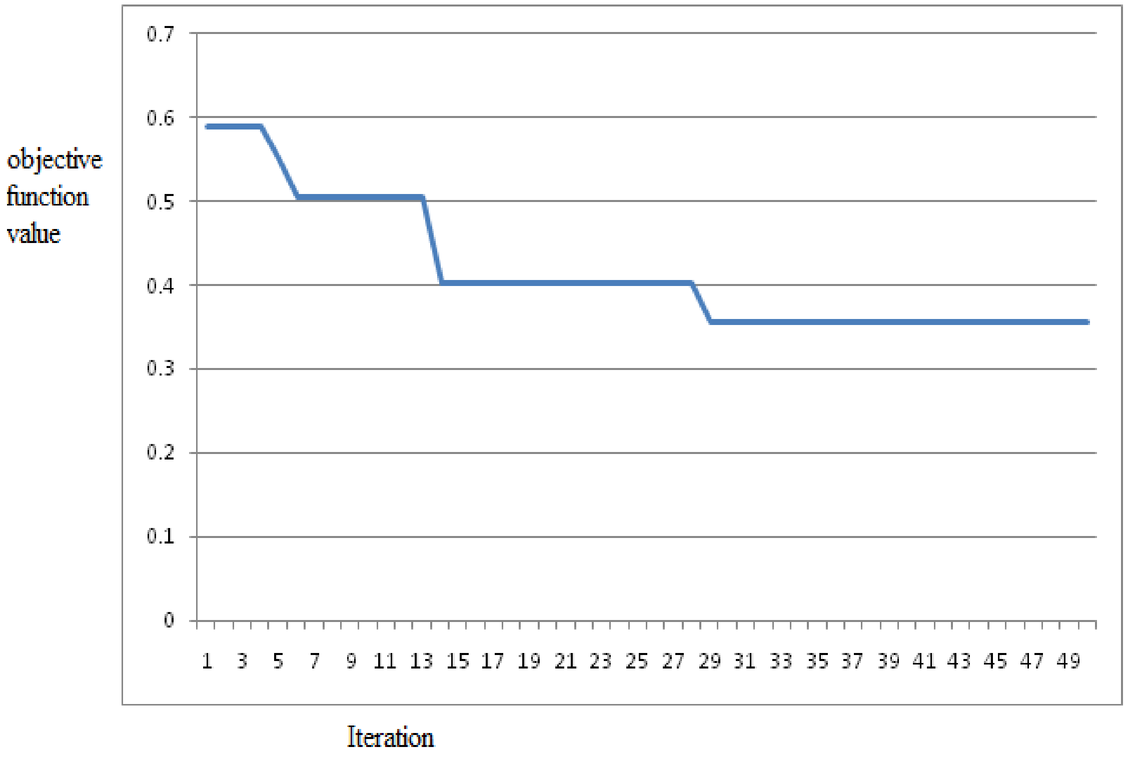


Figure 6.8: Convergence characteristics

In island mode the system is disconnected from the grid. Here in this work bus 7 to bus 14 was separated from the grid as shown in Figure 6.1.In this mode if a bolted three phase fault is applied for 0.01 to 0.05 sec at bus 12 then fault current and bus voltage for every bus are shown below in Table 6.7. Before fault the rated output current is 0.6 p.u. from the inverter. Inverter is operated in voltage control mode. Voltage sag during fault is also shown below in Table 6.7. Fault current is shown in figure 6.10.

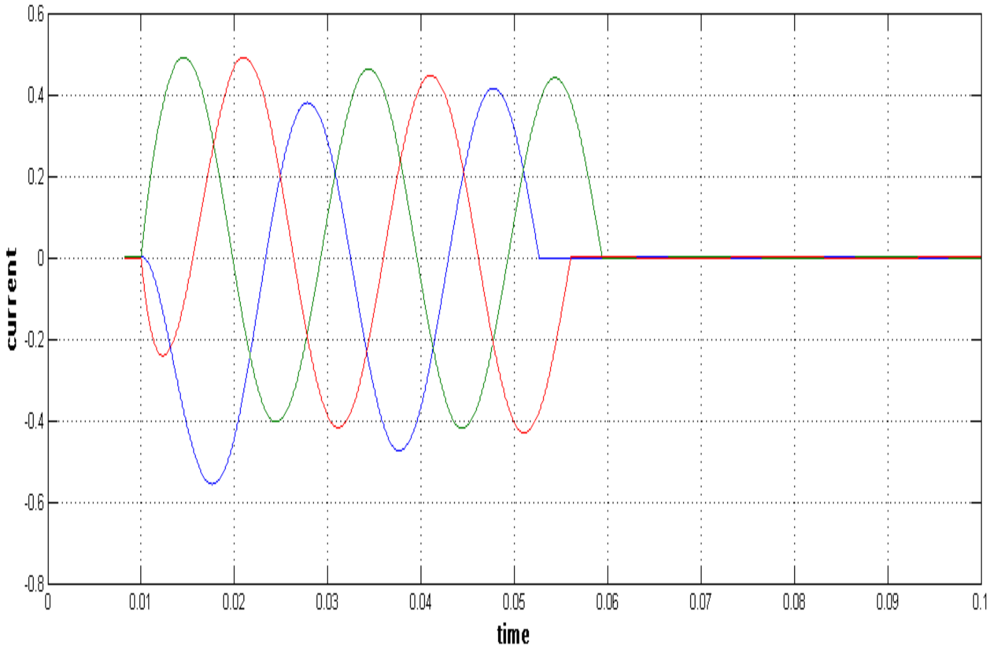


Figure 6.9: Fault current (in pu) in island mode

Table 6.7: Voltage and current after fault

Fault bus		12
Fault current at bus 12		0.41pu
Fault current IBDG		0.8 pu
Voltage (in pu)	bus 7	1.04
	Bus 8	0.7
	Bus 9	0.6
	Bus 10	0.6
	Bus 11	0.6
	Bus 12	0
	Bus 13	0.175
	Bus 14	0.4
Harmonic factor		1.5%

6.5.1. Observation on faults in island operation

From the above it is shown that the current contribution from IBDG is 0.8 pu that is only 133 % percent above the rated current. For higher efficiency of controller harmonic presence in the system is also minimized. If it is operated by other type of DG like SBDG it must be above this. IBDG have a current limiting capacity which is discussed previously. If it is operated grid connected mode then fault current may be high. To show this grid connected operation is done.

6.6. Faults in grid connected system without DG, and with inverter based DG, and synchronous based DG

Maximum DG mainly natural based DGs are connected to the grid through inverter based DG. Diesel generator or combustion engine is mainly synchronous based DG which is used for emergency purpose. For this here these two types of DG are considered for grid connected operation. DG is connected at bus 8. For grid connected operation grid synchronization is required. Figure 6.9 shows the grid synchronization operation. A phase controller has to be designed for this purpose. The phase controller provides a phase difference, δ diff, between output voltage of inverter and grid .The value of the phase difference, δ diff and approximate power flow can be calculated from (6.1). A model of the phase controller is shown in Fig. 6.10. The phase difference error signal generate by the equation (6.2)

$$P_{in} = \frac{V_{abc1}.V_{abc2}\sin\delta}{X} \qquad (6.1)$$

Where δ is the phase difference between output voltage of inverter V_{abc1} and input voltage to the grid V_{abc2}. X is reactance between inverter and grid.

$$\delta_{error} = P_{average2} - P_{ref} \qquad (6.2)$$

This generated error passes through a low pass filter. After that it passes through the PI controller which is applied to minimize the error of specified power output value after that it is added with phase of output voltage of the inverter. The cut-off frequency of the low pass filter has to be set at the appropriate value to attenuate the disturbance from measurement, but high enough to provide a good transient response of the phase controller. Here the cut of frequency is set at 100 Hz. In last step, phase difference controller is used *dq* to *abc* transformation to transform the modulating signal to the abc reference frame. For SBDG design, an equivalent linear model is designed from its short circuit data. And model is designed as a constant PV source which voltage and output power is constant. Table 6.9 and Table 6.10 show the IBDG specification and SBDG specification.

First a three phase fault is applied at bus 12 for 0.1 sec to 0.5 sec without DG all the current wave forms are observed. After that simulation models are developed for SBDG and IBDG then an equivalent linear circuit is considered from is short circuit current incase of SBDG and connected to the network at bus 8 by replacing the synchronous condenser. IBDG is operated in voltage control mode for grid connected mode which is previously discussed and fault current is also measured thus considering all the dynamics, fault current and voltage sag during fault is try to find out in this work. Pre fault, post fault voltage for every bus and fault current is shown in Table 6.11 and 6.12.

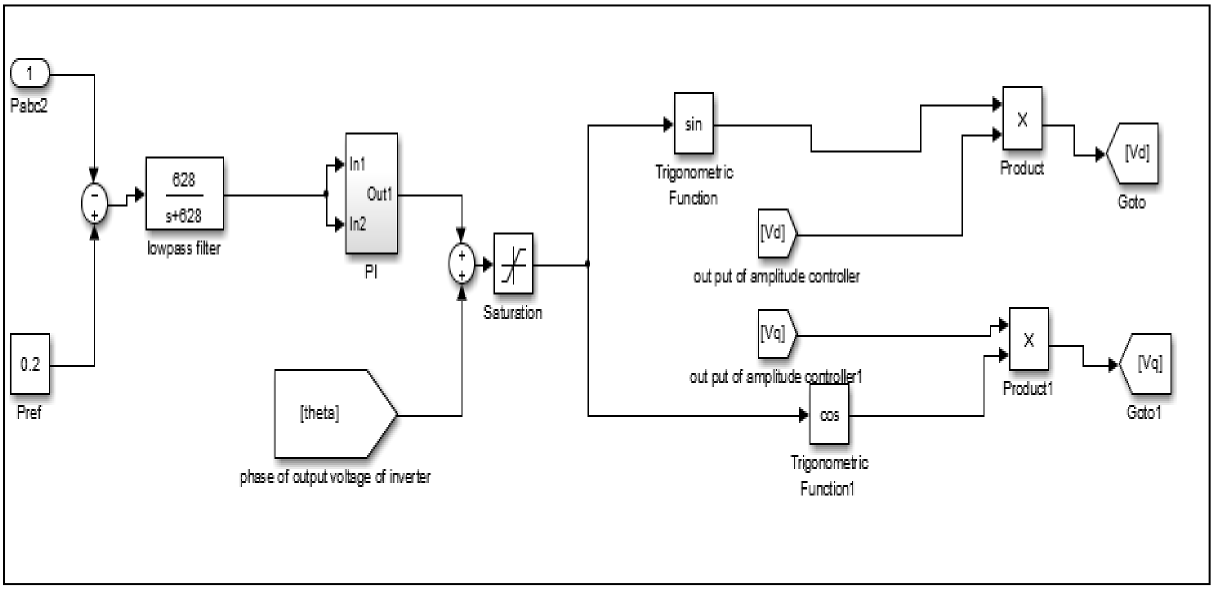


Figure 6.10: Phase controller for grid synchronization and constant active power

Table 6.8: Inverter based DG specification with grid connected mode

DG characteristics	Parameters
Switching frequency	30KHZ
DC voltage	3 pu
Output ac voltage	1 pu
L	5.44×10^{-5} pu
C	0.343×10^{-3} pu
L	0.1×10^{-5} pu
OUTPUT ACTIVE POWER	0.2 pu
OUT REACTIVE POWER	0.01 pu
Harmonic	2.639%

Table6.9: Synchronous based DG specification with grid connected mode

Machine characteristics		Parameters(pu)
Output voltage (phase)		1
Output power		0.2
Synchronous reactance	X_d	1.305
	X_q	0.474
Transient reactance	X_d'	0.202
	X_q'	0.243
Sub transient reactance	X_d''	o.15
	X_q''	0.18

Total output load=2.590

So DG penetration level= $\frac{\sum DGoutput}{totalload} = \frac{0.2}{2.259} = 0.07$ or 7%

6.6.1. Three phase fault analysis with no DG, with IBDG, with SBDG

The value of K_P and K_i are obtained by using genetic algorithm by minimizing the steady state error of the system. In this case steady state error is minimized up to 0.3 with the optimum value of K_p=10.086 & K_i=5.116 .If a three phase fault occurs at bus 12 with presence of DG the corresponding output current and voltage of the network are shown below. For grid synchronization phase controller value K_p and K_i is found as 1 and 0.1 by using genetic algorithm. Figure 6.11, 6.12, and 6.13 show the fault current wave forms of network without DG, and with IBDG with SBDG respectively.

Table 6.10: Fault current

DG	Bus no	fault current(pu)
NO DG	12	0.8
With IBDG	12	0.9
With SBDG	12	1.2

Table 6.11: Voltage after and before three phase fault

Bus no	Bus voltage after fault			Pre fault voltage
	Without DG (pu)	With DG(IBDG) (pu)	With DG(SBDG) (pu)	Without DG (pu)
1	0.8	0.86	0.8854	1.06000000000000
2	0.79	0.85	0.876	1.04500000000000
3	0.7	0.83	0.864	1.01000000000000
4	0.58	0.8	0.817	1.03344515969360
5	0.6	0.68	0.8	1.03010511040702
6	0.42	0.56	0.568	1.07000000000000
7	0.47	0.7	0.8	1.12251662001201
8	0.4	0.9	0.87	1.09000000000000
9	0.7	0.75	0.724	1.08473344278762
10	0.401	0.6	0.705	1.07499449680866
11	0.362	0.4	0.625	1.06933127433170
12	0	0	0	1.05726716684432
13	0.27	0.4	0.559	1.05475371442633
14	0.214	0.6	0.595	1.05403456467163

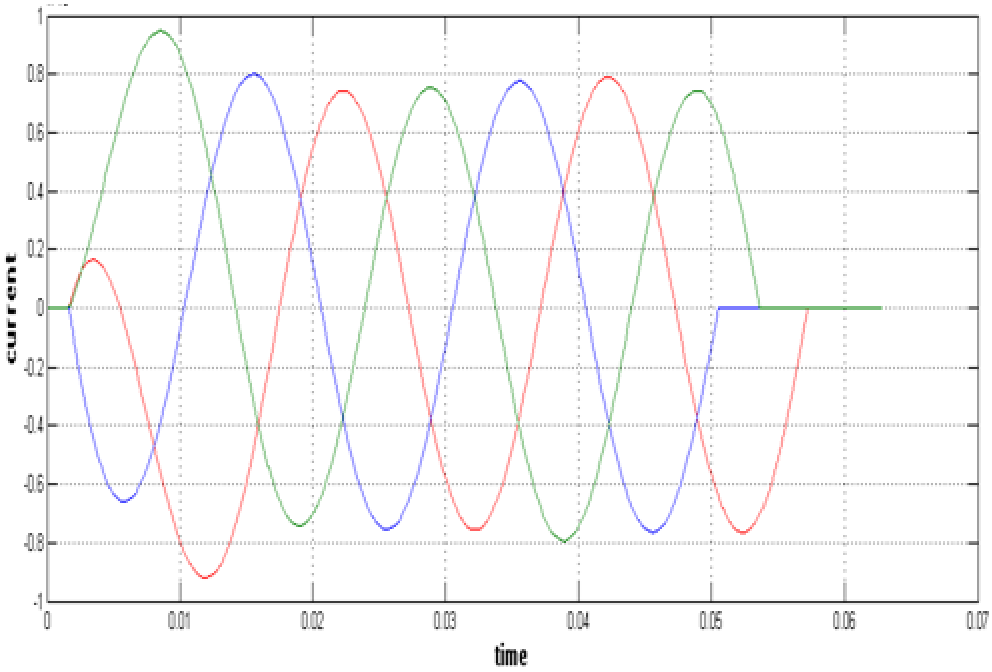


Figure 6.11: Fault current (in pu) without DG (time in sec)

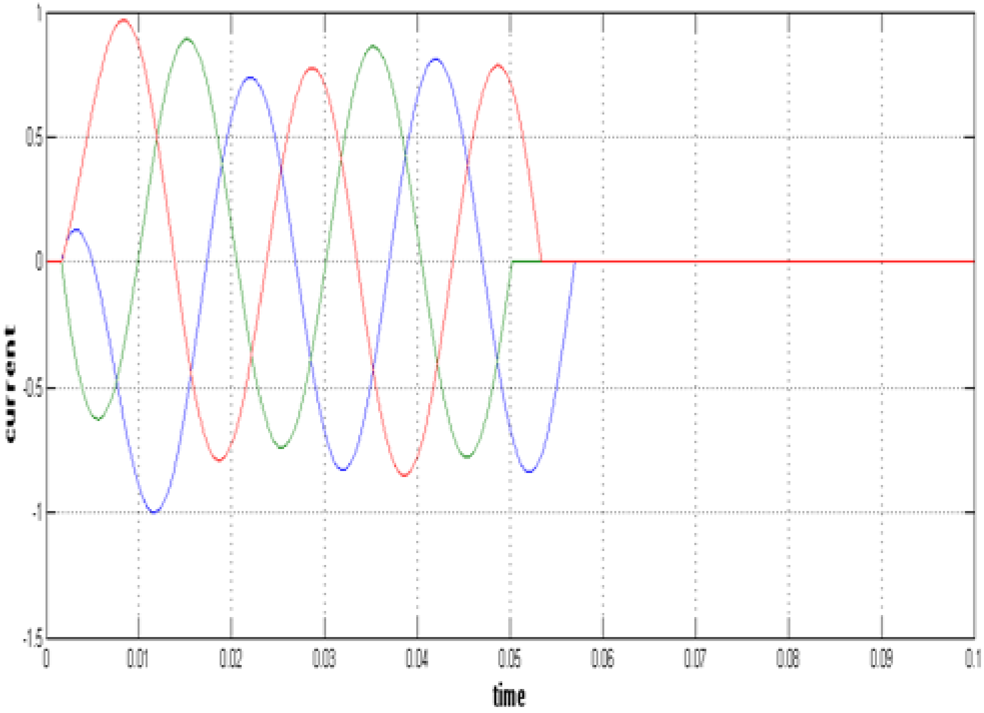


Figure 6.12: Current (in pu) at bus 12 during fault with IBDG (time in sec)

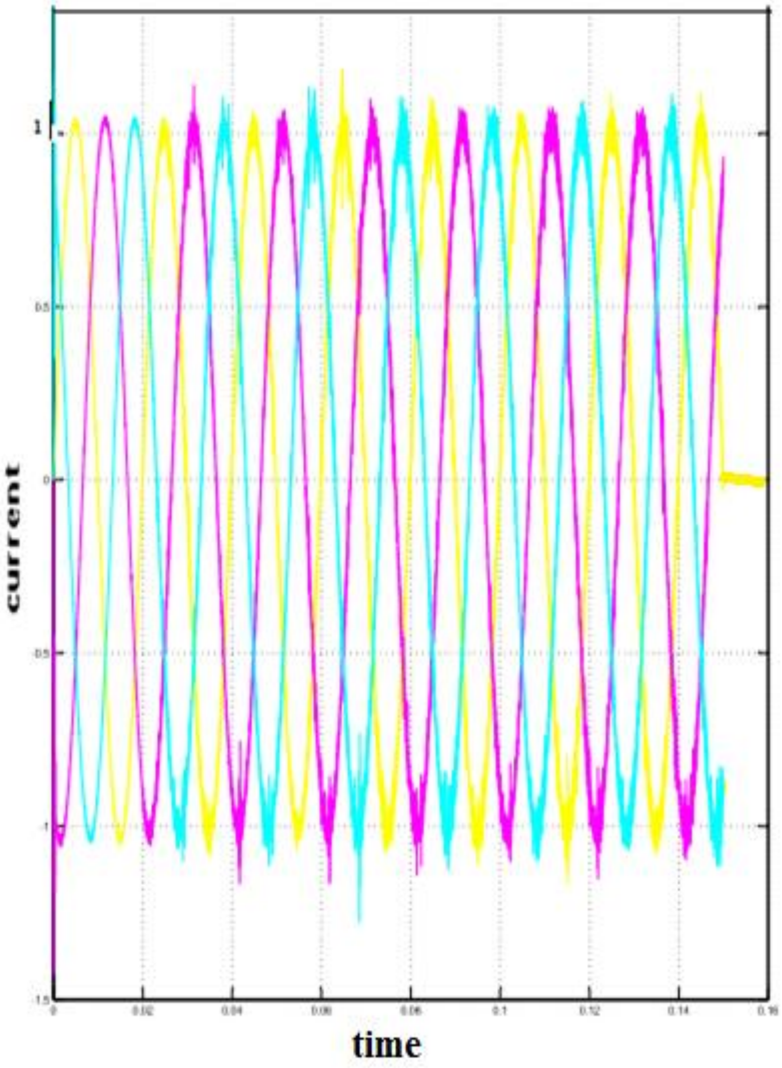


Figure 6.13: Fault current (in pu) due to SBDG (time in sec)

6.6.2. Fault Observation in grid connected mode

From Fig 6.11, 6.12 and 6.13 it is found that fault current is maximum for SBDG and minimum for the system without DG. Voltage sag is minimum for SBDG. Since SBDG is operated at voltage regulated mode, SBDG wants to keep the voltage constant. So voltage deviation is minimum by regulating the reactive power. It can therefore supply constant active power but variable reactive power.

In case of system without DG operation, synchronous condenser is present in the system of standard IEEE14 bus network at bus no 8. So in this case also voltage deviation is minimum at bus 9. But fault current is lower than SBDG and IBDG. But in case IBDG, it is operated at voltage control mode with active power control that is the current supplied by the IBDG generally maximum up to 1.3 to 1.5 of rated current. Therefore the current is limited altogether .But here DG penetration level is only 7%. If penetration level is increased, fault current level may be increased. But voltage controller circuit operates to keep constant voltage at the output. So voltage sag is also minimized. Another impact of IBDG is that it increases the harmonics of the input fault current. So a perfect design of low pass filter is required. For protection system designing it is also considered otherwise protection device cannot identify or differentiate the temporary fault and permanent fault.

From the above result it is also found that for same load response the fault current is less for island mode. Because here only IBDG is present and this will not give the fault current above 1.33 unit of rated current. So a different suitable protection system will be required for this purpose. For selection of the values of K_p, K_i i.e. for the gain controller tuning purpose, optimization technique is used allowing faster convergence in island mode. In contrary, it is observed that the gains of controller do not decrease in grid connected mode.

6.7. Both IBDG and SBDG connected network

Sometimes both types of DG are connected to the system. To analyze this, at bus 14 SBDG and at bus 8 IBDG are connected to the network. The output power of the IBDG and SBDG both are 0.2 pu. All the specifications also remain same for this system. Penetration level is increased hereafter. Because total input active power from DG is now 0.4 pu, the

Penetration level= $\frac{\sum DGoutput}{totalload} = \frac{0.4}{2.259} = 0.177$ or 17.7%

Figure 6.14 shows the wave form of fault current and table 6.12 gives the output voltage of the every bus during fault with both type of DG.

Output fault current = 0.95 pu

Table 6.12: Output voltage after fault considering both DG

Bus no	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Voltage(pu)	0.89	0.885	0.871	0.625	0.8	0.82	0.851	0.9	0.8	0.8	0.7	0	0.5	0.9

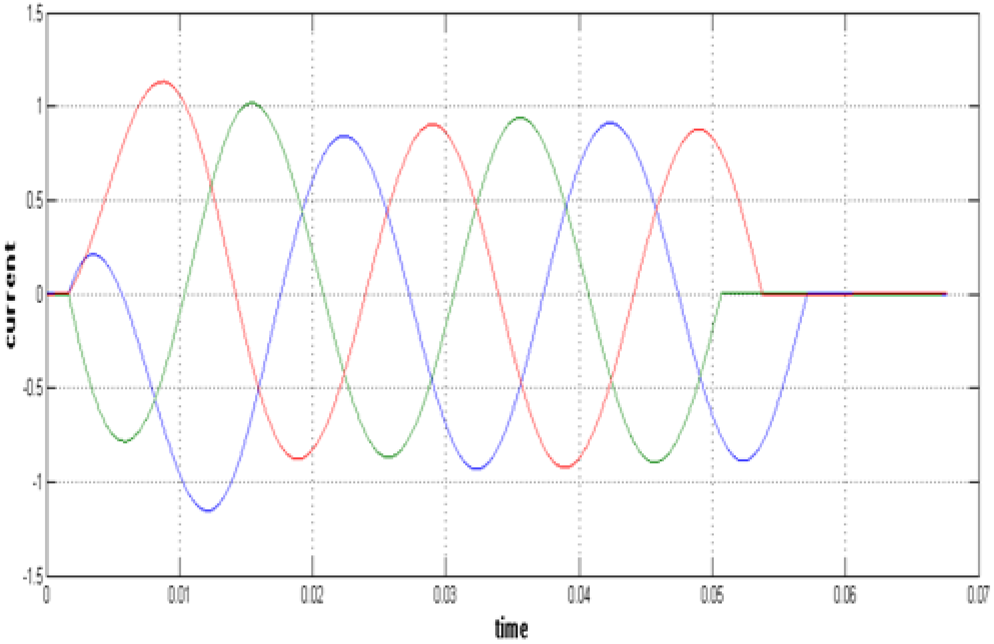


Figure 6.14: Fault current (in pu) considering both type of DG (time in sec)

6.7.1. Study on fault using IBDG and SBDG simultaneously

From the output waveform (Figure 6.14) of fault current it is seen that fault current remains almost same as that of IBDG connected system. But voltage is improved during fault due to presence of DG in bus 8 and 14 .These buses are voltage and active power controlled i.e they are acting as a PV sources. Due to the presence of SBDG at bus 14, bus voltage value has been improved to 0.9 pu. From above result it is concluded that if both types of DG are considered then the network is dominated by IBDG in case of fault current.

7. Conclusion & future scope

7.1. Conclusion

As per the requirement of clean energy, consumer requires high reliability and quality for sensitive load; hence the need for distributed resources is slowly rising. Distributed resources i.e. fuel cells, micro turbines, solar cells and wind turbines, are mostly electronic inverters based devices. These inverters are incorporated with the AC network resulting in changes of the fault response throughout the system. In order to analyze the impact from the increase of fault current due to the installation of inverter based DGs, model of these DGs are required to be analyzed. In Chapter 5 the proposed model of inverter based DGs are discussed by implementing the *abc* to *dq0* transformation. The control strategy can be divided into two parts: voltage control and phase angle control. Simulation results of the stand alone operation and the grid connected system with inverter based DG are obtained for time domain analysis in both the cases. The dq0 transformation is used here for design of controller of inverter based DG. The voltage and phase controllers, based on the dq0 transformation have been illustrated for inverter based DG transient operation. For the tuning the PI or PR controller genetic algorithm is used. It is shown that the steady state error value is minimized very smoothly.

Interrupting capability of circuit breakers is determined by fault calculations in power systems. The calculation of fault current at the system buses is done traditionally by applying the system Z bus matrix. The results of merchant plants, such as independent power producers (IPP), are not considered in the classical fault current calculation. New progresses in deregulation have brought new generation sources to the system. Especially in the presence of inverter based DG, the computation of fault current by applying the Z bus matrix may not be appropriate due to the complexity in guessing the transient impedance of the inverter based DGs. A simulation strategy which can be applied to calculate the fault current is discussed in this work.

7.2. Future scope

In this work a detailed analysis of inverter base DG is carried out. This model takes a large amount of memory. It requires long time for simulation. A simplified model is necessary for large system fault analysis. Otherwise it becomes very complex to analyze. It is also time consuming. Alternative software can be used to reduce time consumption.

Here genetic algorithm is used for tuning the PI and PR Controller. If any other optimization technique is used it may give better optimization.

In presence of IBDG relay co-ordination is maintained for traditional protection system. This protection system may not be suitable if IBDG penetration level is increased.

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