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A Novel Power Sharing Control Method for Distributed Generators in DC Networks

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A NOVEL POWER SHARING CONTROL METHOD FOR DISTRIBUTED GENERATORS IN DC NETWORKS

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ABSTRACT

A NOVEL POWER SHARING CONTROL METHOD FOR DISTRIBUTED GENERATORS IN DC NETWORKS

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The power sharing control method is a desirable solution to integrate multiple renewable energy generators into the grid and to keep them working synchronously. Power sharing control between different distributed generators is an important consideration for the stabilized operation of the power grid network. In this thesis work, a novel method is used with the concept of droop control technique and is designed to control power from each individual generator in DC network particularly. The proposed power sharing control method can be widely applied to grid connected network and to islanded power grid network for obtaining high efficiency of power distribution and also provides higher stability.

An efficient power control method to share the load demand power is designed based on the concept of droop control. This method does not follow sequential or predefined topology of power sharing but uses the availability of power from each generator as a factor of control. The proposed controller can be applied to an individual distributed generator to regulate its output power quickly and accurately. The power sharing control method was formulated, modeled and verified by simulation studies of steady state and transient stability tests. The optimal coupling resistance for power sharing was also identified. The interaction of the controller and the communication delay was also studied. The interference of communication delay is negligible for the power sharing controller. The system is simulated in MATLAB/SIMULINK environment.

This thesis is dedicated to my parents, my sister Grace and my brother John for believing in me and providing me with everything I need. And to my advisor for the support throughout my thesis work.

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ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DG	Distributed Generators
IEA	International Energy Agency
LCL	Inductance Capacitance Inductance
MPPT	Maximum Power Point Transfer
PI	Proportional Integral
PV	Photo Voltaic
PWM	Pulse Width Modulation
THD	Thyristor Harmonic Distortion

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Nowadays, the use of renewable energy has increased due to environmental concerns and increased price of fossil fuels. Continuous development in industrial and commercial sectors has become a burden to the traditional power grid and hence the demand for renewable resources integrated grid systems has increased. Traditionally, alternating current is being used due to its ability of stepping up and stepping down of the voltage based on the needs at the load end. Recently in the field of electric power generation, transmission and distribution, the use of DC power has drastically increased. The aim of the thesis is to integrate the DC power network with the AC power network and not the replacement of AC with DC.

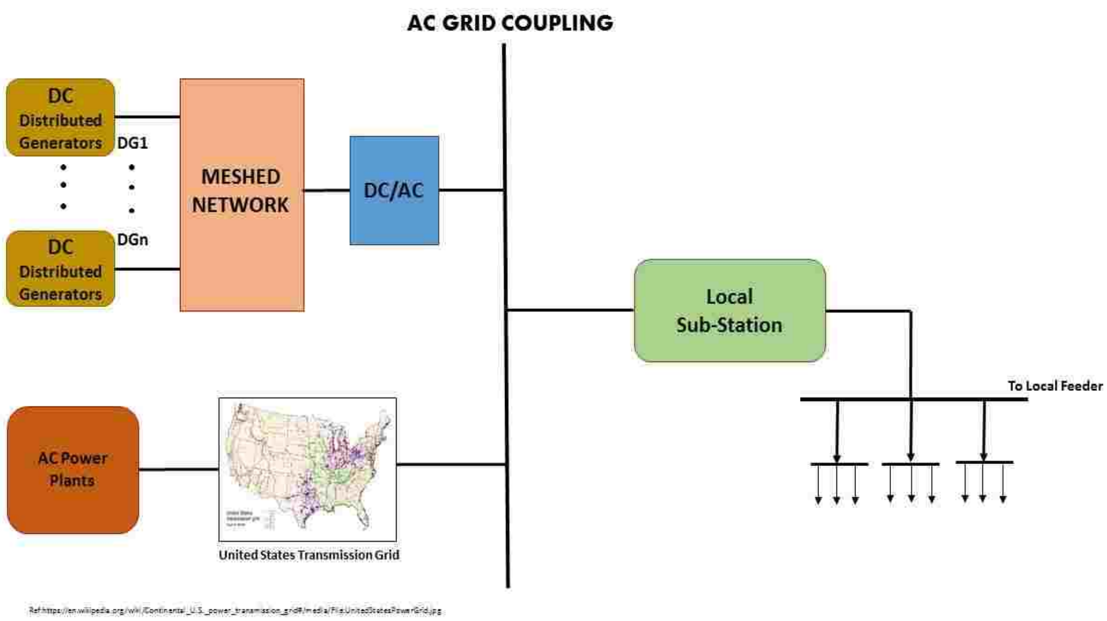

Figure 1. Integration of DC and AC Power Network

Fig.1 shows the integration of the DC and the AC network, where the DC distributed generators and the AC generating systems are connected to the same grid network. The DC distributed generators require a DC-AC converter system to be integrated with the AC grid. When there is broader access to electricity, the efficiency of the transmission grid is found to be more balanced. When the demand increases, the generating capacity finds it difficult to meet the required demand. This could be rectified by installing microgrids with renewable energy sources as the primary source of electric power. Here, multiple generators are connected to a single microgrid to meet the demand at the load end of the microgrid. The microgrid also has access to be integrated with the traditional grid network. The integration of the distribution system enhances energy management, conversion efficiency and grid reliability[1, 2]. DC microgrids are currently in trend as the renewable energy generators can be used as the primary source of power efficiently[1, 2]. The recent demand is for the photovoltaic and wind energy based DC microgrid systems. Remarkable development in the electronics technology has brought in power converters which can completely work on DC power. The load power demand is also exceedingly increasing for DC source. These strategies bring in high efficiency on the working of DC microgrid systems.

1.1.1 DC MICROGRID

Microgrids can operate autonomously or can be grid connected and based on the type of power; it can be AC or DC. Tremendous advancement in the field of DC energy has led to the introduction of the DC microgrids in the power network. The DC microgrids have better efficiency and compliance with the customer electronic loads as well [1]. The microgrids usually tend to use renewable energy as their primary source of power. Droop control is used for the voltage control and regulation in the converters and generators connected to the microgrid. The DC microgrids has proved to provide added efficiency and reliable energy transfer [3]. The use of DC distribution system has become outspread due to their harmonic management and synchronization [2]. The reliability of the network is ensured by integrating it with the main power grid. Since there are power electronic AC-DC and DC-AC converters, it makes it accessible for the integration of the microgrid with the traditional AC grid as well.

The DC microgrids has found its vast application in the field of data and telecom industry which requires islanded or individual grid system for their independent work nature[4, 5]. Areas located far from the main grid can rely upon the installation of microgrids, as the access to the main grid would be inconsiderate. Islanded microgrids can be built with their own energy resource and does not need to be integrated with the grid. The microgrids use their own energy storage system as a backup source and this ensures reliability of power at all times.

The integration of DC microgrid systems with the AC systems ensures power reliability and availability by using DC-AC converter interface [2]. When the power demand is higher than the power generated in the microgrid, it absorbs power from the AC grid and when the power demand is lower than the generated power, it sends back the power to the grid. Different topologies are used for the interconnection of the converters namely, single, parallel and aggregated converter systems [2]. A single converter system is usually used for low capacity systems and also serves as a direct interconnection between the AC grid and the converter. Parallel converters are usually used in high power capacity applications where different generators are connected in parallel to the grid. This topology also ensures higher power exchanging capability between the DC microgrid and the AC grid. The aggregated converter system is usually referred to as a hierarchical converter systems.

Recent developments in the power industry symbolizes an increasing demand for DC power at the consumer end as most of the products are electronic and require a DC power source. Moreover, the effect of fossil fuels is degrading the environmental conditions and hence the need and usage of renewable energy generation is highly in demand. Most of the renewable energy like the photovoltaic generation and the wind generation provide DC power and hence the need for conversion and rectification can be avoided. This reduces the losses caused due to the process of rectification and conversion and therefore increases the efficiency of the power generation and transmission. Decrease in voltage drops across the lines helps in the increase in power transmission efficiency. Most of the energy generation systems uses energy storage systems as backups to avoid blackout and instability issues. In DC networks, the battery and energy storage systems can be directly connected to the generating plant as it does not require the process of rectification. The response time during instability is higher in DC networks when compared to AC networks.

The DC distribution enhances the incorporation of renewable energy sources as it eliminates conversion and saves 2.5% to 10% of the generated energy. Uninterrupted power supplies are conveniently reliable using DC power as it can be easily backed up to the energy storage systems such as batteries [6]. The DC distribution system enhances the voltage stability during the co-existence and integration of the DC with AC systems, which is usually carried out by the reactive power optimization in the integrated AC system[7].The power quality converters using DC source boosts the power quality standards as the first stage of DC supply offers power factor correction in the AC integrated network[6].

1.1.2 INTEGRATED DISTRIBUTED GENERATORS

The power industry is currently witnessing a transition from centralized generation to distributed generation of electric power. The rise in the use of distributed generation has been the result of increase in the use of renewable energy resources so as to diminish the use of fossil fuels and other environmentally degrading power resources. The distributed generation of electric power also provides increased energy security and highly environmentally friendly solution to growing power demand [8]. The distributed generators are considered to be small power resources, mostly renewable, located near the consumer end to provide an accelerated fixation to the environmental problems by offering exact platforms for the renewable energy resources [9]. Higher reliability, reduced losses and increased voltage profile are the effects of the usage of distributed generation of electric power [10]. The distributed generation can be installed without the consideration of the size and capacity and only depend on the generated power and the power in demand. The five major factors that influence the increased usage of distributed generation has been defined by the International Energy Agency (IEA) [11], namely, development in distributed generation technologies, constraints on construction of new transmission lines, increased customer demand for highly reliable electricity, electricity market liberalization and concerns about environmental climatic conditions.

The demand for renewable distributed generation has always been high for its worldwide availability of resources which has been attributed to two main reasons [12], the installation and maintenance costs for the renewable energy sources based generation has found to be declining in the recent years and the centralized grid design is weakening which serves as a way to integrated distributed generation based grid networks. The distributed generation can be considered as network reconfiguration to minimize the energy losses, maintain the power balance between the generators and also provides isolation to the occurring faults by changing the state of sectionalizing and switching ties [13]. The distributed generation has various benefits including reduced line losses and improved voltage profile by integration of distributed generation, power quality improvement, system reliability and network security enhancement, reduction in operation and maintenance costs and augmented system productivity [14-21].

1.1.3 VIRTUAL INERTIA CONTROL OF DC MICROGRIDS

The virtual inertia plays an important role in the outcome from the system as it is directly related to the frequency of the output power generated. Nowadays, power systems make use of power electronic interfaced systems to improve the efficiency and time response of the power network. In these type of systems, the inertia is very small and is hard to control. If the virtual inertia becomes uncontrollable, the impact is seen in the output produced by the entire power network. The contribution of renewable energy based power systems, including solar and wind, towards the total electric power generation has increased in the recent years. The basic power system is classified into generation, transmission and distribution networks. The classification is the same both in AC and DC power networks. In the traditional power systems, the large inertia slows down the system frequency response and hence this allows ample amount of time to control the system. A renewable microgrid usually has smaller inertia and hence the control system must be very fast and accurate as the system frequency response will also be high.

Virtual inertia control refers to the fact that in the case of a frequency drop in the system due to increased load, the energy stored in the generation system is used to produce the increased amount of electrical power required by the load. If the generation system uses a wind turbine, then the energy required is taken from the stored energy in the rotational mass of its turbine. In case of a solar converter, additional DC link capacitors are used to meet the stored energy requirement. The entire aim of the virtual inertia controller is to maintain the system frequency within limits. The inertia of the power system plays an important role in the system frequency. Large inertia refers to slower frequency response and vice versa. In traditional systems, the power network has large inertia and hence this increases the frequency response of the system. In recent years, all the traditional systems are being replaced with power electronic devices and hence the inertia of the system is much smaller which leads to faster frequency response in the system. Based on the system frequency response, the control system must be implemented. Here the control systems must be fast and accurate to meet the fast response of the system.

The larger inertia of the traditional power systems slows downs the system frequency response and hence provides enough time for the control actions to take place within the system. Usually, renewable microgrid has smaller inertia and hence the control systems in these power systems must be reliably fast as the time response and the frequency response will be high in the system. The distributed virtual inertia method[22] provides a control method to increase the virtual inertia of the system by using the method of inertia emulation. The inertia emulation is carried out by controlling the charging and discharging of the DC link capacitance over a certain range and by adjusting the PV generation whenever necessary. By using these methods, the efficiency of the system can be improved by reducing the impact caused due to low inertia in the system. For the independent working of a microgrid, the supply-demand balance must be maintained in the system. When the supply and the demand does not match, the rate of change in the grid frequency is determined by the inertia coefficient of the system. The inertia of large microgrid systems are usually small due to the integration of large number of power electronic interfaced distributed generators. The control process is carried out by increasing the system inertia and by adjusting the generation in the PV systems. The efficiency is improved by utilizing the energy storage components in the PV systems which includes the DC link capacitor. However, the charging and discharging of the DC link capacitor does not have any effect on the energy efficiency of the system. Here the inertia emulation is carried out by making the systems work at maximum power point tracking (MPPT). If the generation in the PV system is more than demand, then the system works in inertia emulation mode. Here the DC link capacitor is used for this control. Since the size and voltage range of the capacitor is limited, its contribution to virtual inertia is also limited. If the emulated inertia or the change in frequency is beyond the range of the DC link capacitor, then the PV generation is also adjusted. Thus, the inertia emulation is carried out in two steps including the capacitor control and the PV generation control.

In adaptive virtual inertia control method[23], voltage droop control and coefficient are used to increase the inertia of the system. When a system drives a load, certain amount of voltage drops in the generator-converter system which is referred to as voltage droop. This refers to the fact that when the load in the system suddenly changes, changes in the voltage of the system can be seen accordingly. Here, the change in the DC voltage is reduced by adjusting the droop curve at transient events. In DC microgrids, the inertia of the system is usually insufficient, and this leads to poor voltage quality. When there is a large disturbance in the system load, the DC bus voltage changes and this may cause harmful impacts on the loads and the renewable systems connected to it. Different methods for the improvement of the virtual inertia in a system is being carried out. Ultra-capacitor is used to improve the transient response, but this method is not cost effective and also this remains idle during the steady state operation of the system. Rotational kinetic energy of the wind turbine is also being utilized to increase the virtual inertia supply to the system. But the virtual inertia supplied in this case is very weak and is also incapable to meet the demands of the system[23].

The auxiliary power is supplied by the swinging of the voltage droop curve. In our case, the droop is estimated to be 4%. The droop curve is developed by plotting P vs V_{dc}. A reference point is marked on the curve (in our case, the reference point is considered to be 400V) and also a steady state operating point is marked. The steady state operating point is always higher than the reference point. When the power demand changes, there is a droop in the system. Hence, the operating point changes to the point where the voltage is equal to the voltage caused by the change in power demand. Similarly, when there is a power deficit, the operating point changes simultaneously to enhance the controlled operation by injecting the virtual inertia to the system. For ensuring stable operation and preventing the absorbed power from exceeding the maximum value, the swing range of the droop curve has to be limited.

1.1.4 EXISTING POWER SHARING SYSTEMS

The distributed generators based DC systems are integrated with the main AC grids to avoid the occurrences of blackout and instability. By integrating, the excess power generated by the distributed generators can be injected to the main grid. This in turn helps the consumers to sell the excess generated electric power from their microgrid systems. The power sharing between the different generators is crucial as it maintains the stability within the entire grid system. The power demand has to be met by the generators equally. If a generator is not in full load working condition, the other generators must be able to meet the power demand by proper power sharing between them. The power demand has to be met by the generators even when the system is experiencing instability. Instability occurs due to sudden increase or decrease in load connected to the network, lack of a generating unit, etc. The system has to provide efficient power sharing even during the absence of a backup storage system. The power sharing is usually carried out by using a battery source as a backup to supply power during an interruption in the generating systems. The battery sources cannot withstand the higher power demand for a longer period of time. This can only be rectified by proper power sharing between the generators, the grid and the backup sources.

Power sharing is performed also by using current sharing techniques by maintain the voltage constant throughout the system. A common current sharing method is the master-slave current sharing scheme which allows to generate effective reference voltage value among the converters [24]. A current sharing compensator is used in the current sharing loop which generates a signal proportional to the difference between the converter voltage signal under consideration and the reference signal. The main disadvantage of this master slave technique is that the entire system is shut down to generate the reference signal value[24].

In recent times, droop control based power sharing techniques are used where a virtual output impedance is set on each connected converter. Droop constant or a virtual impedance is set for each converter to act as the reference values [25]. This technique also makes use of the droop gain for the control of power sharing among the generators. The slope of the load regulation is determined to provide the voltage regulation and the power sharing control among the generators using the droop current sharing technique[26]. A feedback signal proportional to the output current is generated to modify the output voltage loop characteristic. The maximum droop range is also calculated to maintain the droop value within the reference value. The droop based power sharing techniques follows three control methods, namely, centralized, decentralized, and distributed systems. The main limitation of the droop based power sharing technique is the poor voltage regulation occurring due to the high droop gain produced.

The DC bus signaling technique is also used for the power sharing control[27]. This system also uses the centralized, decentralized or the distributed method of control in a hybrid based technique. This method helps in controlling the level of the DC bus and also provides source scheduling during the time of load shedding. The controller operates using a set maximum power point and decreases the bus voltage when there is increase in the load current according to the voltage droop characteristic of the converter. It also implements a charge controller and a load interface converter for its control strategy. This system minimizes the mismatch in the output voltage of each attached converter but neglects the effect of the cable resistance.

Adaptive droop control method is used to rectify the problems created such as poor voltage restoration and instantaneous voltage deviation due to the fixed droop value control[28]. Here a proportional droop index value is introduced to calculate the droop value based on the figure of merit. The boost converters used along with the generators acts as an interfacing module between the generating source and the grid network. Here the distributed energy resources are connected in parallel to share the load current which is in proportion to the available input power. It uses a virtual droop resistance value based on the input parameters for the internal power sharing control.

The main disadvantages of the existing power sharing systems include poor load sharing and circulating current between the converters

1.2 OBJECTIVE OF RESEARCH

The aim of the thesis is to design, simulate and analyze a power sharing controller for distributed generators in DC networks, with several advantages including improved efficiency and optimized synchronization over the previous converters. The system designed in the thesis can fit commercial renewable power networks. The working efficiency of the system is maintained by providing proper power sharing between the distributed generators connected to the DC system. Droop control is used as the principle to design the controller in each converter. The stability analysis is performed for the system designed. Testing of the model is performed using the MATLAB/SIMULINK software.

Proper power sharing between the distributed generators has to be maintained for the efficient working of the DC system. Renewable energy resources are used as the primary source of power for the distributed generators. The DC-DC converters are used as an interface between the generators and the grid. The converters are connected in parallel along with the grid and the load by the means of coupling resistor. The contribution of power to the load is analyzed for both the converters and the grid. The static and the dynamic stability analysis is performed for the converters. Step down and step up of the load power is performed for different coupling resistance values to evaluate the most efficient working combination. The total harmonic distortion percentage is calculated for all combinations of coupling resistances. The efficiency of the system is calculated by using the input power from the generator and the output power to the load. Modelling is carried out by connecting the converters in parallel to the grid and the load and the simulation is processed to perform the stability and efficiency tests for the power sharing among the distributed generators.

1.3 THESIS OUTLINE

Chapter 1 explores the DC microgrids with the distributed generator systems. The usage of renewable energy has increased in recent times. The usage of renewable energy as the primary source of power in the microgrids have been discussed. It also discusses the existing power sharing control methods in the DC distribution system. Chapter 2 discusses the principle and working of droop control. The existing droop control in AC and DC distribution systems has been discussed. The droop equation for the proposed model of power sharing has been derived.

Chapter 3 discusses the principle and working of the proposed model of power sharing in DC distribution systems. The entire model for single and parallel units have been explored. The modelling and working of a three phase rectifier with closed loop control has also been discussed.

Chapter 4 discusses the simulation of the single unit and the parallel units distributed generator based DC systems and the three phase rectifier. It also discusses the output waveforms and the measured output values for the system. This chapter also discusses about the stability analysis including the static and the dynamic stability tests.

Chapter 5 discusses the performance analysis of the developed model. It explains the THD analysis for the single unit based system and the steady state and dynamic performance analysis for parallel unit based system. The steady state performance analysis includes the THD analysis, efficiency analysis and the output power error analysis. The dynamic performance analysis includes the power shoot analysis and the stability time analysis. The grid power contribution is also explained with two different cases of system modeling. This chapter also includes the communication between the grid and the distributed generators. The extension for external control has also been discussed. Chapter 6 concludes by explaining the reason for the power sharing between the distributed generators and for choosing 3.0Ω as the least coupling resistance value.

CHAPTER 2

DROOP CONTROL DESIGN FOR DC GENERATOR POWER SHARING SYSTEMS

2.1 INTRODUCTION

In Chapter 1, existing power sharing methods in DC distribution systems were discussed. This chapter introduces the design of a novel droop controller in particularly for DC networks including their role in power sharing control. Originally applied to AC networks, droop control is used to maintain the rated voltage across the system[29]. Power sharing and control is sustained by maintaining the voltage constant throughout the operation of the system. The ability of the generators to perform efficient power sharing is controlled by the controller of each converter. The DC-DC converters acts as the interface for power sharing for each generator with the grid and the load connected to it. The effect of power sharing on the stability of the system is higher. This model is designed to withstand the crucial effects of instability occurring at each generator-converter unit.

2.2 DROOP CONTROL IN DC NETWORKS

In paralleling of converters in a DC system, droop controller is used as the principle to maintain proper power sharing between them. The droop controller eliminates the error occurring in maintaining the rated constant voltage across the system. The droop control can be carried out in different methods [30]. Droop is usually considered as a delay or a drop in the required voltage at a particular instant of time. The delay or the drop from the rated voltage is usually taken as the error signal used for the generation of the feedback signal send to generate the duty cycle signal for the switch of the converter. The error signal is generated when the external voltage is lower than the output voltage or the rated voltage required to meet the specifications of the converters.

In an alternative method, a voltage droop controller is used to generate the feedback signal which uses various signals from the converter as reference and source.

In microgrid networks, droop control strategy is commonly used to maintain the rated voltage across the grid system. The droop control is adopted to control the power sharing between the converters and the grid system[31]. For the voltage droop control, the power transferred between the converters is monitored, and the feedback signal is generated based on the error occurring in the system. Microgrids contain generating units, energy storage units and interfacing between the converters and the grid. Equal and efficient power sharing has to be maintained between them for proper stabilized working of the microgrid system. The power transferred is analyzed and calculated and a function of converter variables and constants are generated and is sent to the droop controller. A reference voltage signal is used to generate the error or the feedback signal for the droop controller. Generally, the rated voltage of the system is used as the reference signal.

2.2.1 STUDY OF AC DROOP CONTROL

AC droop control is mostly opted for as the control method for AC microgrid systems both in islanded and in integrated modes. Real power-frequency droop control and reactive power voltage magnitude droop control are conventionally used in distributed energy resources[32]. An exponential droop control strategy is used to eliminate the reduction in the response time in the system. The exponential droop control is assumed to cooperate better with the load as the grid network can be simplified by merging of the voltage sources. In AC grid systems, the frequency and the voltage of the grid has to be maintained within a limited range. The exponential droop control strategy is used to maintain the frequency and the grid within the limited range and this improves the efficiency of the system[33].

During the integration of the converters in the microgrids, the communication links are eliminated to improve the efficiency. Hence the droop control is considered to be operating in independent, autonomous and wireless mode[34]. The voltage and frequency based is commonly used in low voltage AC microgrids. In case of non-linear loads, this system may face instability and hence there would not be an efficient voltage regulation in the grid network. Otherwise, the system works efficiently with fast response time and higher voltage regulation. This droop control method helps in proper power sharing among the generators and helps in avoiding overstressing and aging of the sources[34].

The microgrids experience low frequency relative stability problem in integrated distributed generator systems. Low frequency modes are set up for each power demand for the inverters connected to the distributed generator systems. When there is a change in the power demand, the low frequency mode shifts and this causes the dynamic power sharing to shift to new locations causing instability in the system. A decentralized droop control method is used to restore the instability caused due to the low frequency mode shifts. This system helps in adjusting the dynamic performance of power sharing by adapting transient droop gains. Static droop along with adaptive transient droop function is set up for the effective power sharing strategy. The transient droop gains are set up using analyzed small signals to obtain the absolute required transient and steady state response. The adaptive droop functions are introduced to the control to obtain the active damping of the power sharing modes and to increase the reactive power controllability. Hence, preserving the dynamic and transient stability of the distributed generators connected to the system[35].

Droop control is used as the primary strategy for the power sharing control in distributed generators in AC microgrid systems. The frequency change is related to the change in real power, and the change in voltage is related to variations in the reactive power. Hence, the frequency droop control is adopted for maintaining the real power and the voltage droop control is adopted to maintain the reactive power across the system[36].

2.3 DROOP CONTROL FOR DC DISTRIBUTION SYSTEMS

Microgrids, themselves can be considered as integrated systems for power generation and power consumption as they contains various parts such as the distributed generators, energy storage units, control devices and controllable load, all operating in coordination[37]. The design of the DC microgrids flourished with the improvement in the use of the renewable energy sources[38]. The usage of photovoltaic mode of generation and, wind energy generation systems, enhanced the construction of DC microgrids in islanded networks as well as integrated power networks. DC microgrids can usually operate in grid connected mode as well as in islanded mode. Grid connected operating mode of microgrid helps in improving the power supply reliability, improve the distributed generator utilization, reduces the impact of inconsistent power supply and also improves the power quality[39]. The energy storage units are used to regain the stability of the system when the microgrid is operating in islanded mode. Voltage droop control is used to improve the efficiency of the power sharing between the integrated systems connected to the microgrid network. Virtual impedance control is also used along with the droop control, but the control method has to measure and analyze the output current. A function of converter control output variable is used to remove the output current sensing. The droop controller is modified with the converter output variables which are proportional to the output power in the system[31].

Conventional energy resources are being replaced by renewable energy resources for their efficiency, availability, and environmentally-friendly factors. Among the renewable energy resources, the photovoltaic generation is becoming prominent due to various reasons including clean resource characteristic, continuous improvement in solar modules and economic incentives from the government. According to the International Energy Agency, the estimated cumulated PV capacity in the world has reached 228GW by 2015[40]. The PV based DC microgrids also has high efficiency, reliability and controllability advantages over the AC microgrids.

The currently available PV based microgrids use the maximum power point tracking method to extract the solar energy. These methods work efficiently only when a DC bus voltage regulator functions along with it to provide constant DC voltage output. The disadvantage of using MPPT includes the battery overcharge and the overvoltage conditions when the PV penetration increases. To avoid this problem, the capacity of energy storage devices was increased which in turn led to the increase in system investment and maintenance cost. Though the energy storage devices portrayed the sufficient capacity, it showed the following difficulties during working, when the PV penetration increases, the maximum power of the PV generation is higher than the load demand and the battery charging power. The state of charge of the energy storage devices reaches its maximum and it cannot be charged further.

Various other methods were realized to overcome the difficulties in the existing systems which included centralized method of regulation of PV output power and output DC bus voltage[41] [42], usage of central controller for mode switching, supervisory control for PV and battery storages, etc. These methods were implemented and as a result displayed various problems such as, communication lines being required for the supervisory controller[41]. A failure in the communication line at any battery or energy storage devices would result in power disruption. This problem was overcome with the help of power line signaling method. Though the system is reliable as it requires only the power line for communication, the implementation of the line is indeed tedious. A central controller was replaced with distributed or decentralized controllers[42], but the regulation of the DC bus voltage was still carried out by the battery or the energy storage devices. Universal controllers[43] were used to replace the central or distributed controllers. This method involved switching between two different configurations, but this method cannot work efficiently with one stage PV structure.

In all the existing methods, the PV controller is composed of two components which includes the MPPT controller and the grid voltage regulator. Both the components make use of the inner voltage loop for control but the switching between the two modes is tedious. To reduce the transition trouble between the modes, anti-oscillation methods are required.

The limitations of all the existing methods led to the need to unify the MPPT and the voltage bus regulator as to avoid the transition between different control configurations during the PV operation. Here, a droop control strategy is used for the PV power control and the DC bus voltage regulation in the PV sources used in DC microgrid. The DC bus voltage and the differential of PV output power is used for the control. The droop operates as the voltage source for the PV sources and also operates as the MPPT controller for the DC bus voltage regulation. Here, the PV sources supplies the maximum available power when it is connected to the grid. During islanded operation, the PV sources automatically backs off the generation to meet the load consumption and it can also supply maximum power to the microgrid as long as there is sufficient load. This method does not require any controller transition, communication lines, or any bypass storage for the DC bus voltage regulation[40]. Here, a compound PV controller is used usually referred to as the PV coordinated controller. This controller unifies the MPPT controller and the DC bus voltage controller. The PV sources, along with the droop control, have the ability to operate as voltage sources when required.

The proposed system has the following features. The PV sources can autonomously regulate the DC bus voltage and can also share the load with other PV sources. The maximum available power is transferred to the DC microgrid as long as the grid is connected or as long as there is sufficient load. There is no controller transition required as there is no switching of modes. The system is completely decentralized and hence it does not depend on any communication system. The PV array is connected to the load using DC-DC converters as the interface. The droop controller helps in maintaining the PV sources to work in maximum power transfer mode when it is in grid connected mode. Using this mode of DC bus regulation, the power sharing between the converters can also be maintained efficiently. The voltage across the entire system is maintained constant as the rated voltage. This droop controller helps in controlling the power across the load connected to the system. The power control is established using the droop control by maintaining the voltage constant.

2.3.1 DERIVATION OF DROOP EQUATION DC NETWORK

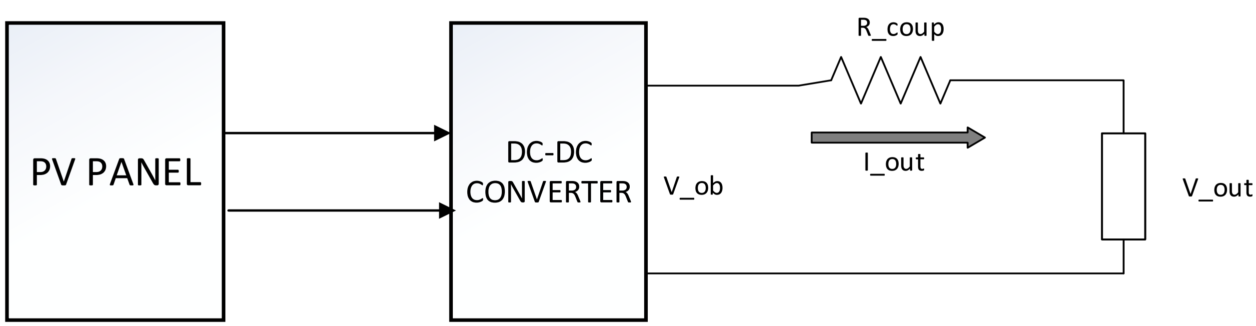

Figure 2. Block Diagram of Proposed Model

A DC-DC converter is used as an interface between the photovoltaic source and the load or the grid system. A coupling resistor is used to connect the converter to the external grid or the output load to provide proper stability to the system. The designed system can be operated in any percentage of the load based on the power demand at the load end of the system. This is obtained by controlling the current required for the specified power demand as the voltage is always maintained constant. The droop controller is used to maintain the voltage constant and to regulate the power based on the demand in the DC network. The basic idea is to regulate the output voltage of the converter so as to maintain the desired load power. By regulating the output voltage of the converter, the output current to the load and to the coupling resistor can be controlled, thus, regulating the output power to the grid based on the load percentage requirement.

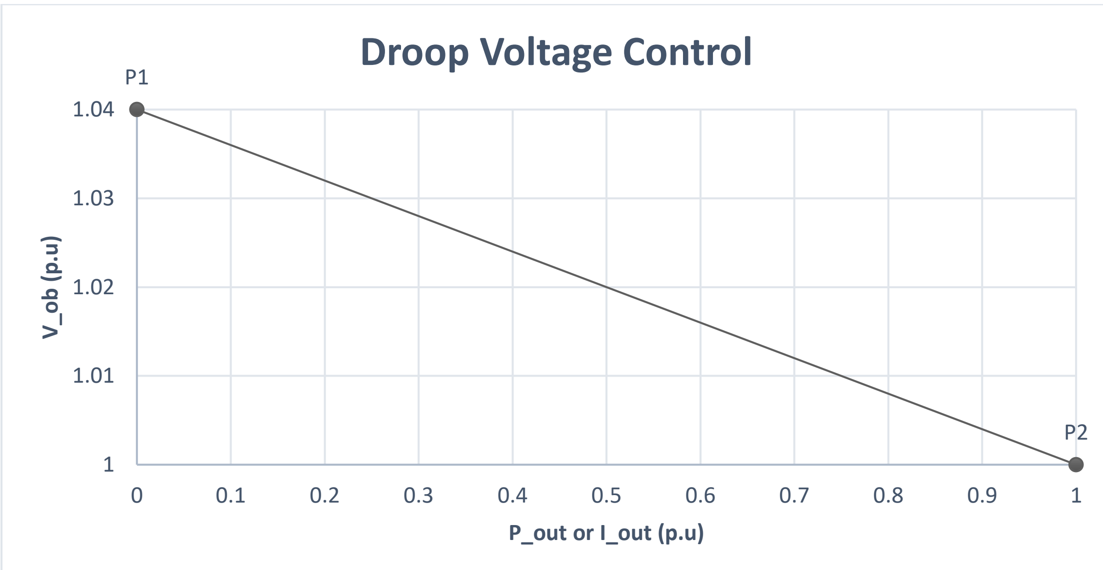

Figure 3. Droop Curve

The entire model is designed based on the fact to maintain the voltage droop to less than 4%. Fig.3 represents the droop curve of the proposed model. The x-axis represents the output power or the load power of the system. This indirectly represents the load current or the output current as the voltage across the entire system is maintained constant throughout. The y-axis represents the output voltage of the converter. Two points P_1 and P_2 are marked on the graph.

When there is no output current, the system is designed to maintain 4% higher droop in voltage and when the system is at rated power, the voltage is also at rated condition. The output voltage at the converter end is dependent on the droop value. From the droop curve, it can be seen that as the output power of the system changes from 0 to the rated value, the output voltage of the converter changes from m*V_{ob} to V_{ob}.

The droop equation is obtained by deriving the relation between the output power or the load power (P_{out}) and the output boost converter voltage (V_{ob}).

$$\frac{P_{out}}{V_{out}} = I_{out} = I_{ob} = \frac{V_{ob} - V_{out}}{R_{coup}} \tag{1}$$

where,

P_{out} is the output power or the load power

V_{out} is the output voltage or the load voltage

V_{ob} is the voltage at the output side of the boost converter

I_{out} is the output current or the load current

I_{ob} is the output current of the boost converter

R_{coup} is the coupling resistance added between the boost converter output side and the load

V_{ob} is derived as a function of P_{out}.

$$V_{ob} = f(P_{out}) = f(I_{out}) \tag{2}$$

Hence, the droop equation is derived as a function of the output current as the output voltage is maintained at the rated value throughout.

The droop controller is designed based on the following equation,

$$V_{ob} = \left(V_{out} + V_{drop_{base}}\right) * \left[1.0 + m * \left(1 - \frac{I_{out}}{I_{out_{req}}}\right)\right] \tag{3}$$

where,

$V_{drop_{base}} = I_{out\_req} * R_{coup}$

m is the droop factor

I_{out_req} is the required load current

Here, $V_{drop_{base}}$ is a calculated value and not a measured value. I_{out_req} is a value given to the controller based on the load percentage required, i.e, when the requirement is full load, then $I_{out\_req} = I_{rated}$ and when the requirement is half load, then $I_{out\_req} = \frac{I_{rated}}{2}$ and so on. Here, the calculated output voltage of the boost converter is the reference voltage for the calculation of the duty cycle value. Hence, the droop equation controls the proper power sharing between the converters. The converter output voltage changes based on the change in the coupling resistance, the connected load and the power demand of the entire system. When the load connected to the system changes, the load current changes and hence there is a change in the converter output voltage. The droop value can be considered as a function of the load current considering negligible coupling resistance.

CHAPTER 3

MODELLING OF POWER SHARING CONTROLLER AND DISTRIBUTED NETWORKS

3.1 DISTRIBUTED GENERATOR BASED DC NETWORK

The control for the power generation using photovoltaics was developed based on the droop control. Here, the resistor is added between the converter and the load to act as a coupling device to the grid. Though the coupling resistance is included, it is usually considered to be negligible when compared to the load resistance. The duty cycle calculations are performed by neglecting the coupling resistance value to assume that the voltage is equal at each node. The PV sharing is achieved by using proper droop coefficient setting. This method allows the PV sources to work in MPPT mode when the DC bus voltage is stable. When the DC bus regulation and power sharing must be performed, the system operated in the VI droop-controlled mode.

The PV array is connected to the DC bus through a DC/DC boost converter. The PV sources can operate in MPPT mode when they are grid connected and they automatically shift when there are changes in the load consumption to regulate the DC bus voltage. During the regulation of the DC bus voltage, the load sharing is performed in centralized control method. Here, the MPPT control and the regulation of the DC bus voltage are unified in the same control configuration. The main advantage of the proposed system is that it does not require transition or switching between the two modes. The input and the output voltages of the PV converters can be maintained with a single duty cycle. The droop coefficient is calculated based on the system and it is noticed that the droop coefficient is inversely proportional to the steady state load current.

3.1.1 SINGLE DISTRIBUTED GENERATOR UNIT

The model is designed by using the PV panel as the energy source and is interfaced to the load or the grid using the DC-DC converter. A coupling resistor is used to interface the converter with the grid. The system is designed to produce a rated power of 3.5kW with a rated voltage of 400V. The input source is set to generate a voltage of 220V. The controller generates the signal to the duty cycle for the efficient working of the system by maintaining the rated output power and voltage.

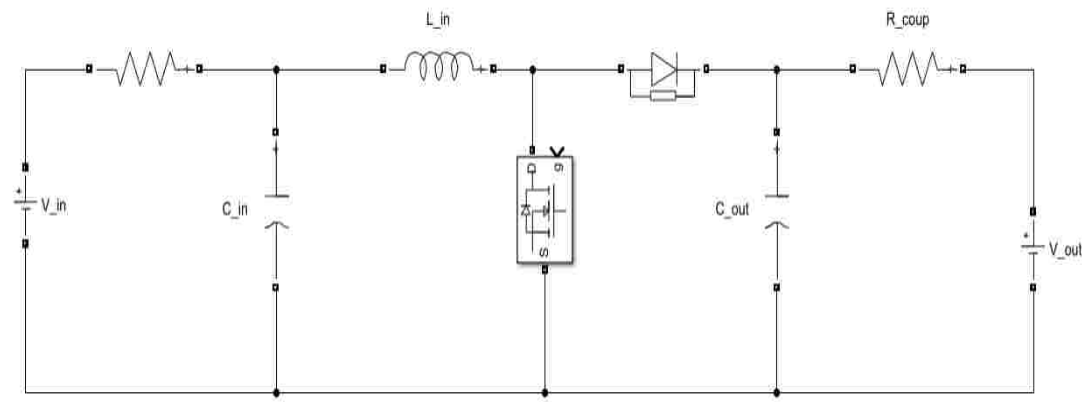

Figure 4. Matlab Model of Proposed Single Unit System

The value of the capacitors and inductors connected to the system are calculated as follows.

$$M(D) = \frac{V_{dc}}{V_{in}} = \frac{1}{1-D} \tag{4}$$

From (1),

$$D = \frac{V_{dc}-V_{in}}{V_{dc}} \tag{5}$$

Here, V_{dc} = 400V and V_{in} = 220V, hence

$$D = \frac{400-220}{400} = 0.45 \tag{6}$$

The value of capacitance is calculated using the formula,

$$C = \frac{D*V_{dc}}{R*2\Delta V_{dc}*f_s} \tag{7}$$

Here,

$R = \frac{V_{dc}^2}{P} = \frac{400^2}{3.5k} = 45.714\Omega$

$\Delta V_{dc} = 5\% * V_{dc} = 0.05 * 400 = 20V$

f_s =20000 Hz which is the switching frequency

Hence (3) becomes,

$$C_{out} = \frac{0.45*400}{45.714*2*20*20000} = 4.922\mu F \quad (8)$$

The inductance value can be calculated using the formula,

$$L = \frac{D*V_{in}}{2\Delta i_l * f_s} \quad (9)$$

Here,

$\Delta i_L = 15\% * I_{dc} = 0.15 * 8.75 = 1.3125A$

Hence (4) becomes,

$$L_{in} = \frac{0.45*220}{2*1.3125*20000} = 1.886mH \quad (10)$$

The L and C values are calculated as above to maintain the rated voltage across the system by maintaining the calculated duty cycle.

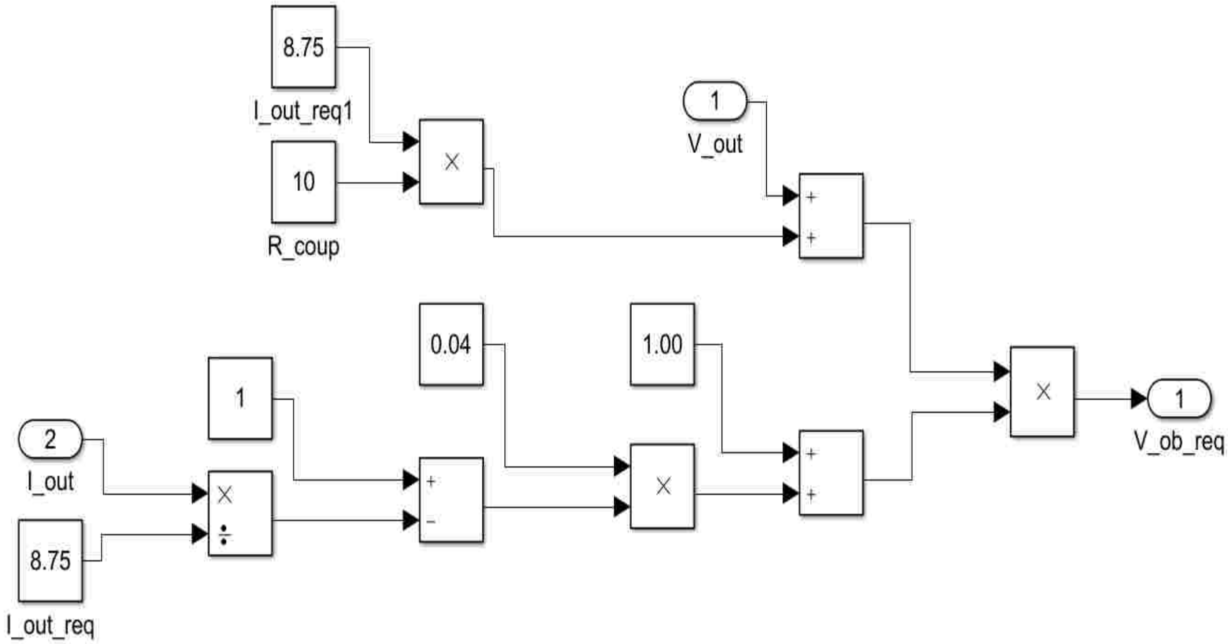

Figure 5. Droop Controller Block

The output voltage and current are monitored in the droop controller block. The voltage and current across the load are given as the input to the droop controller. The droop controller is designed based on the equation (8). Here the system is designed for full load rating and hence the required output current is taken as 8.75A. This block generates the required output voltage for the converter to maintain the rated voltage across the system. The calculated signal is given to a PWM generator for the generation of the duty cycle to be given to the switch connected in the DC-DC converter.

3.1.2 PARALLEL UNITS BASED DISTRIBUTED GENERATORS

Two distributed generators are connected in parallel to the load and the output grid. The power sharing between the two generators is controlled using the droop control applied to the system. The working of the parallel unit is similar to the working of the single unit. Here the power to the load is shared between converter1, converter2 and the grid. The total power demand is shared efficiently between the converters and the grid even if neither of the converters work in full load conditions. The droop controller and the duty cycle generators are built similar to the single unit distributed generator.

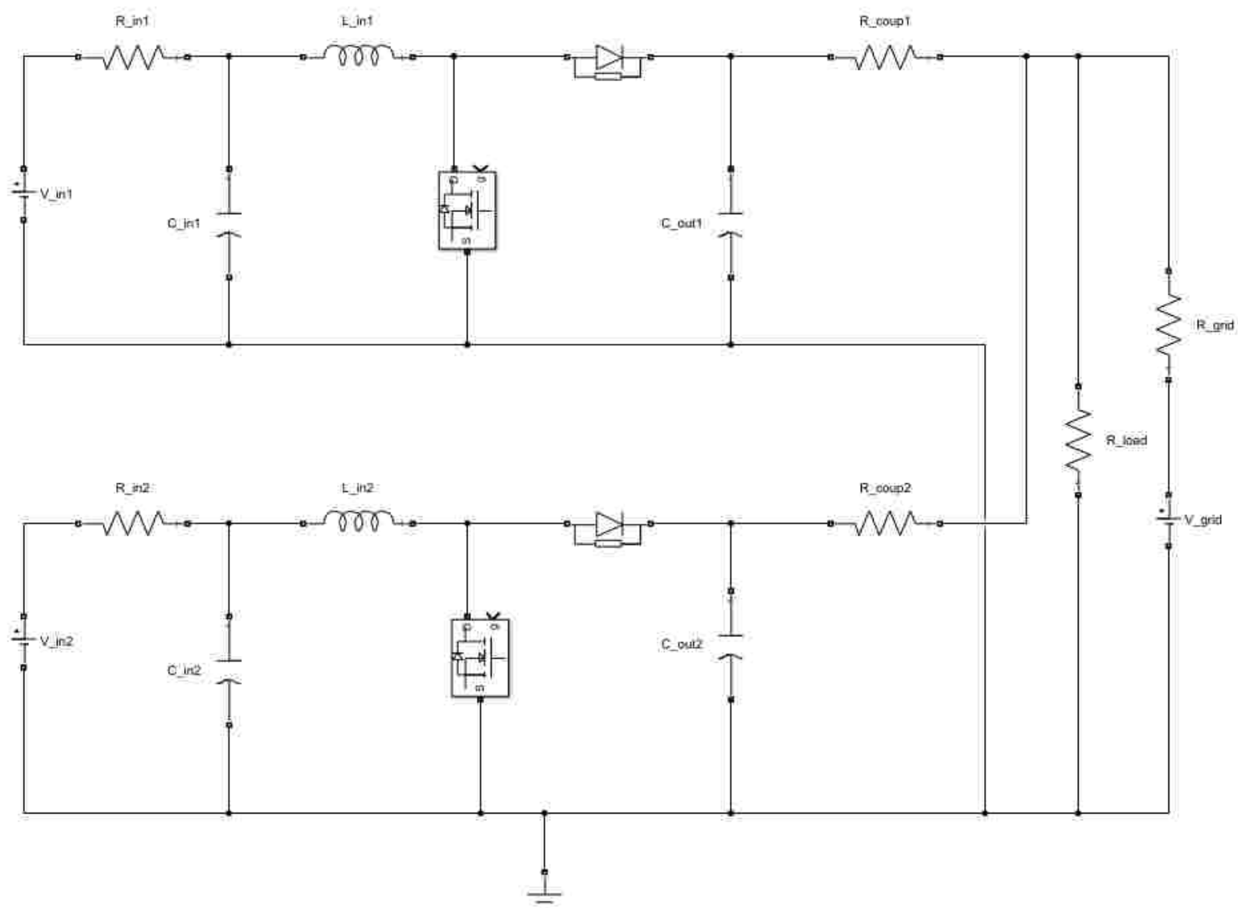

Figure 6. Matlab Model of Parallel Connected Distributed Generators

Photovoltaic generation system is the energy source for both the units. The distributed generators are connected in parallel to enhance the power sharing between the converters. The converter is used to boost the voltage to the rated value. The controller of both the units is set up in such a manner that it can produce the required output power even if one of the unit connected in parallel does not operate in full load capacity. This enhances the entire grid system to produce continuous power flow to the load. This in turn reduces the instability caused in the system and also reduces the risk of blackout, as the load power can be shared between the converters efficiently.

3.2 THREE PHASE RECTIFIER WITH CLOSED LOOP CONTROL

The rectifier is a device that converts AC signal to DC signal where the switching device carries out the process of rectification. The three phase rectifier designed is a control system where the output voltage and the output current is controlled by using a closed loop control. A PWM based rectifier is designed with fast responses to changes in the input current and in the load while operating with unity power factor and sinusoidal AC supply currents to produce a regulated DC supply. Here a closed loop control is used which helps in generating a regulated output voltage[44]. The output filter is designed in such a way to remove the harmonics from the output signal waveform.

The closed loop control is being done to monitor the output voltage and also to maintain a steady output waveform. There are various methods in closed loop or feedback control of the output voltage and current which includes voltage controlled rectifier, current controlled rectifier, etc. The harmonics and the reactive power causes decrease in the output voltage and current and hence the control of the output voltage and current is required for the efficient working of the controller.

The rectifier circuit works with high efficiency and is very robust but result in total harmonic distortion (THD) of nearly 30% which brings down the efficiency of the entire system. The entire design is carried out to obtain a harmonic distortion of less than 5%. Here bidirectional flow of current is seen and it is possible with the help of the input LCL circuit.

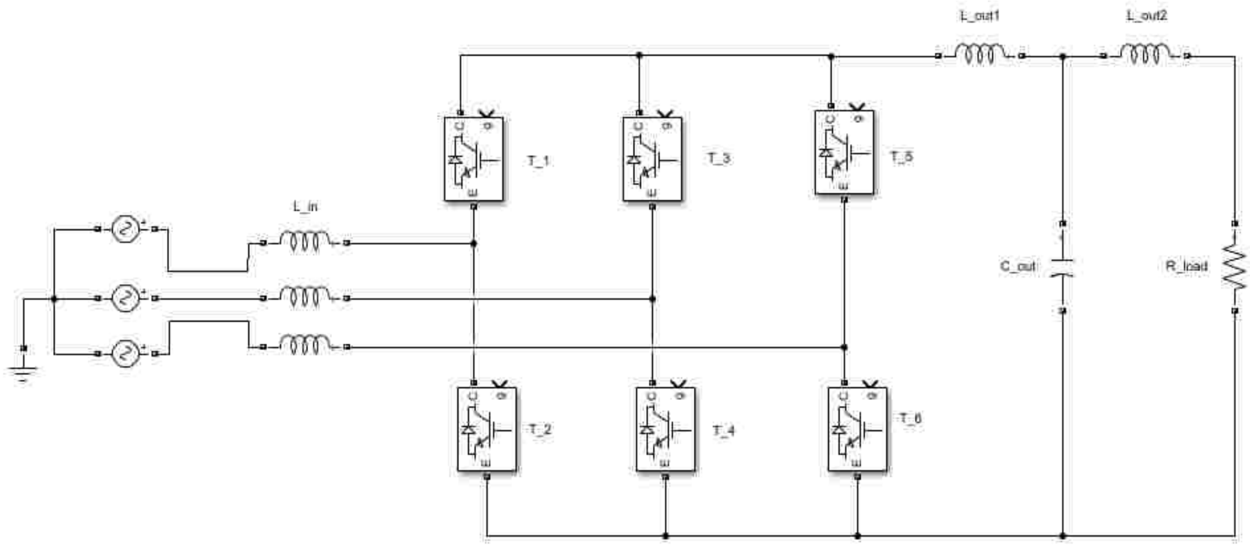

Figure 7. Matlab Model of Three Phase Rectifier

The rectification process is carried out by the switching circuit which consists of 6 IGBT switches. The input three phase AC signal is given into the rectification unit or the switching circuit, which rectifies the AC voltage signal into DC signal. Only one switch from the series, (T_1, T_3, T_5) is turned on at a time, and the similar is followed for the other series (T_2, T_4, T_6). Both the top and the bottom series works simultaneously for the process of rectification. The gate signals for the 6 switches are produced by the signal generator with the input from the voltage controller. These gate signals determine which switch has to be turned on and turned off. The gate signal is obtained based on the input from the voltage controller circuit.

The AC supply is given to the switches through an LCL filter. Hence the voltage control has to be carried out by determining the voltage and current before and after the introduction of the LCL filter. The inputs given to the voltage controller include the three phase input voltage from the supply, three phase input current from the supply, the three phase voltage across the delta connected capacitor in the input side, and the input current given to the switches which is after passing through the LCL filter and the output DC voltage. The closed loop control is carried out by the voltage controller. The PI controller is used to generate the error signal for the reference voltage signal. The AC current control system indirectly controls the AC source current by controlling the converter three phase input voltage and also the three phase input current. The output voltage across the load is given to the comparator which compares it with the reference value of 400V. The error signal is given to the PI controller, from which the output reference voltage is generated.

The output from the voltage controller is given as the input to the signal generator. A 2-level PWM generator is used for the signal generation. The 2-level PWM generator generates 6 pulses when a three phase signal is given as the input. The reference voltage signal, which is a three phase signal, is given as the input to the PWM generator. The output from the PWM generator is given to a demux component which splits the signal to 6 such that to be given to the 6 gates of the switching circuit.

The voltage controller block is designed based on the following equations. The reference input voltage is given by,

$$V_i^* = v_{if}^* + v_{ih}^* \tag{11}$$

Here,

$$v_{if}^* = v_s - 2(Ru_e + \omega L u_r)I_s^* \tag{12}$$

where,

v_s, u_e, u_r are the input three phase voltage given to the rectifier.

R is the internal resistance connected in the system

L is the inductance value connected to each line

ω is the angular frequency of the input

I_s^* is the reference signal from the PI controller after multiplying with the input.

The value of v_{ih}^{*} is usually a constant and changes based on the application. Here the value is taken as 0.

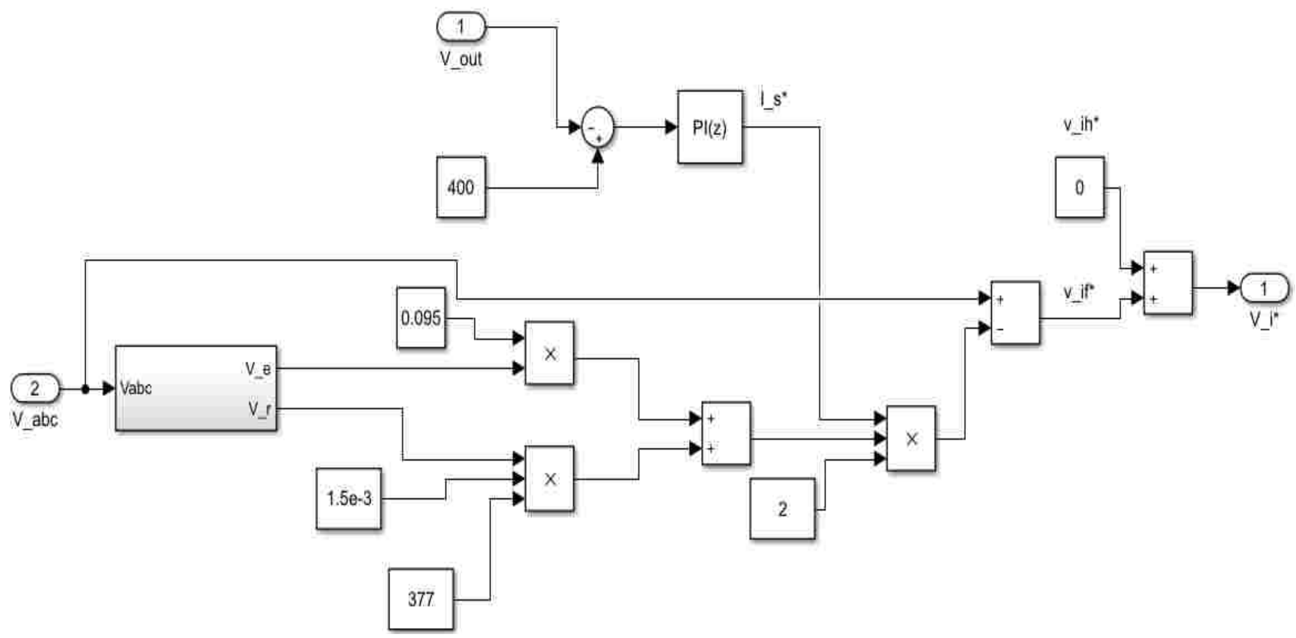

Figure 8. Voltage Controller Block

3.2.1 FILTER DESIGN

An LCL filter has been used for better harmonic reduction and output waveform shaping. The transient response of the system is also determined by the output filter connected to the load and the switching circuit. The filter also helps in reducing the switching frequency harmonics produced in the system.

The transfer function of the LCL filter is given by,

$$H(s) = \frac{1 + C_{out}s}{L_{out1}L_{out2}C_{out}s^3 + C_{out}(L_{out1+}L_{out2})s^2 + (L_{out1+}L_{out2})s} \tag{13}$$

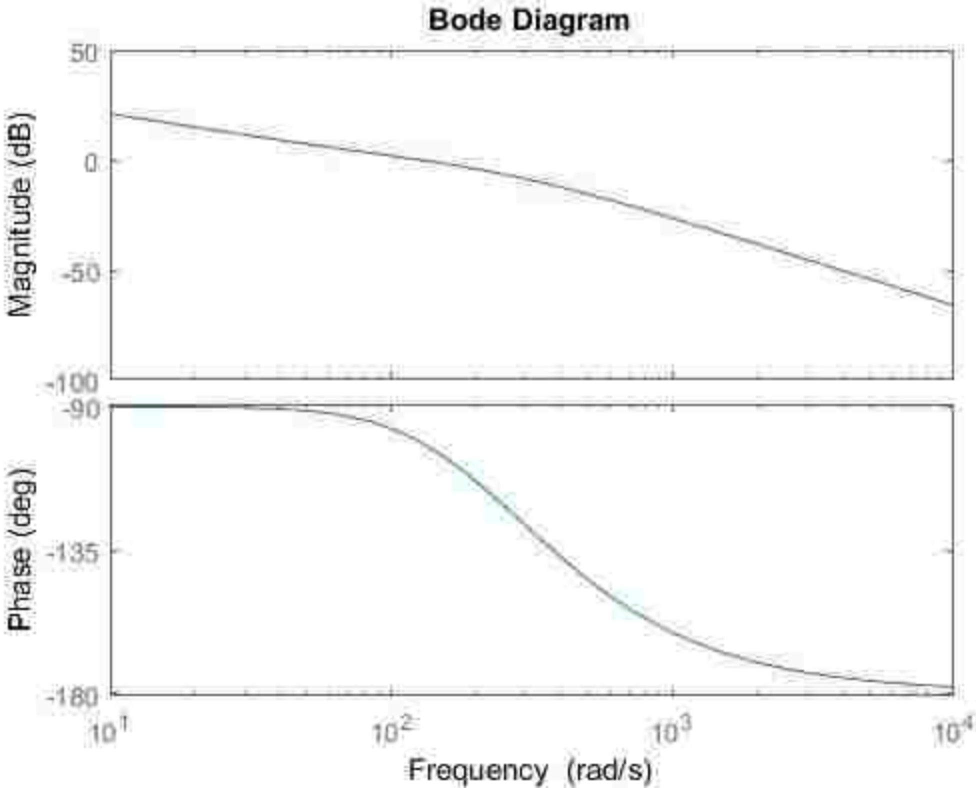

Figure 9. Bode Plot of LCL Filter

CHAPTER 4

SIMULATION RESULTS

4.1 SINGLE UNIT DISTRIBUTED GENERATOR

Simulation has been performed using the MATLAB/SIMULINK software. Fig.10 shows the Simulink model of single unit distributed generator. The input source is considered to be the PV source and the output voltage source represents the grid connection to the converter. The coupling resistor acts as the interface between the converter and the grid system. The value of inductors and capacitors connected in the system are calculated using the duty cycle calculation. The measured values of voltage and the current output is given to the droop controller block for the generation of the required converter output voltage signal. This signal is in turn given to the duty cycle generator for the duty cycle signal generation, which is given as the switching signal to the connected MOSFET switch in the DC-DC converter.

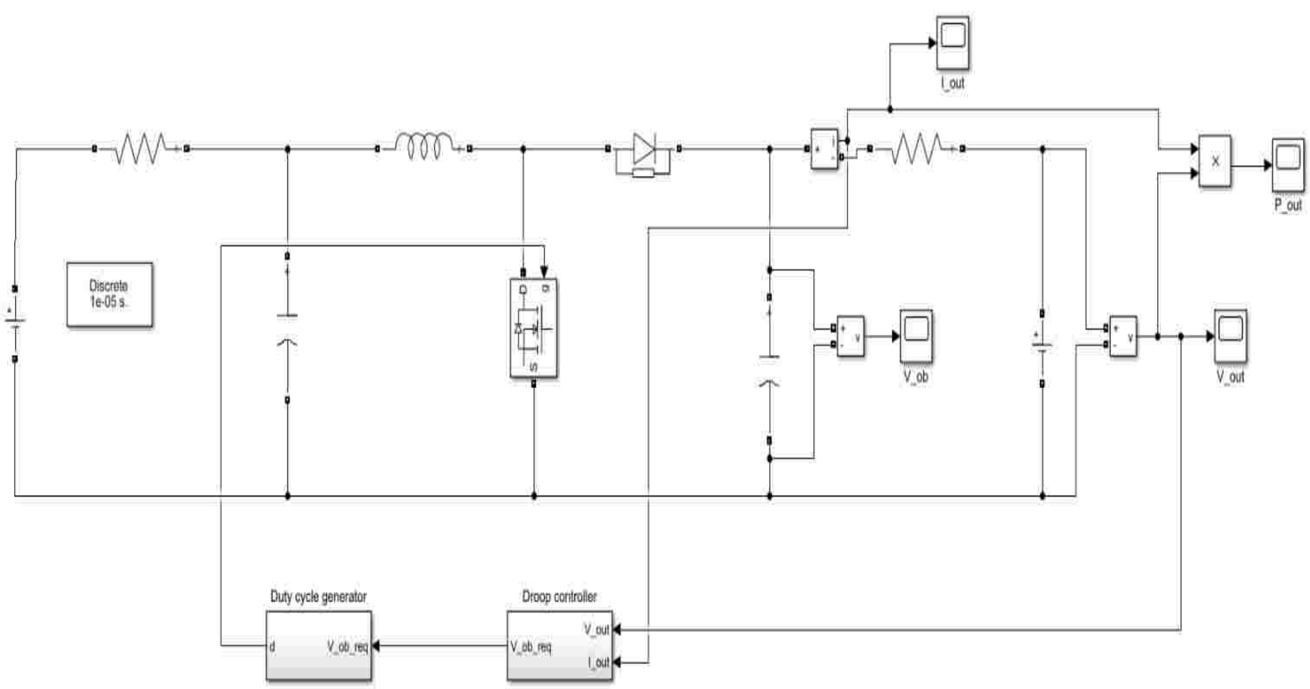

Figure 10. Simulink Model of Single Unit Distributed Generator

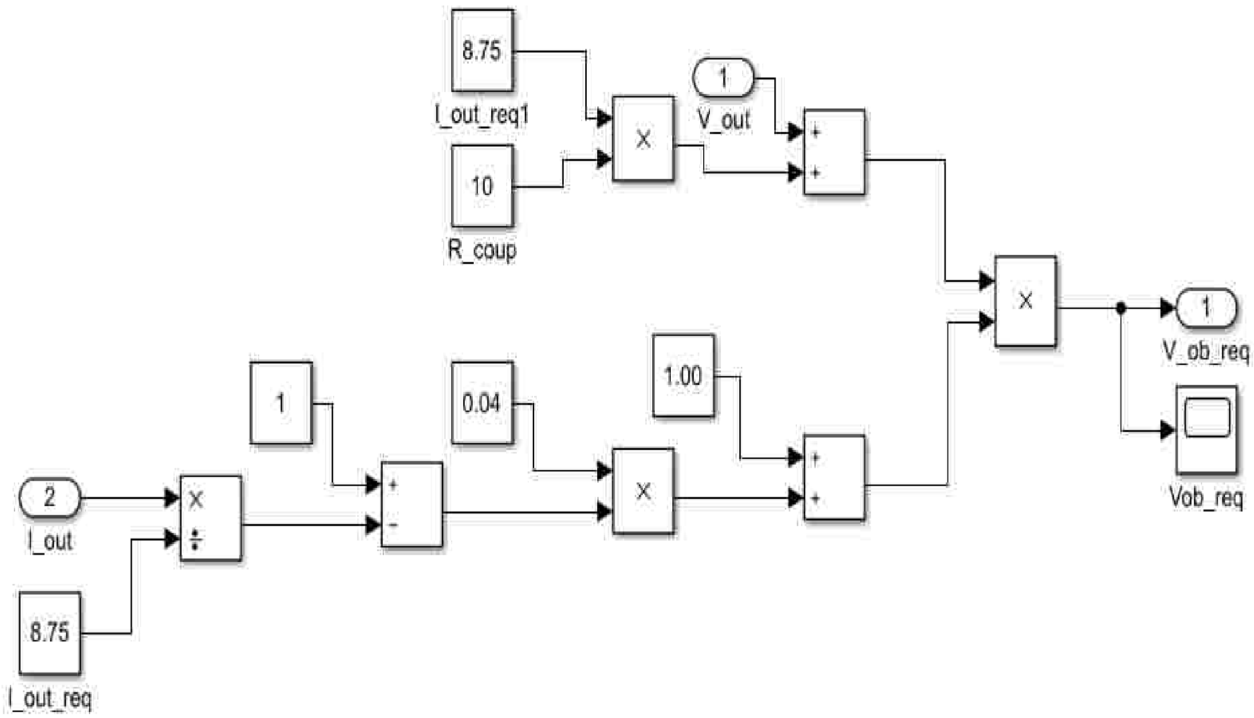

Figure 11. Simulink Model of the Droop Controller Block

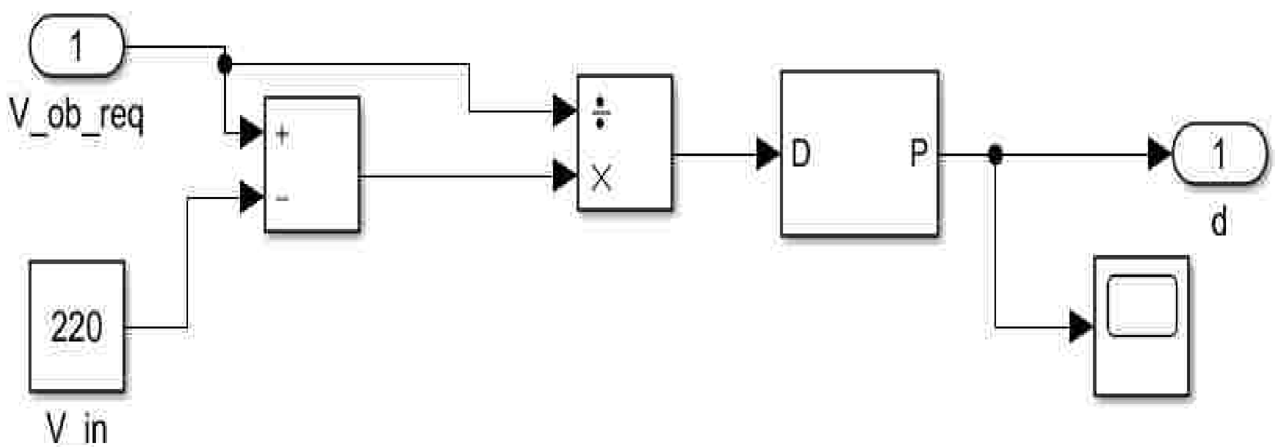

Figure 12. Simulink Model of the Duty Cycle Generator Block

The droop controller block is designed based on the droop equation generated. It generates the signal required for the duty cycle generation based on the load demand. The value changes based on the changes in the output load power. In the duty cycle generator block, a PWM generator is used to generate the switching signal for MOSFET switch. The standard duty cycle equation is used to build the duty cycle generator block to avoid instability issues in the system. The duty cycle is given to the switch to enable the conversion operation of the boost converter. The components are designed to obtain rated values of output voltage and power.

Table 1. Component Values of Simulink Single Unit Circuit

V_{in}	220V
R_{in}	0.001Ω
C_{in}	100nF
L_{in}	1.886mH
C_{out}	4.922µF
R_{coup}	10Ω
V_{grid}	400V

Figure.13 represents the output waveforms of the single unit system. The per unit values are used to generate the waveforms. The base value of the output voltage of converter is 487.5V, output current of converter is 8.75A and output power of converter is 3.5kW. The single unit system generates the rated values of power for all types of load values. The coupling resistance changes based on the load connected to the system. The single unit system is connected to a grid at the load side. The output voltage of the converter has to be higher than the rated voltage to maintain the drop across the coupling resistance. Hence the output voltage of the converter is maintained at 487.5V. This in turn maintains the rated voltage and power of the single unit system. The primary peak of the voltage and power is negligible as it is maintained within allowable limits and the system then continues to maintain the rated voltage with the least harmonics.

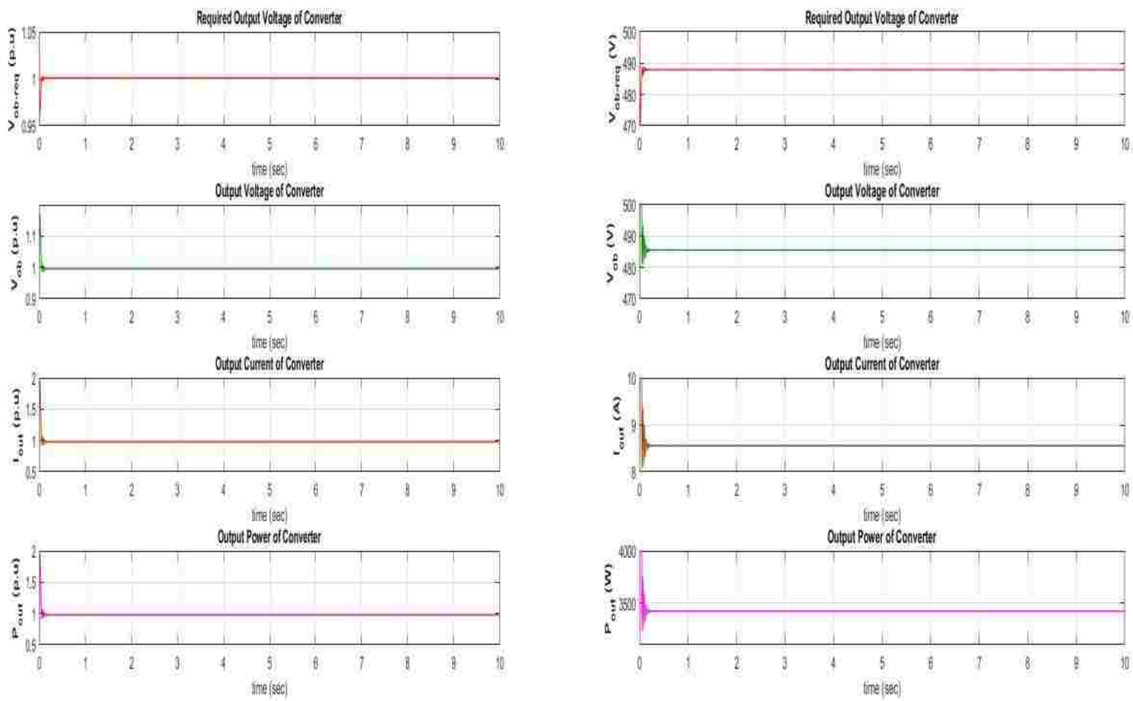

Figure 13. Output Waveforms of Single Unit Generator

The measured output values are presented in Table.2. The output current causes a voltage drop of 85.5V which is compensated by the converter output voltage of 485.6V. When there is a change in the output load, the output current changes to compensate the change in the load and to meet the system requirement.

Table 2. Measured Output Values of Single Unit

V_ob_req	487.9V
V_ob	485.6V
I_out	8.55A
P_out	3425W

4.2 PARALLEL UNITS BASED DISTRIBUTED GENERATOR SYSTEM

Two single unit systems are connected in parallel to the load and the grid system. Fig.15 represents the Simulink model of the parallel units based distributed generator system. The input energy sources are considered to be PV generator systems. A constant voltage source is used to represent the output grid system.

All the values are similar to the single unit systems except for the grid and the load values. The parallel units based system is designed to meet the power sharing requirements. The load power or the power demand is equally divided among the distributed generators based on the working conditions of the generators. The power is contributed equally by the generators when they are operating in full load conditions. When any of the generator experience maintenance or technical interruptions, it would only be able to generate load lower than the full load capacity. During this condition, the converter at full load generates the rated power and the remaining power demand is met by the other converter and the grid. As one of the converter's capacity decreases, the input power from the grid increases to meet the power demand.

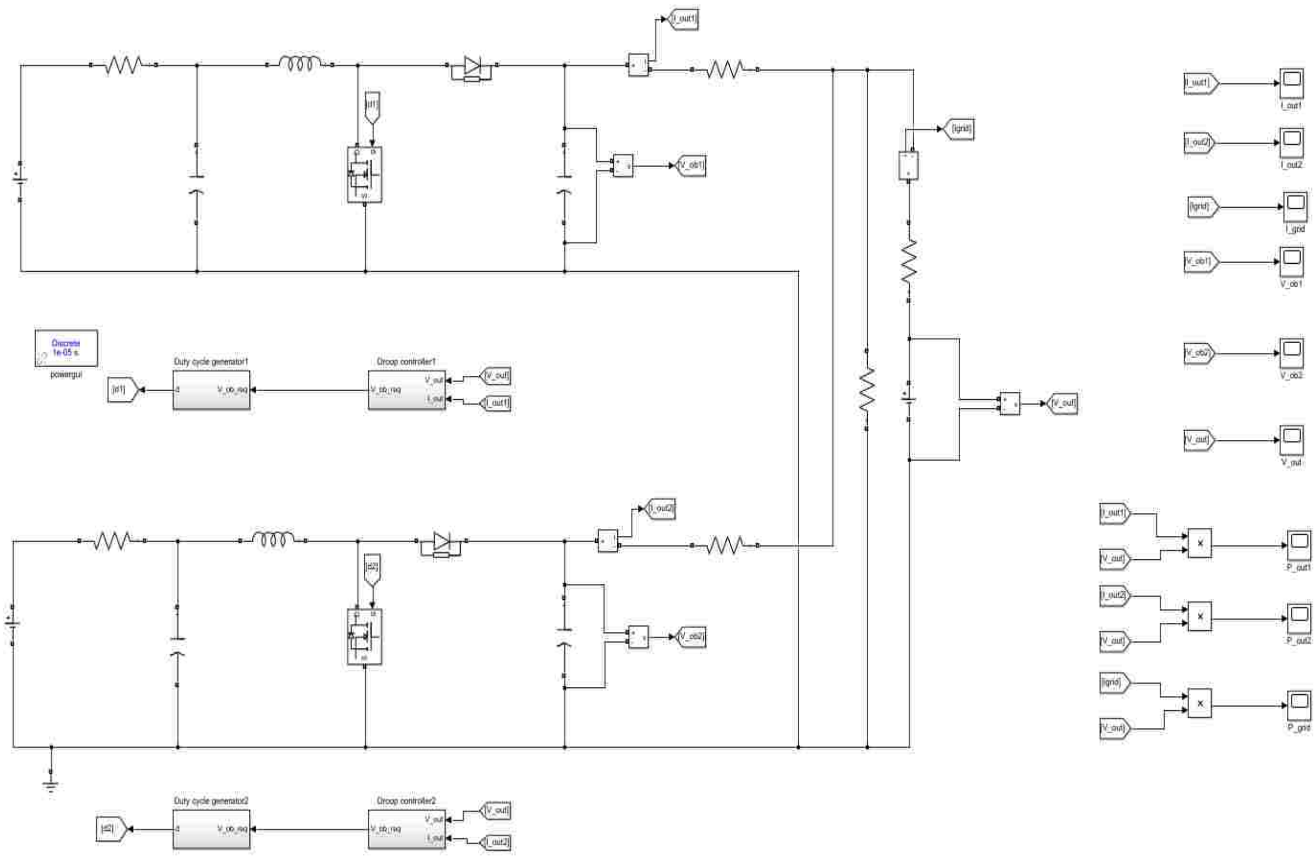

Figure 14. Simulink Model of Parallel Units based Distributed Generator Systems

The performance of the parallel units is tested for various values of grid resistance and the minimum value of grid resistance is estimated to be 0.2Ω to deliver efficient performance of power sharing.

Table 3. Component Values of Simulink Parallel Units Circuit

R_{grid}	0.2Ω
R_{load}	16Ω
V_{grid}	400V

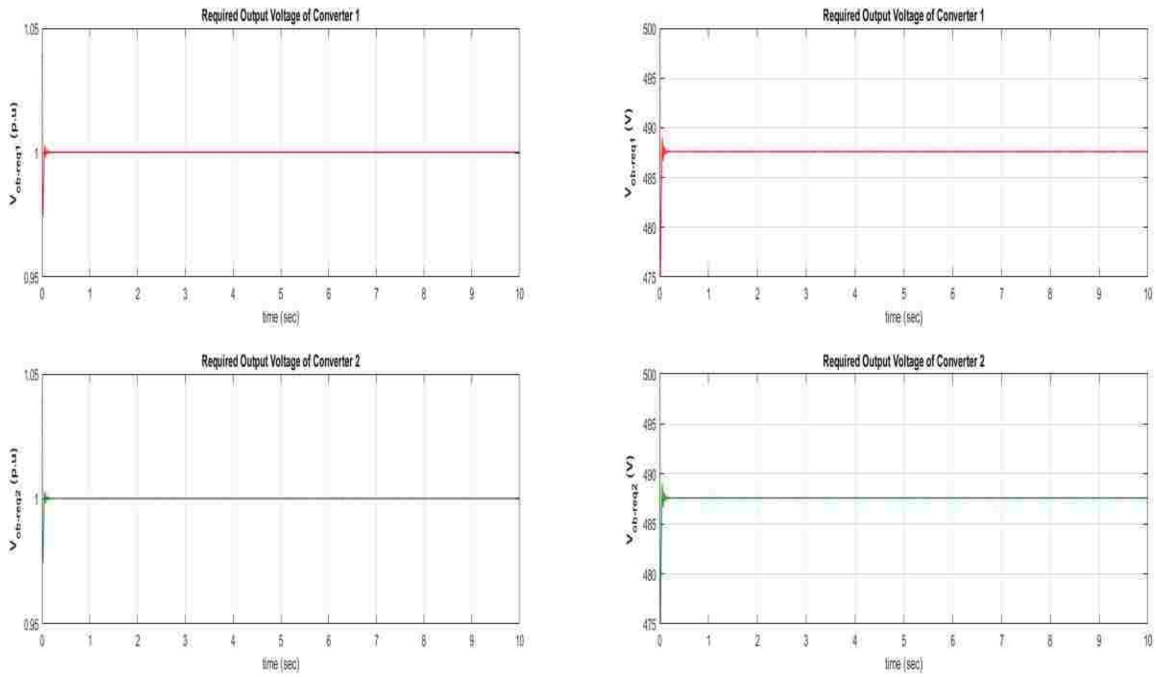

Figure 15. Required Output Voltage Waveform of Converters

The required output voltage is the value calculated using the droop controller block and is always maintained to meet the drop across the coupling resistance. The system provides efficient power sharing as the values across both the converters are equal. Fig.16 represents the measured output voltage of the converter. The system shows only a drop of 2.11V between the required output voltage and the measured output voltage of the converter. The power sharing between the converters is entirely controlled by the droop controllers of the converters. This indicates that the calculated output voltage of converter is the key factor for the power control between the distributed generators. The base value of output voltage of the converters are taken as 487.5V to meet the voltage drop across the coupling resistance of 10Ω.

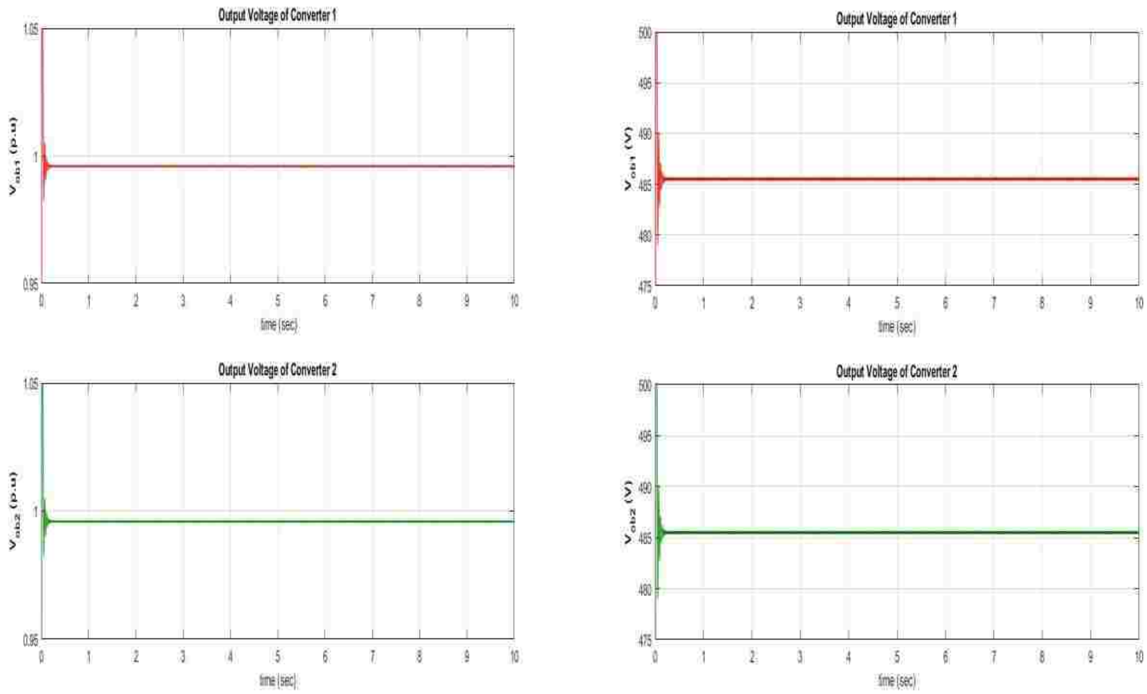

Figure 16. Measured Output Voltage Waveform of Converters

The output voltage of the converter changes for the change in load and for the change in the coupling resistance. Fig.17 represents the current waveform of the converters and the grid. All the waveforms are graphed using the per unit values of the system. The base value of output current of each of the converters is taken as 8.75A and the base value of the input current from the grid is taken to be 7.5A. The voltage across the entire system is maintained to a constant of 400V and so the power control is carried out by controlling the output current of the converter. As the converters changes from no output power to full load power, the converter output current must change from 0 to 8.75A, the rated value of output current. The waveform indicates that both the converters generate equal amount of output current to maintain the stability in power sharing between the converters.

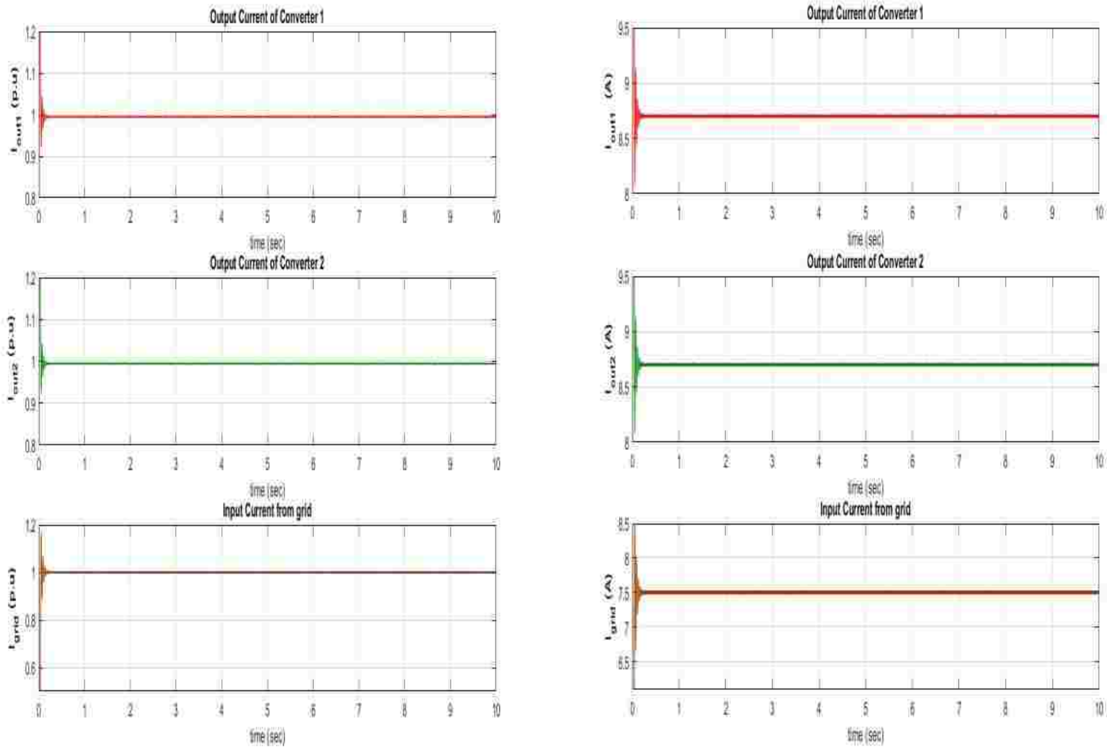

Figure 17. Measured Current Waveform of Converters

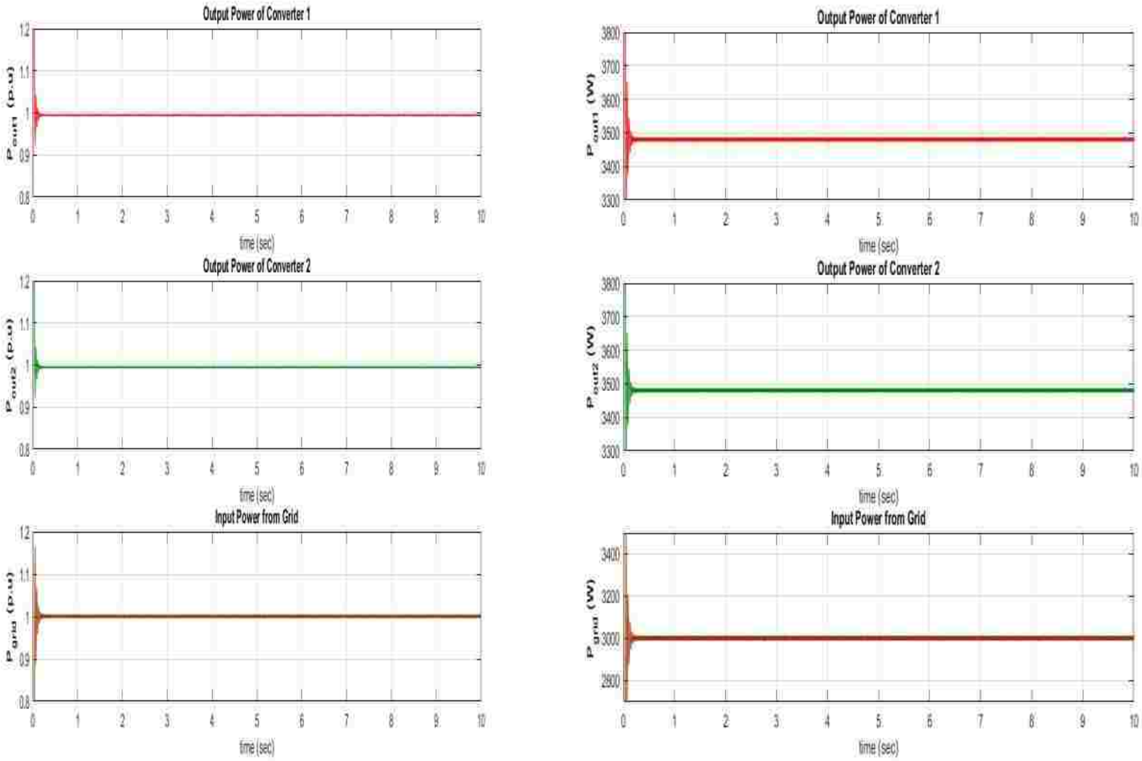

Figure 18. Measured Power Waveforms of the Model

The power output waveforms are represented in Fig.18. The base values of the output power of each converter is taken as 3.5kW and the base value of the input power from the grid is taken as 3.0kW. The parallel converters exhibit equal power sharing among the converters. The converters operate at a full load condition delivering a power output of 3.5kW each. The load connected to the system is 10kW. And hence the remaining power is given to the system by the grid which is about 3.0kW. Even if there is an interruption in any of the converter system, the other converter shares the power efficiently and the remaining power is contributed by the grid. The performance of the system is analyzed by measuring the output current and power of each of the converter. The output current and power contribution of each of the converters connected to the load are equally shared and the system stability is maintained.

Table 4. Measured Output Values of Parallel Units

V_ob_req1	487.61V
V_ob_req2	487.61V
V_ob1	485.5V
V_ob2	485.6V
I_out1	8.70A
I_out2	8.70A
I_grid	7.50A
P_out1	3480W
P_out2	3480W
P_grid	3000W

4.3 THREE PHASE RECTIFIER WITH CLOSED LOOP CONTROL

The three phase rectifier is designed with closed loop control technique where the output voltage is taken as the feedback for the controller. Six IGBT switches are used to maintain the output voltage to a rated value of 400V. The efficient switching is ensured by maintaining the required control in the system using the voltage controller. The voltage controller is designed so as to produce the rated voltage of the system. The efficiency of the output DC voltage is monitored by monitoring the thyristor harmonic distortion in the output voltage signal and maintain it below 5% of the rated voltage. The entire system works in a closed loop control as the output voltage is used to determine the switching signal for the input signal provided. The output signal is given to the voltage controller block which generates the reference signal for the generation of the switching signal in the signal generator block.

The voltage controller block is developed based on the voltage control equation generated. The input three phase signal and the output DC signal is given as the inputs to the voltage controller block. The Proportional and Integral (PI) controller is used to remove the steady state error in the signal and to avoid its persistence. The output signal is compared with the reference signal of 400V and the error signal is given to the PI controller. The voltage controller block generates the reference signal to be given as the input to the signal generator block. The signal generator uses a 2-level PWM generator for the generation of the switching signals to be given to the 6 IGBTs connected in the switching circuit.

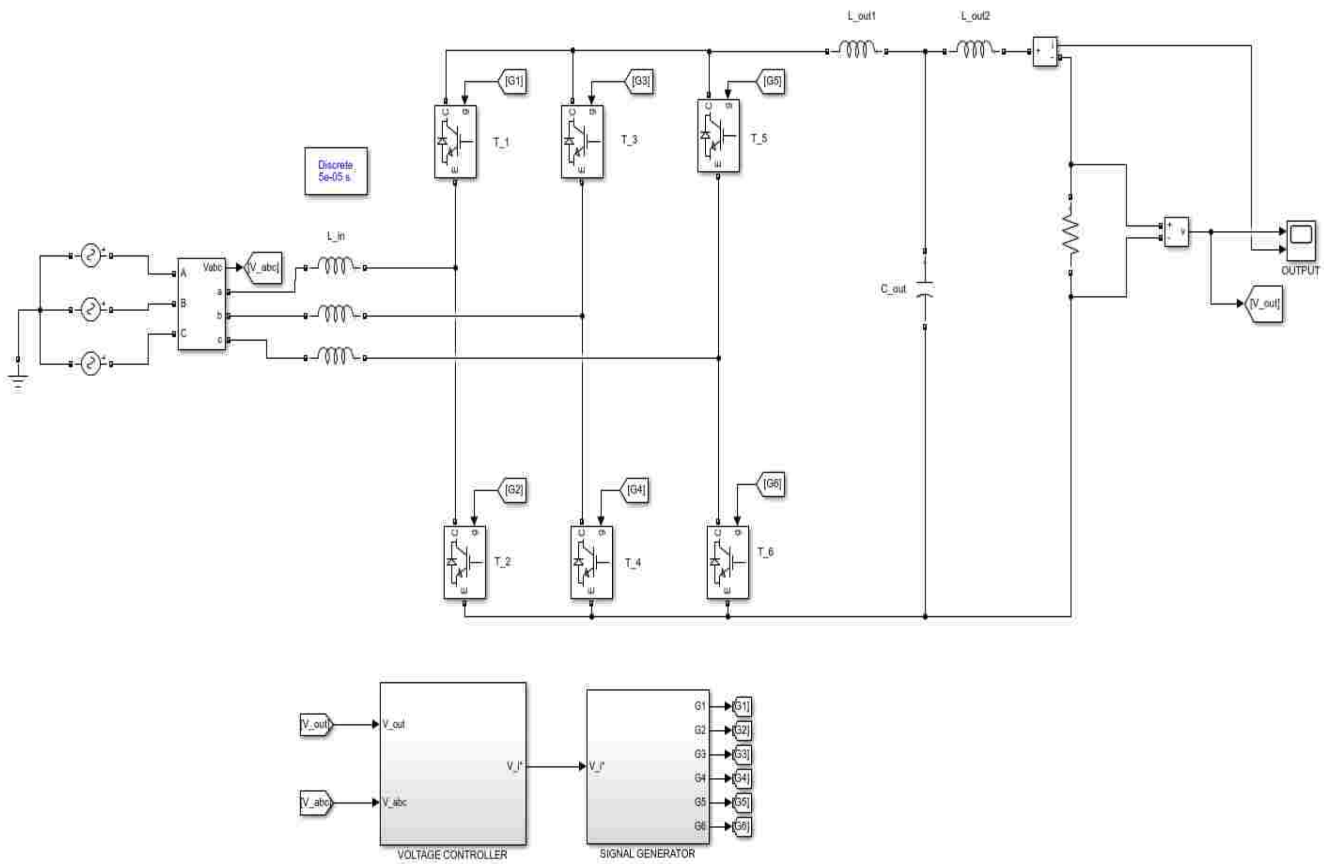

Figure 19. Simulink Model of Three Phase Rectifier with Closed Loop Control

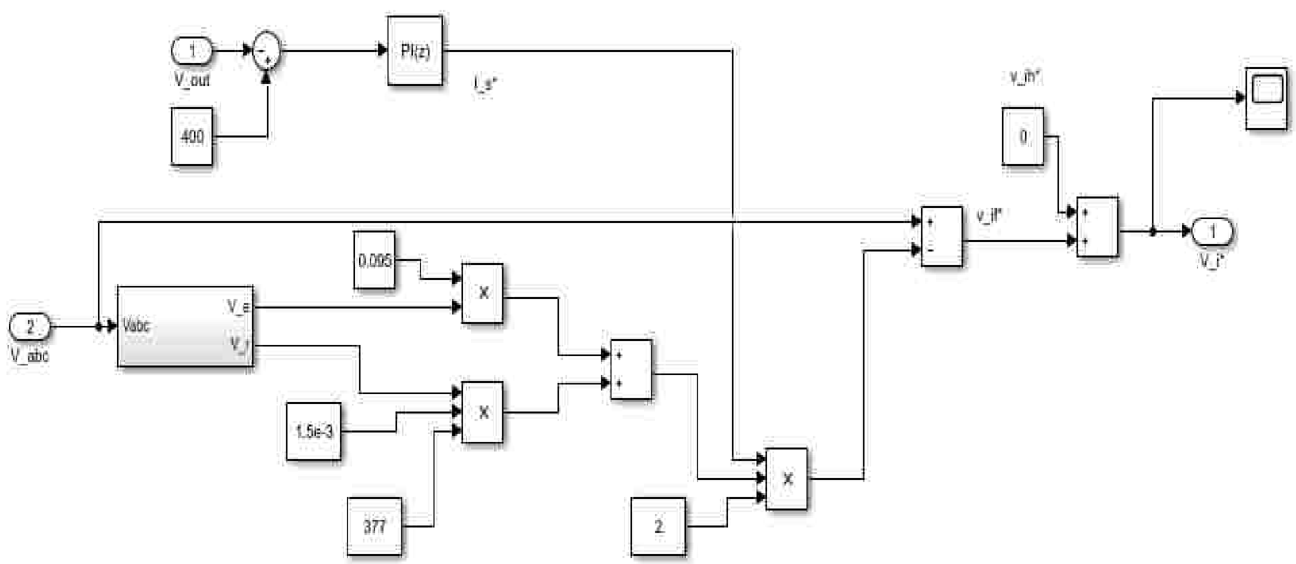

Figure 20. Simulink Model of the Voltage Controller Block

The voltage controller block is designed to eliminate the error occurring in the output voltage and to maintain the output voltage at a constant value. The voltage controller block generates the reference signal for the signal generator. The requirement of the gate signal is to turn on only two IGBTs at a time for the efficient switching and generation of the rated output voltage.

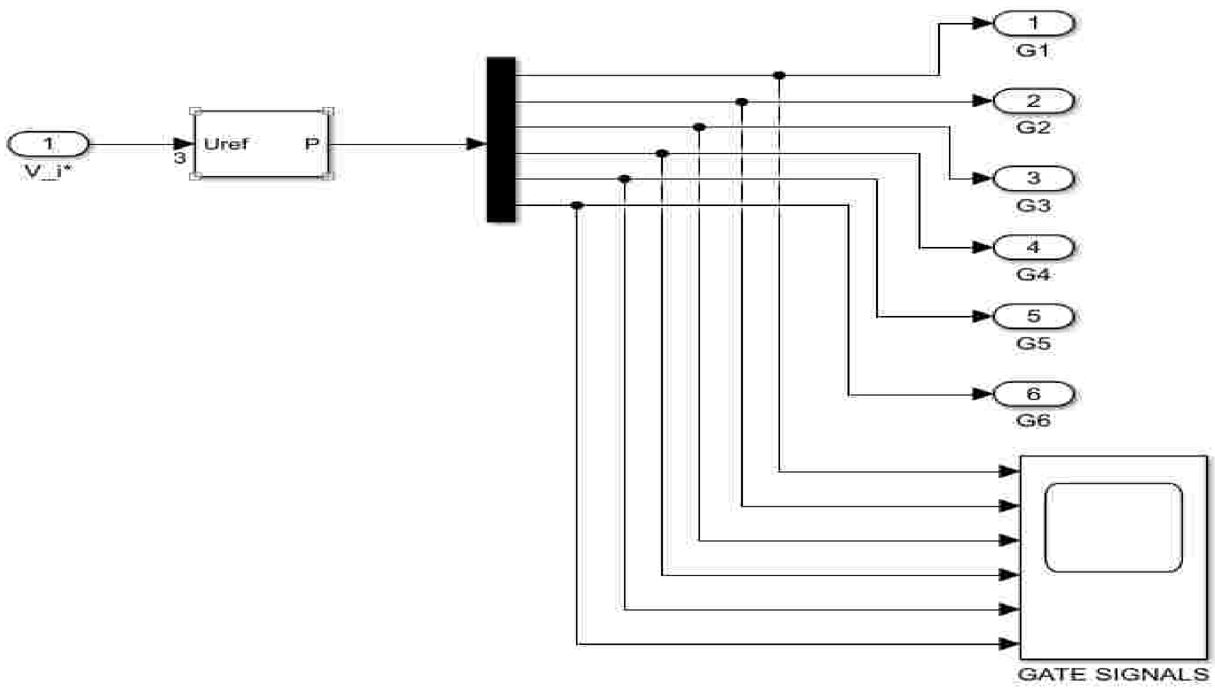

Figure 21. Simulink Model of Signal Generator Block

The component values of the rectifier are estimated and calculated to generate the rated output voltage and current. The input inductance value is set to a very low value of 0.1mH to eliminate any internal harmonics from the input supply.

Table 5. Component Values of Simulink Three Phase Rectifier

V_{in}	208V
L_{in}	0.1mH
L_{out1}	4.5mH
L_{out2}	4.5mH
C_{out}	4500µF
R_{load}	10Ω

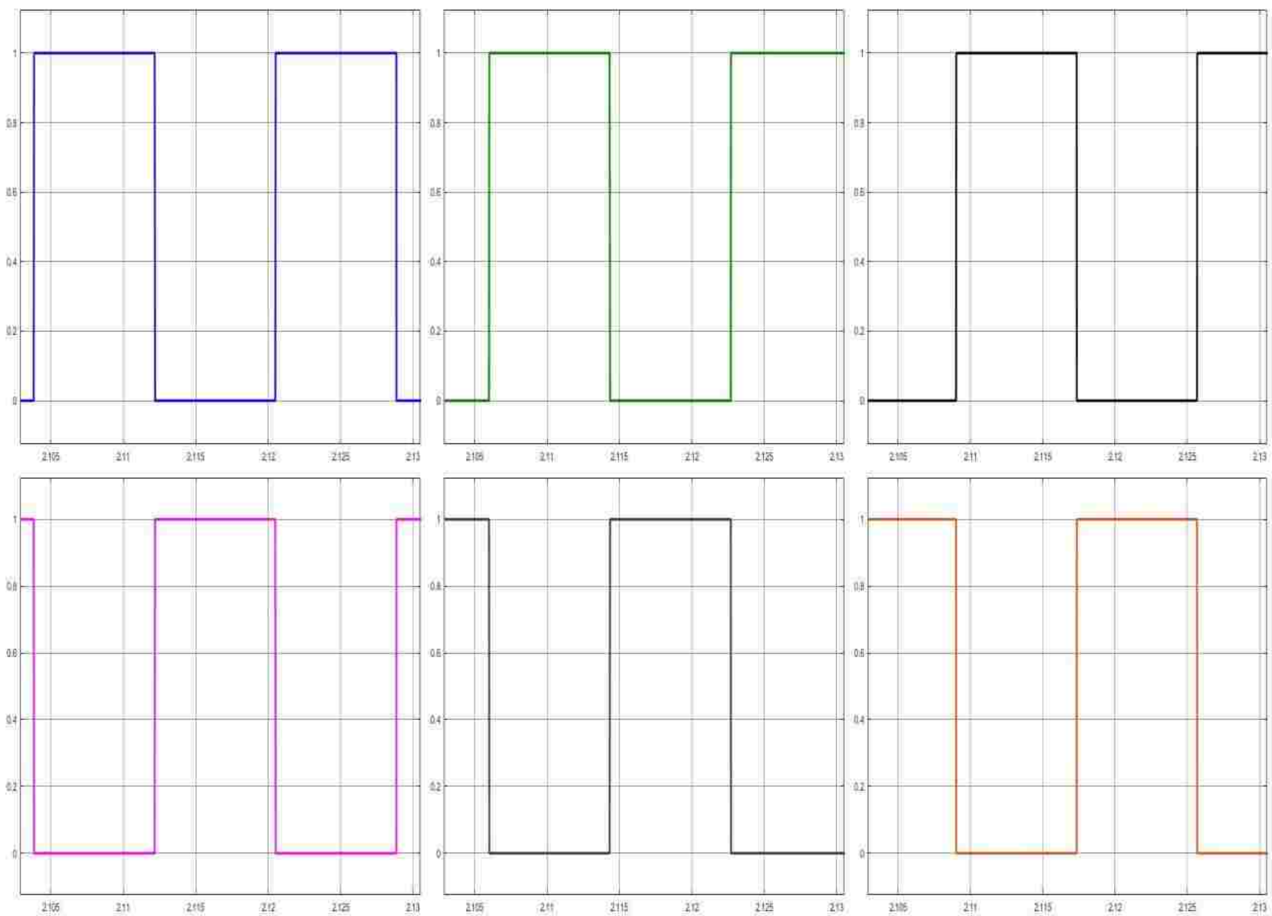

Figure 22. Waveform of Switching Signals

The system is built to maintain the rated voltage of 400V as output and the current is maintained at 40A for a load of 10Ω. The output waveforms are graphed in per unit values where the base value of output voltage is taken as 400V and the base value of output current is taken as 40A. The measured value of output voltage is seen to oscillate with a peak of 405V and lower peak of 395V which is a negligible oscillation.

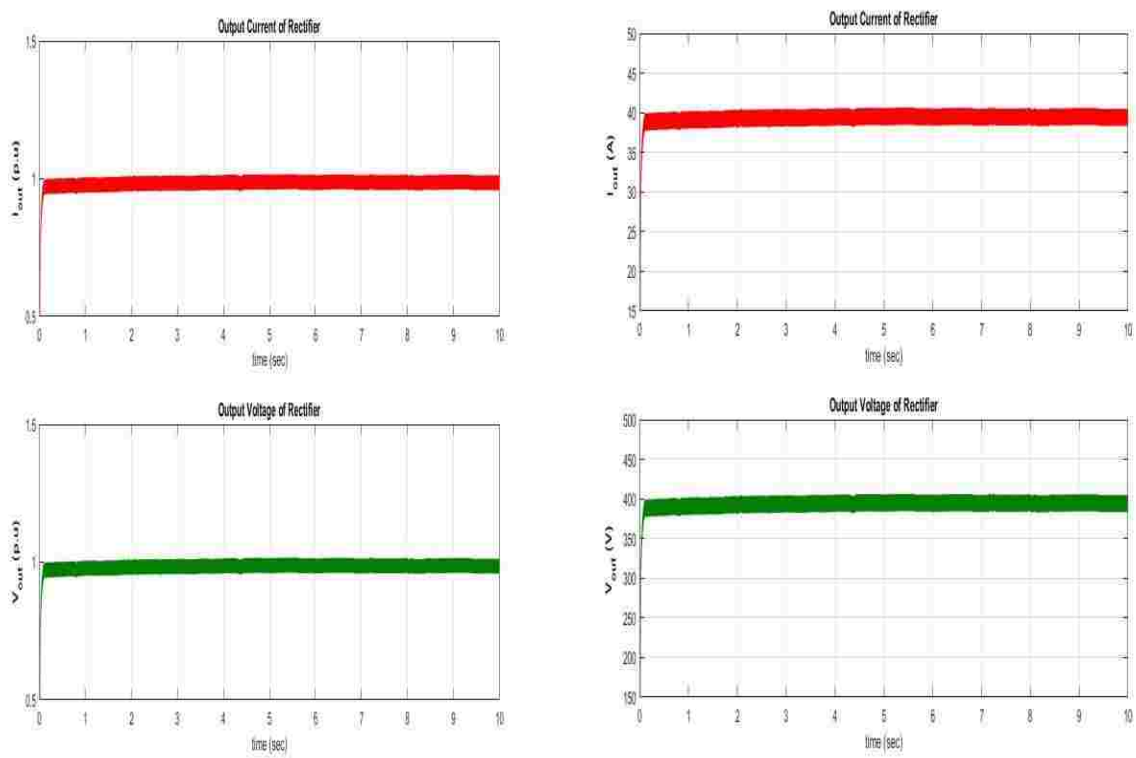

Figure 23. Output Voltage and Current Waveform of Three Phase Rectifier

Table 6. Measured Output Values of Three Phase Rectifier

V_{out}	395V
I_{out}	39.5A

4.4 STABILITY ANALYSIS OF THE DISTRIBUTED GENERATOR BASED SYSTEM

The steady state and the dynamic stability analyses are performed for the developed model. The steady state stability analysis is performed by ensuring the proper and efficient power sharing between the converters. The dynamic stability analysis is performed by allowing one of the converters to change from full load capacity to a lower load capacity.

4.4.1 STEADY STATE STABILITY ANALYSIS

The system is said is to be steady state stable when the power required is shared efficiently between the two converters. When both the converters are in full load capacity, the system is said to be steady state stable when both the converters deliver equal amount of power.

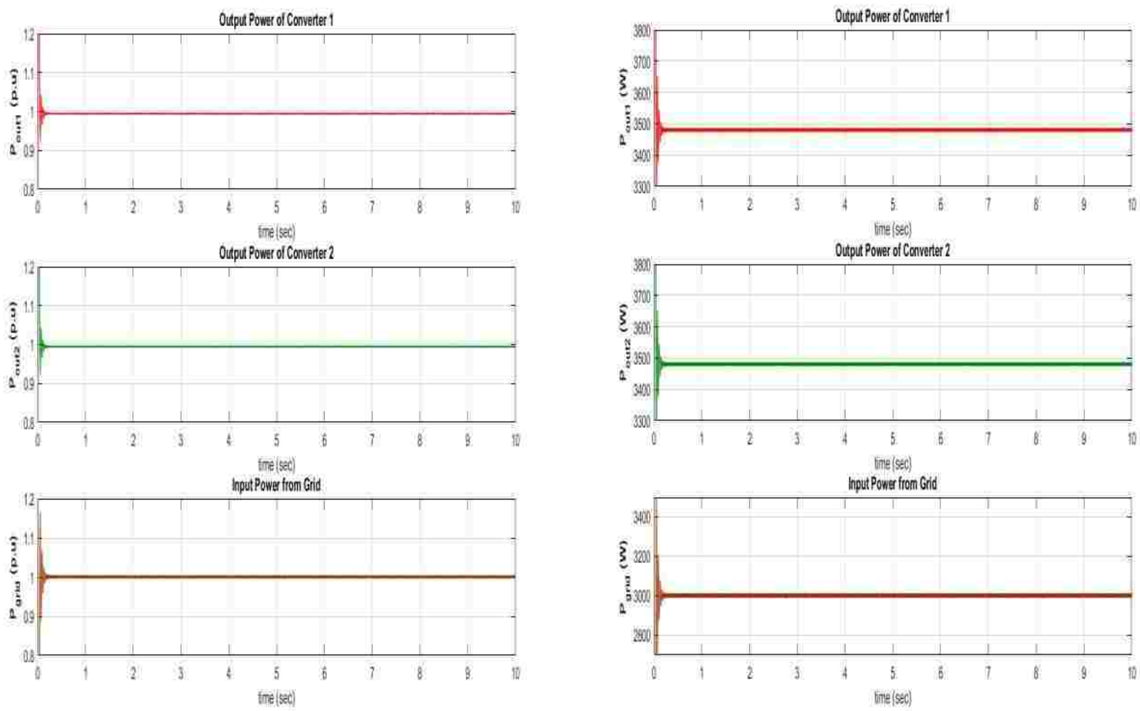

Figure 24. Steady State Analysis

From the above waveforms, the following can be determined. When both the converters are in full load capacity, the converter 1 and the converter 2 delivers a power of 3.5Kw, and the input from the grid is measured to be 3.0kW. Thus, the system is steady state stable as the output power of converter 1 and converter 2 are equal.

4.4.2 DYNAMIC STABILITY ANALYSIS

The system is said to be dynamically stable when the converters share power efficiently when one of the converters operate in a lower load capacity than the other. As the load capacity of one converter changes, the other converter and the grid has to efficiently compensate for the power drop or power increase caused by the converter. The dynamic analysis tests are performed here by maintaining the converter 1 in full load capacity and increasing or decreasing the capacity of the converter 2. The step up and step down analyses are performed in the developed model by stepping up and stepping down the load capacity of the converter2.

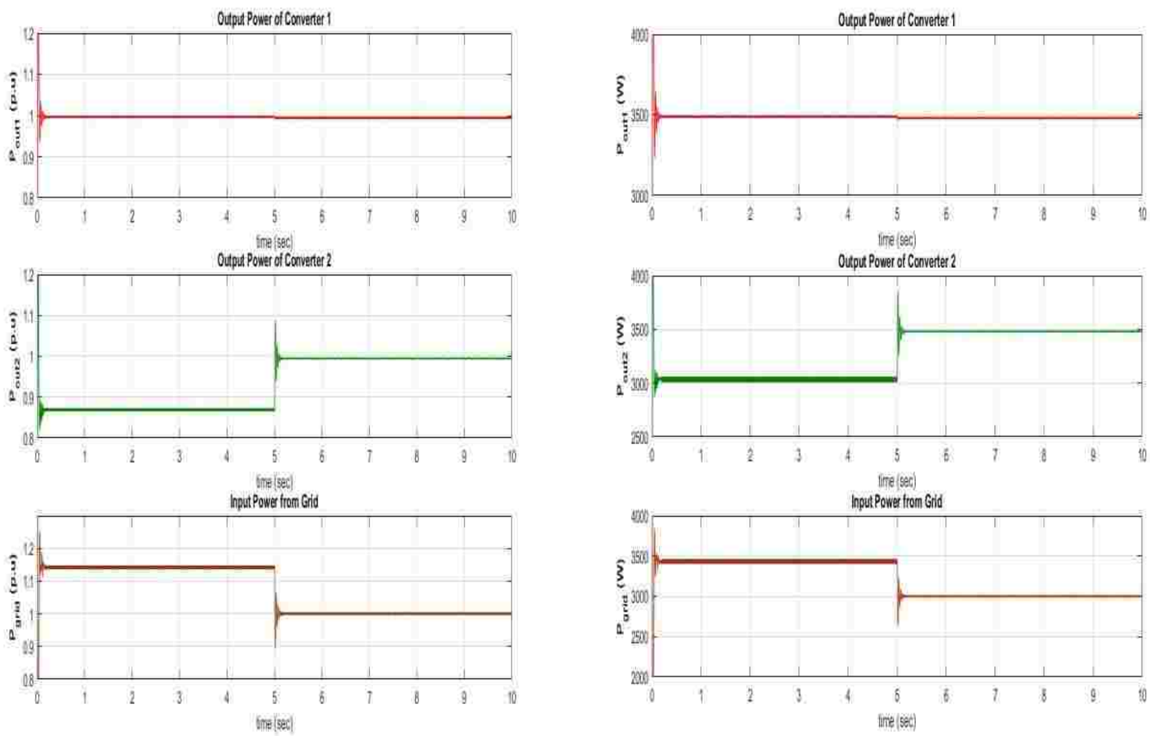

Figure 25. Step Up Analysis

When the converter 2 steps up from half load capacity to full load capacity, the converter 1 remains in full load capacity throughout and the change in the output power is compensated by the grid input. When the converter 2 operates in half load capacity, the grid output power is high and when the converter 2 regains the full load capacity, the grid output power is low. In this analysis, the converter 1 is maintained at full load capacity of 3.5kW and the capacity of the converter 2 changes from half load of 1.75kW to full load capacity of 3.5kW after a period of 5 seconds. When the converter 2 operates at half load capacity, the input power from the grid increases from 3.0kW to 4.75kW to meet the output power demand of 10kW.

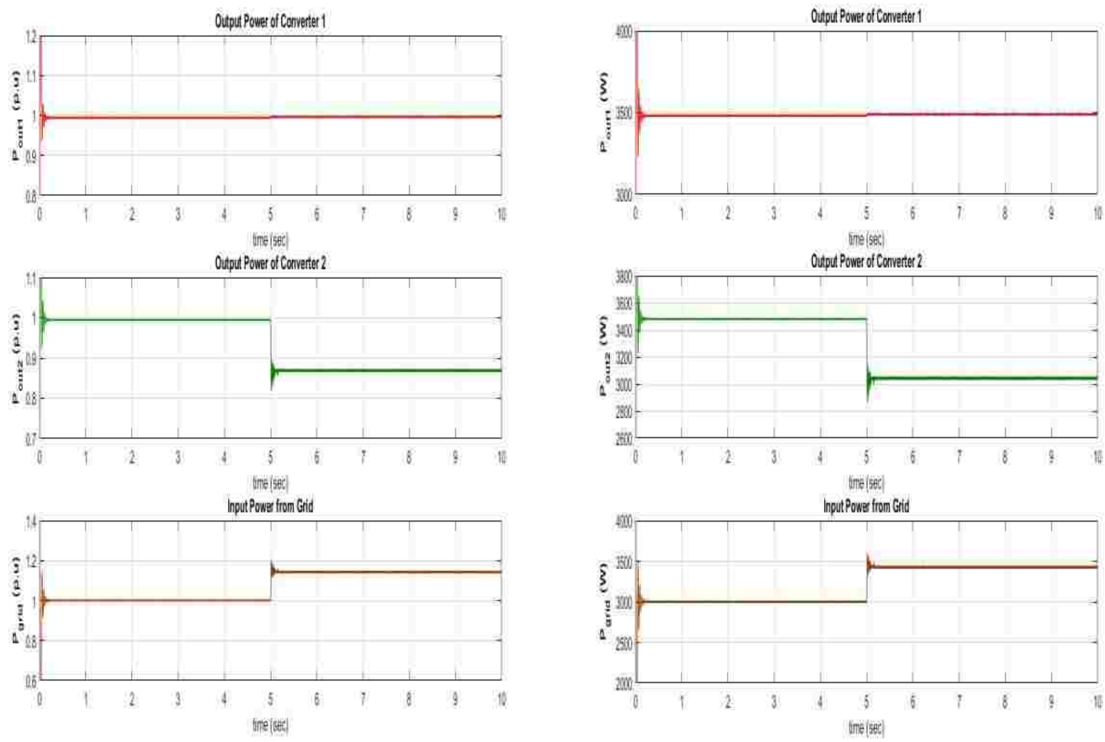

Figure 26. Step Down Analysis

During the step down analysis, the converter 2 output changes from full load capacity to half load capacity. The output power of converter tends to remain in full load while the input power from grid compensates for the change in power. In the step down analysis, the converter 1 is maintained at full load capacity of 3.5kw throughout, and converter 2 changes from full load capacity of 3.5kW to a half load capacity of 1.75kW after a period of 5 seconds. The input power from the grid is seen to compensate the change in the load capacity of the converter by increasing its power input by 1.75kw to compensate the load power demand.

CHAPTER 5

VERIFICATION OF POWER SHARING CONTROL IN DC NETWORKS

5.1 INTRODUCTION

The overall performance of the developed model is analyzed by performing various tests including THD analysis, efficiency, etc. for different values of the coupling resistances and also determining the efficient value of the coupling resistance for the improved performance of the system.

5.2 THD ANALYSIS OF SINGLE UNIT BASED DISTRIBUTED GENERATOR SYSTEM

The THD analysis is performed for the single unit droop controller using the 'FFT Analysis tool' in simulink. The THD analysis is performed on the output current of the converter as the output voltage is a constant value of 400V and hence only the output current has an influence on the output power of the converter.

The THD analysis is performed for different values of P_out by changing the value of I_out_req from 0 to 8.75A. The measured THD value in % is tabulated in the Table 7 below.

The THD analysis curve represents that the system can work efficiently for a value of coupling resistance of above 3.0Ω. The percentage of the harmonic distortion is maintained below 0.11% to maintain the transient stability in the system.

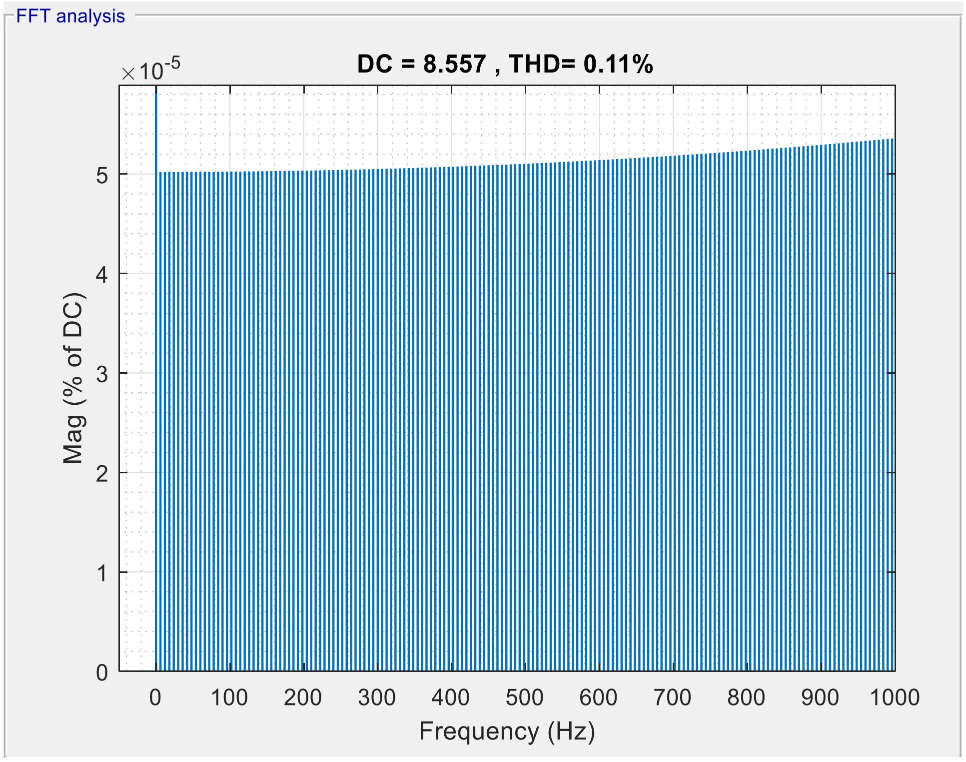

Figure 27. THD Analysis for Output Power.

Table 7. THD Analysis for Different Values of Required Output Current

I_out (A)	P_out (kW)	P_out (p.u)	THD (%)
0	0	0	0
0.05	0.02	0.0057	0.20
0.10	0.04	0.0114	0.17
0.25	0.10	0.0286	0.15
0.50	0.20	0.0571	0.17
0.75	0.30	0.0857	0.12
1.00	0.40	0.1143	0.12
1.50	0.60	0.1714	0.94
1.75	0.70	0.2000	1.31
2.00	0.80	0.2286	1.59
2.50	1.00	0.2857	3.75
2.75	1.10	0.3143	0.11
3.00	1.20	0.3429	0.11
3.50	1.40	0.4000	0.11
4.00	1.60	0.4571	0.11
5.25	2.10	0.6000	0.11
7.00	2.80	0.8000	0.11
8.75	3.50	1.0000	0.11

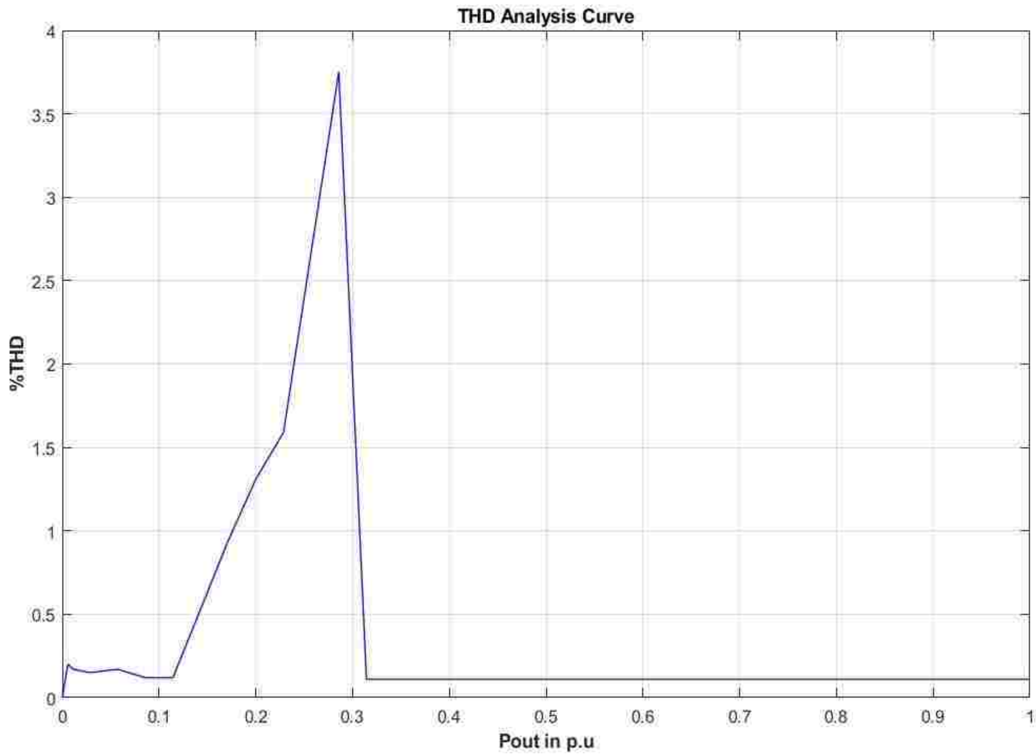

Figure 28. THD Analysis Curve for Single Unit Based Distributed Generator System

5.3 STATIC AND DYNAMIC PERFORMANCE ANALYSIS FOR PARALLEL UNITS

The static and dynamic analysis tests are performed for the parallel units for different values of the coupling resistance ranging from 1Ω to 12Ω. The tests are performed for full load condition and changes are made only to the coupling resistance.

5.3.1 STATIC PERFORMANCE ANALYSIS FOR PARALLEL UNITS

The converters are operated in full load capacity throughout and the changes are made to the coupling resistance value to check the efficiency of the system based on the increase and decrease of the value. The static analysis is performed by various tests including the THD analysis, efficiency analysis and the error occurrence analysis.

Table 8. THD Analysis for Parallel Units

R_coup (Ω)	THD (%)
0.5	2.83
0.75	1.28
1.0	2.04
1.5	0.78
1.75	1.49
2.0	0.61
3.0	0.46
4.0	0.36
5.0	0.29
7.5	0.16
10.0	0.12
12.0	0.11

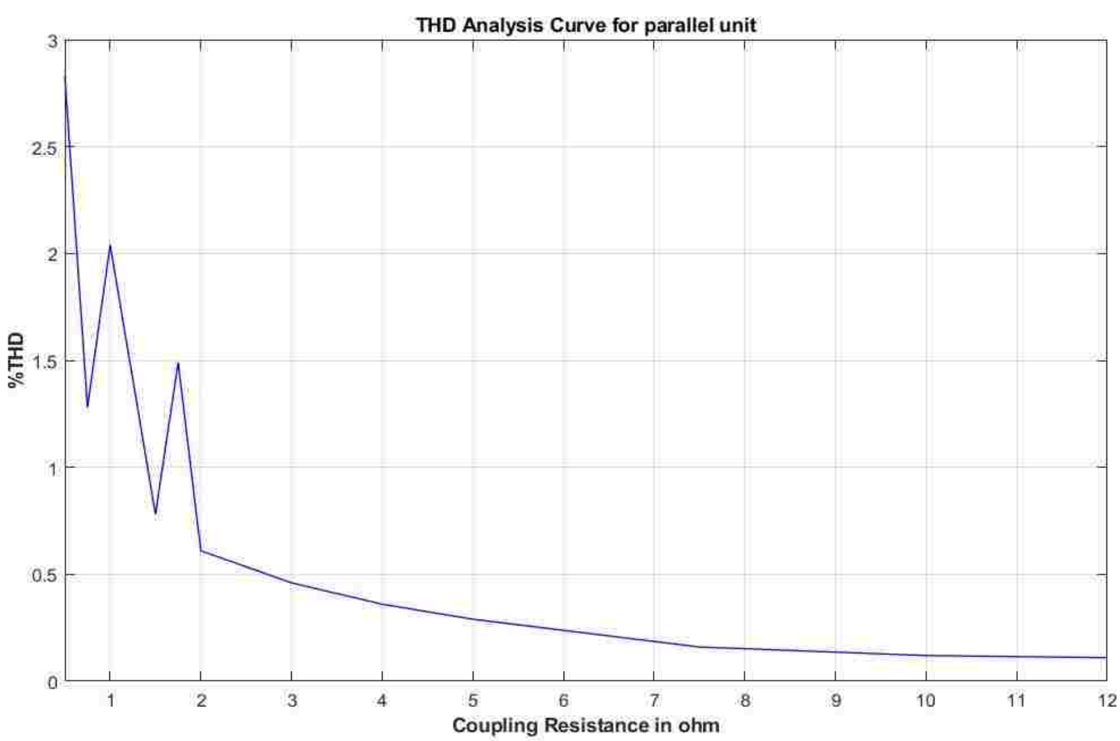

Figure 29. THD Analysis Curve for Different Coupling Resistances

From the THD analysis, it can be determined that the system works efficiently with a coupling resistance of 3.0Ω and above. The parallel unit also shows a harmonic distortion of below 0.20% for a coupling resistance of above 3.0Ω.

The system performance is usually analyzed by checking the working efficiency of the units. The efficiency is calculated by the amount of power delivered by each converter comparing it to the input given to the converter. The efficiency of the converter is calculated using the following formula,

$$\eta = \frac{P_{out}}{P_{in}} * 100\% \quad (14)$$

where,

P_{in} is the input power given to the converter

P_{out} is the output power across the converter

Table 9. Efficiency Analysis of Parallel Units

R_coup (Ω)	P_in (W)	P_out (W)	η (%)
1	4000	3750	93.750
2	4000	3590	89.750
3	4000	3485	87.125
4	4100	3455	84.268
5	4300	3460	80.465
7.5	4400	3450	78.409
10	4500	3481	77.356
12	4500	3455	76.778

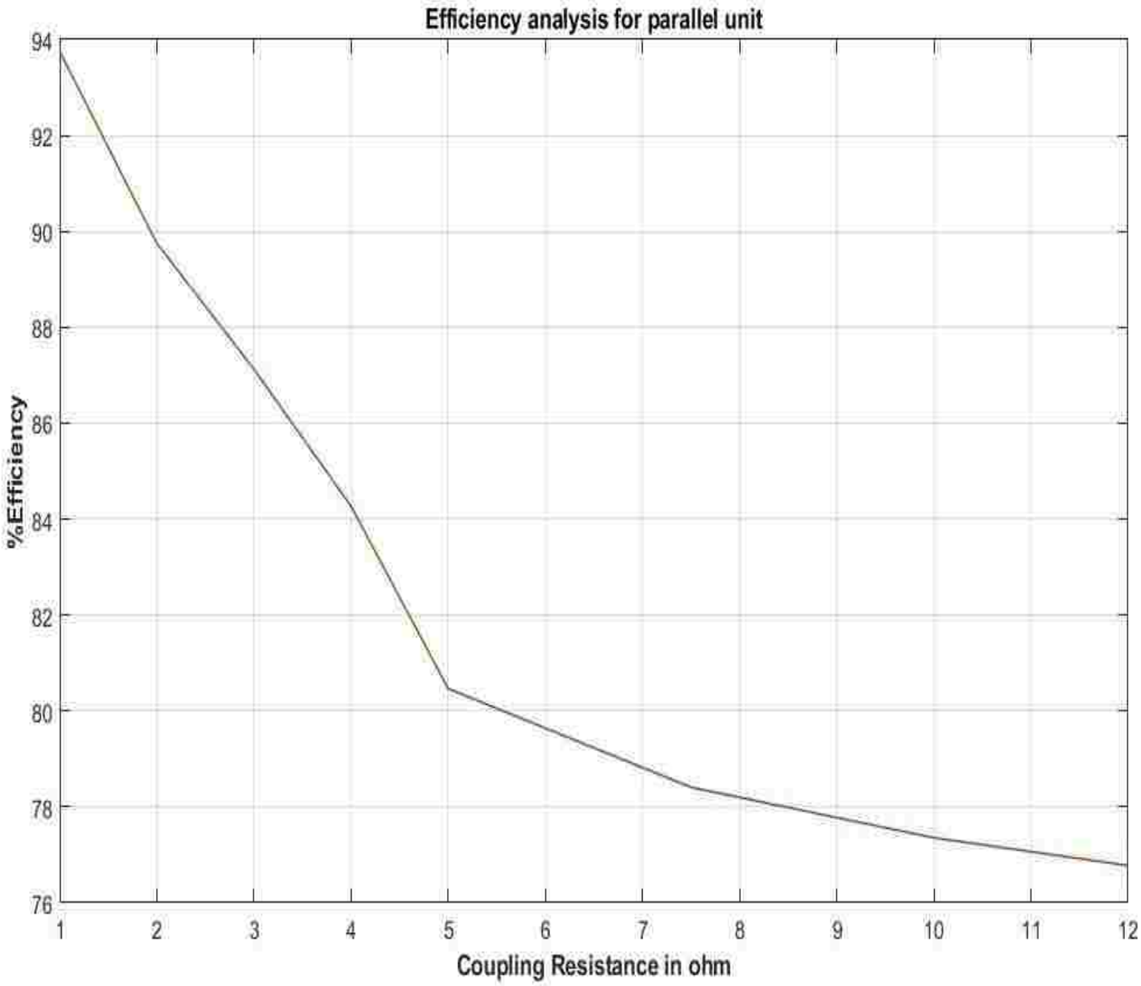

Figure 30. Efficiency Analysis Curve for Different Coupling Resistances

The error in the obtained output power is also analyzed by using the following formula,

$$\Delta P_{error} = \left|1 - \frac{P_{real}}{P_{demand}}\right| * 100\% \quad (15)$$

where,

P_{real} is the measured value of power across each converter

P_{demand} is the rated value of power which is equal to 3.5kW

Table 10. Output Power Error Analysis of Parallel Units

R_coup (Ω)	ΔP_{error} (%)
0.5	7.4286
1.0	7.1429
1.5	5.7143
1.75	1.7143
2.0	2.5714
2.5	0.5714
3.0	0.4286
4.0	1.2857
5.0	1.1429
7.5	1.4286
10.0	0.5429
12.0	1.2857

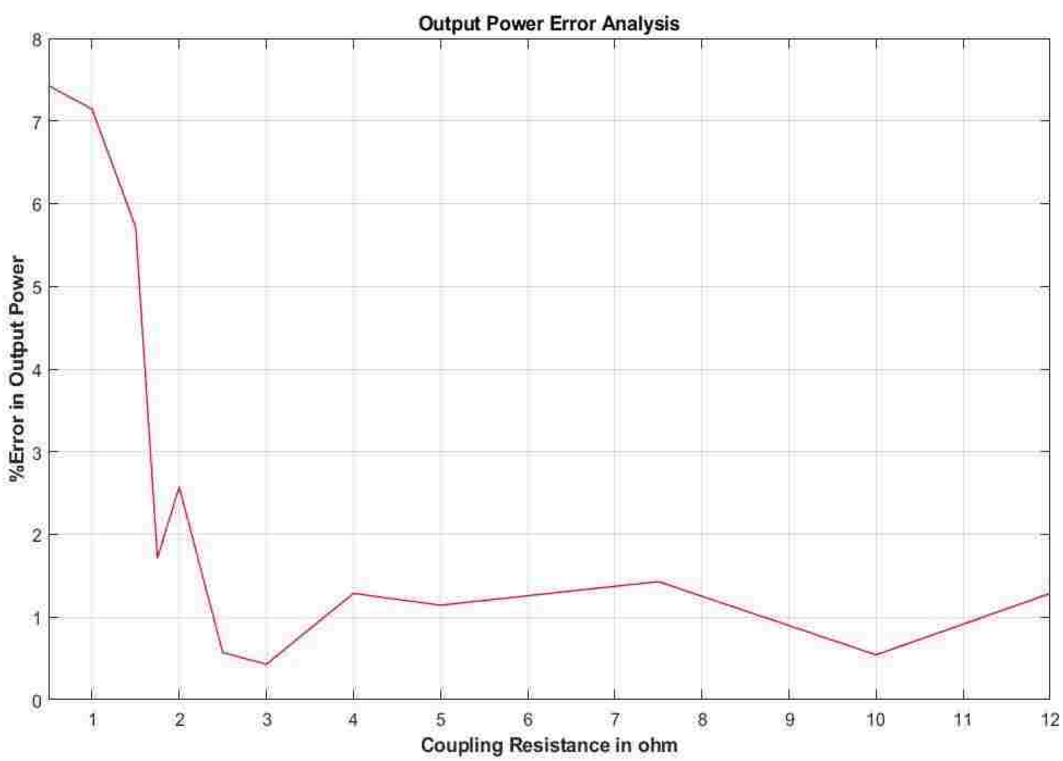

Figure 31. Output Power Error Analysis Curve for Different Coupling Resistances

5.3.2 DYNAMIC PERFORMANCE ANALYSIS OF PARALLEL UNITS

The dynamic analysis is performed by using a step signal to step down the I_out_req value from full load to half load for different values of coupling resistances.

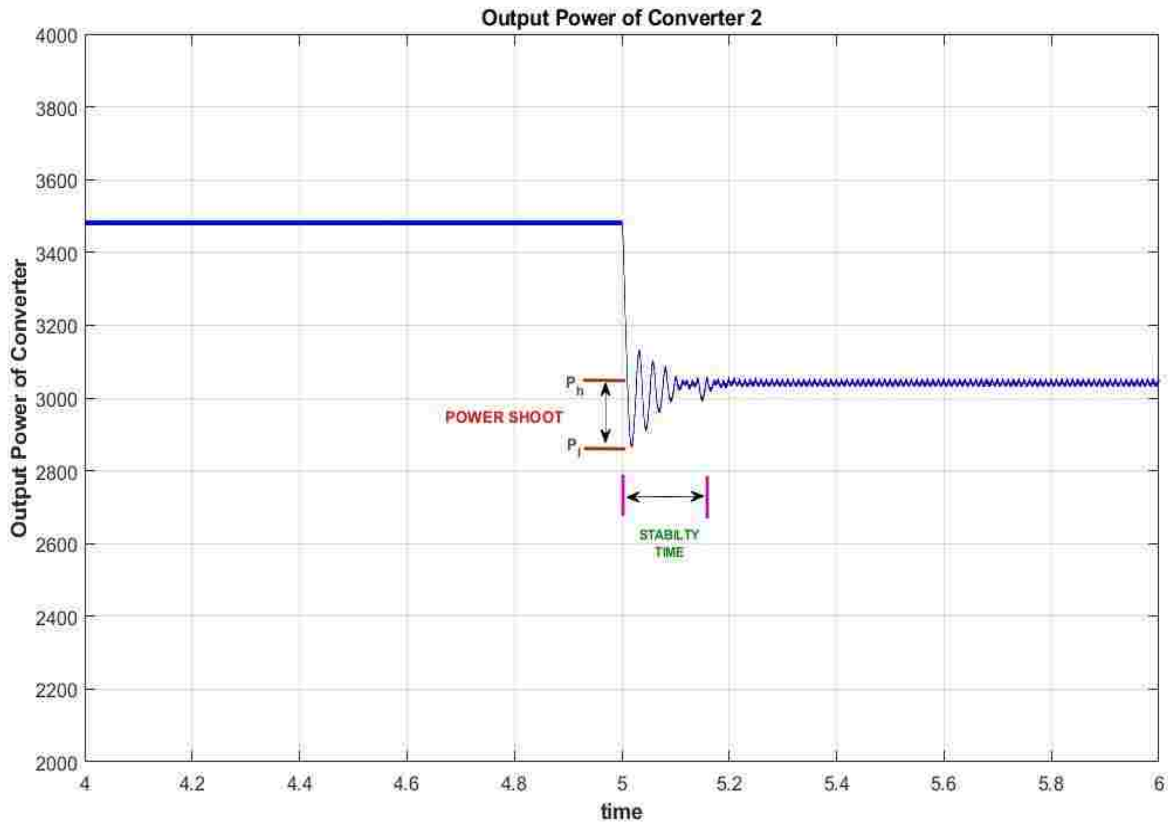

Figure 32. Dynamic Analysis Representation

When the load value changes, there is an additional shoot in the signal and this value is calculated and analyzed. The threshold value of the shoot is set to 5%. Here, 5% of the rated value which is 175W. The error in the power shoot is calculated as follows,

$$\Delta P_{shoot} = \frac{\Delta P}{175} = \frac{P_h - P_l}{175} \tag{16}$$

where,

P_h is the higher value and P_l is the lower value of power shoot as seen in fig.32.

Table 11. Power Shoot Analysis for Parallel Units

R_coup (Ω)	P_h (W)	P_l (W)	ΔP (W)	ΔP_{shoot}
1	2325	2040	285	1.6286
2	2450	2270	180	1.0287
3	2525	2405	120	0.7059
4	2690	2510	180	1.0287
5	2810	2600	210	1.2000
7.5	2900	2790	110	0.6286
10	3040	2870	170	0.9714
12	2940	3096	156	0.8914

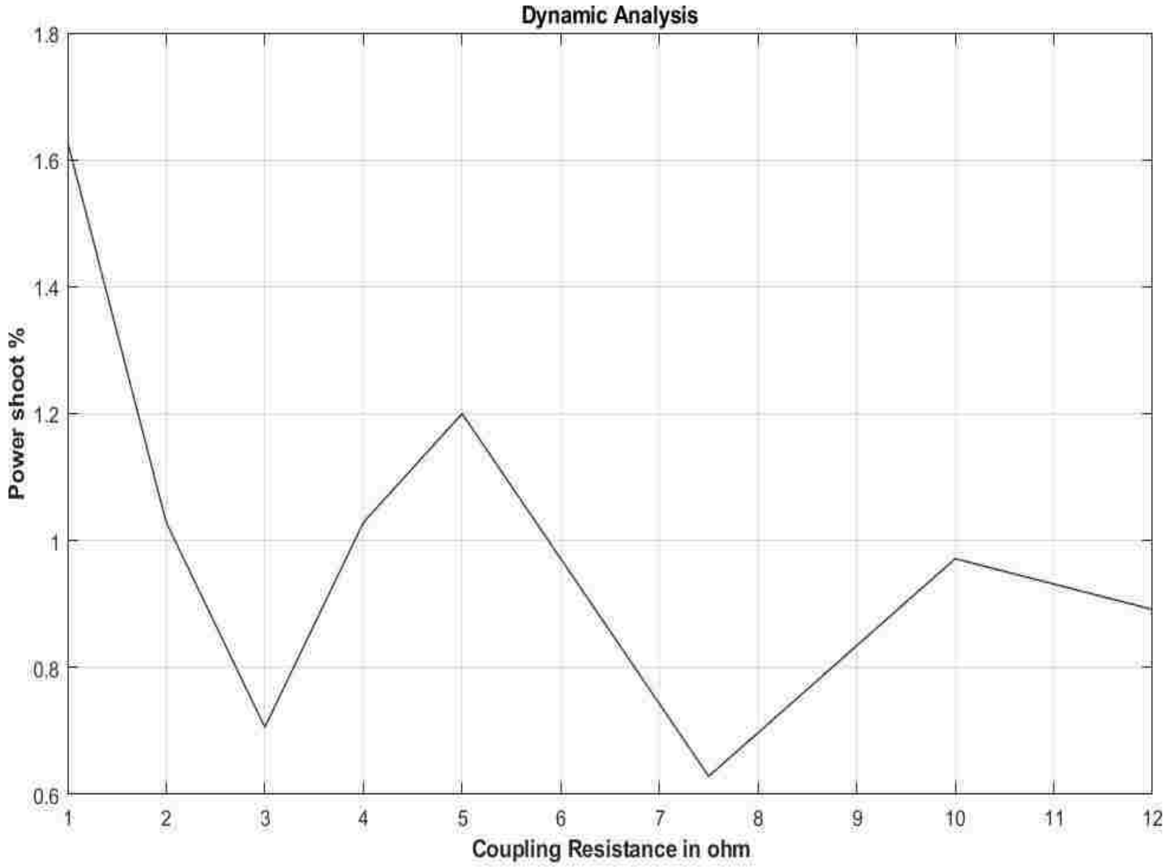

Figure 33. Output Power Shoot Analysis Curve for Different Coupling Resistances

The stability time for each curve is measured and analyzed. In this model, the stability time is calculated to be less than 0.3 seconds for the efficient power sharing between the distributed generators.

Table 12. Stability Time Analysis

R_coup (Ω)	t_start (sec)	t_end (sec)	T_stable (sec)
1	5.0	5.01	0.01
2	5.0	5.03	0.03
3	5.0	5.09	0.09
4	5.0	5.12	0.12
5	5.0	5.12	0.12
7.5	5.0	5.10	0.10
10	5.0	5.10	0.10
12	5.0	5.15	0.15

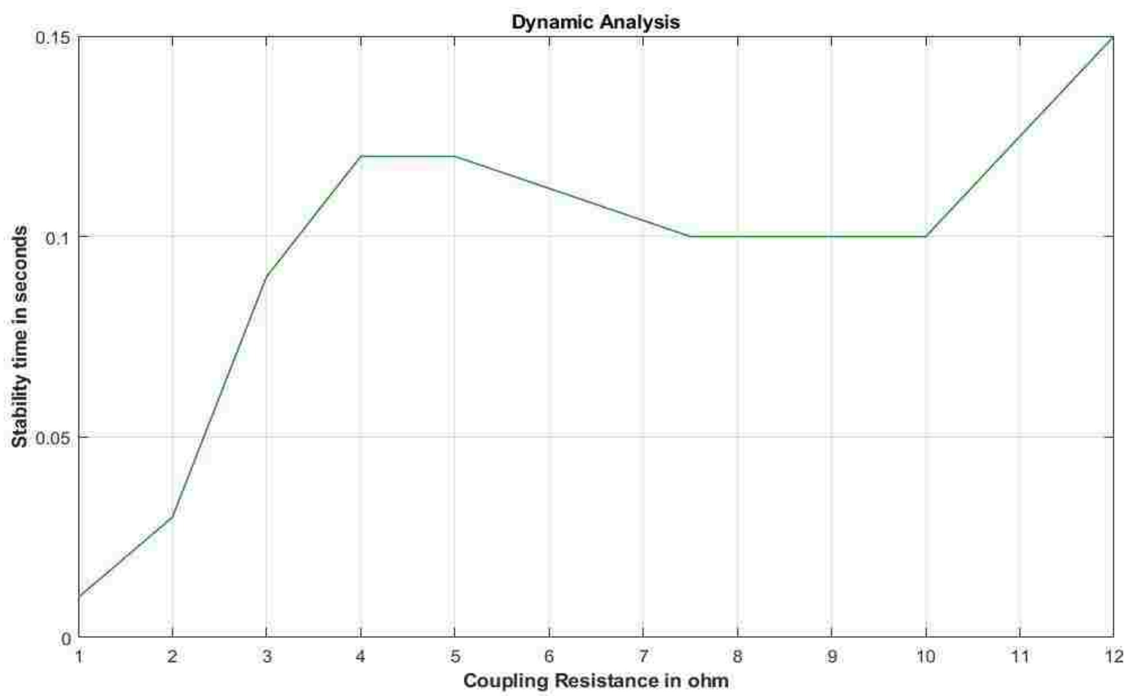

Figure 34. Stability Time Analysis Curve for Different Coupling Resistances

From the above table and figure, it can be analyzed that the stability time for this system is approximately 0.10 seconds. From all the above analysis, it can be seen that the power sharing works efficiently when the coupling resistance is maintained above the value of 3.0Ω.

5.4 GRID POWER CONTRIBUTION

The designed parallel unit based converter works efficiently for any number of converters connected in parallel. For checking the performance of the converters, five distributed generators are connected in parallel and the output power of each converter and the input power from the grid is measured and analyzed. The analysis of the grid power control is carried out by controlling the converter power of each converter connected in parallel to the load. To check the performance of the entire system, each converter is turned ON after a period of 2 seconds.

5.4.1 FEEDBACK POWER TO GRID

Five converters are connected in parallel to the load and the grid. The load power demand is maintained at 10kW. Taking reference of the output waveforms, during the time period of 0 to 2 seconds, none of the converters are in operation and the entire power demand of 10kW is delivered by the grid. During each of the successive 2 seconds, each of the converters is turned ON and set into operation. The converters operate in full load and it delivers 3.5kW output power each and the remaining is compensated by the input grid power.

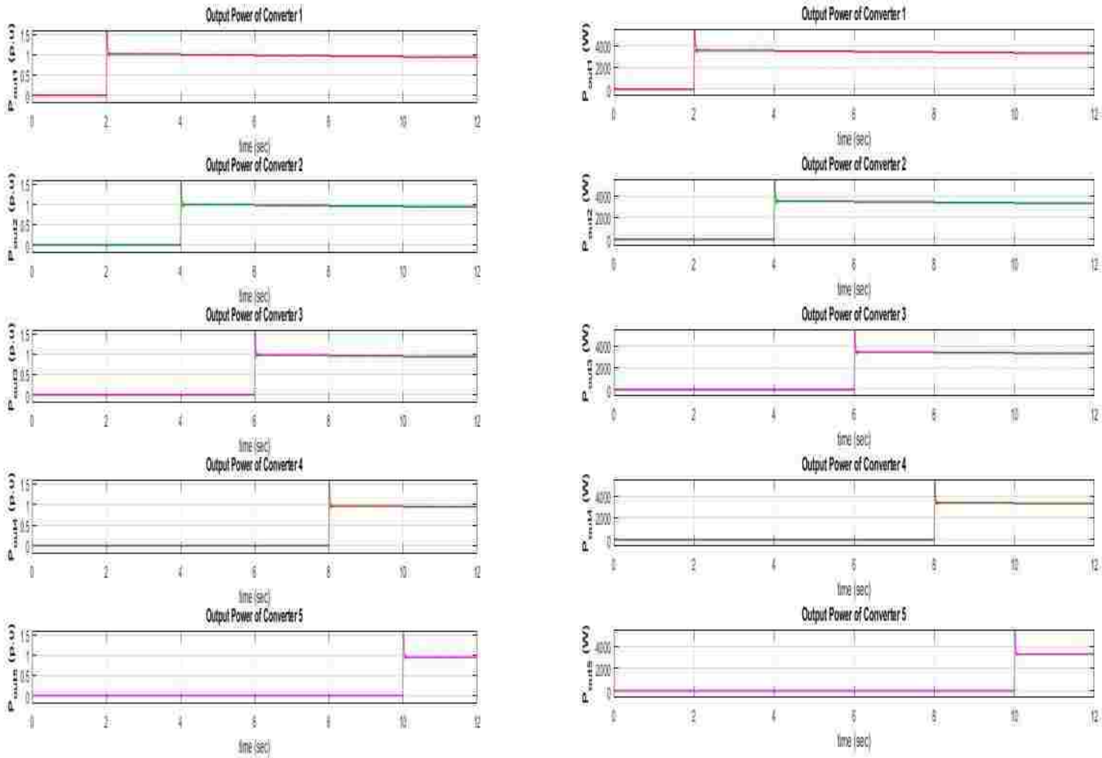

Figure 35. Output Power Waveform of Converters when P_{load} = 10kW

From the grid output waveform, it can be seen that the value is in negative after a period of 6 seconds. This indicates the injection of the generated power to the grid. This in turn helps in saving energy by delivering the excess generated power to the grid. This system can be considered as a bidirectional flow of energy where the grid inputs power when the load demand is not met by the connected converters and the grid takes the power from the converters when it generates additional power higher than the power demand by the load. The highest amount of power supplied by the grid to the system is 10kW.

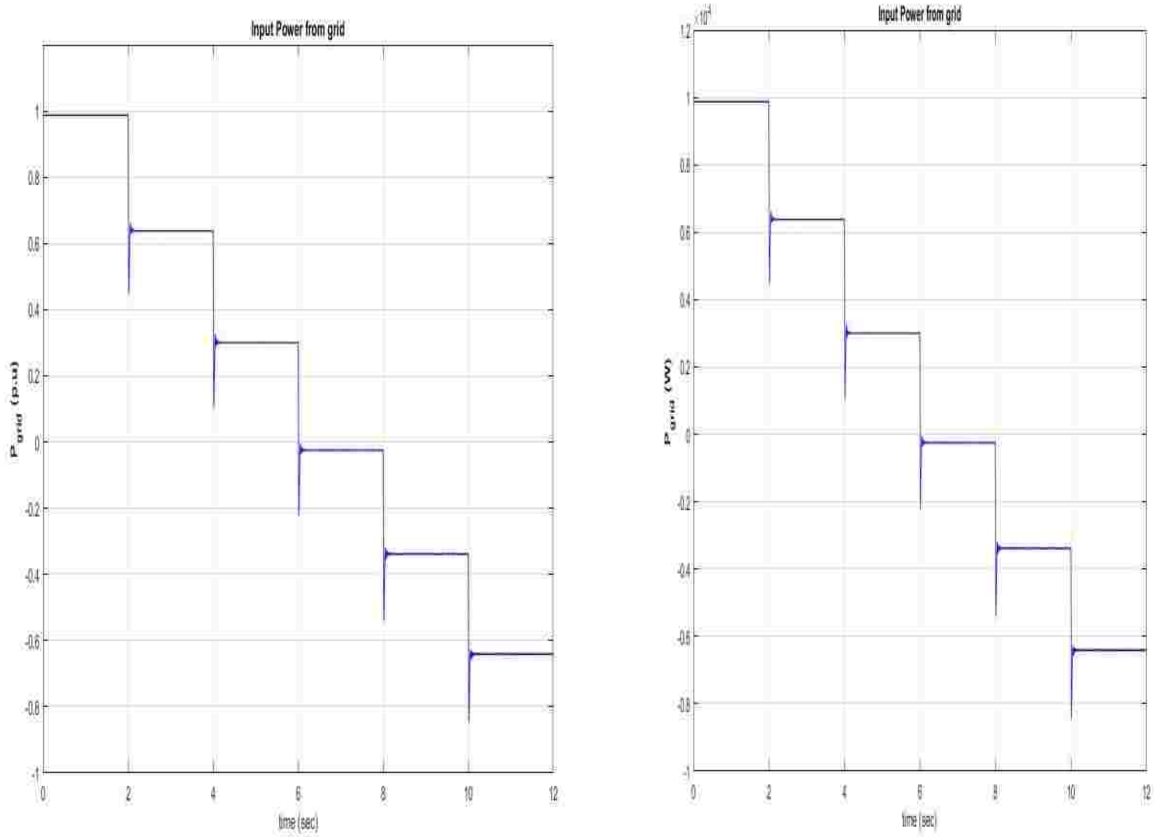

Figure 36. Input Power from Grid when P_{load} = 10kW

5.4.2 LOCAL GRID

The system is modified as a local grid network generating the power required for the load connected to the system. The load demand is increased to 20kW and the output waveforms are analyzed. The converters are operated in a similar manner to the previous control. But the grid operation varies in this method.

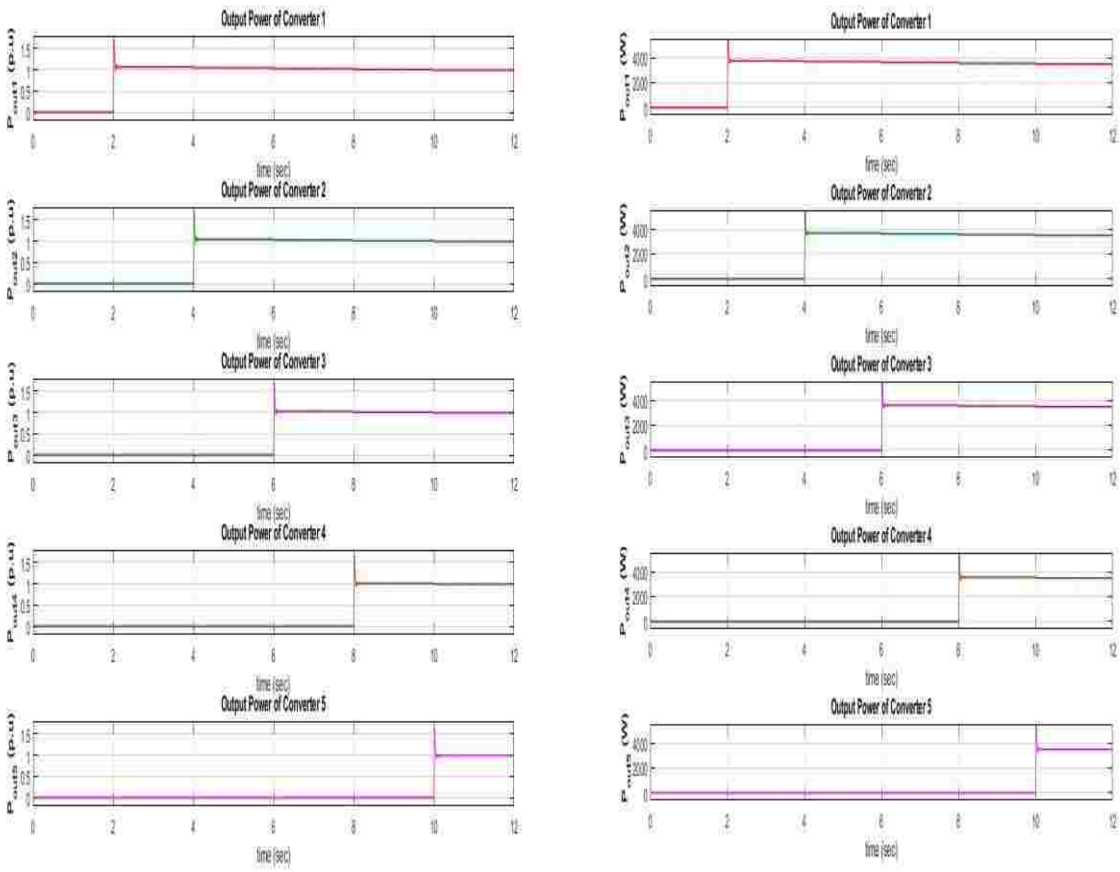

Figure 37. Output Power Waveforms of Converters when P_{load} = 20kW

From the grid power waveform, it can be seen that at the beginning the entire 20kW power is given as input from the grid to the load as all the converters are in zero load capacity or in OFF conditions. As the converters are turned ON successively, the grid power contribution reduces to a value of 2.5kW at the end of the operation when all the converters deliver power. Here, there is no input back to the grid as there is no excessive power generated by the distributed generators.

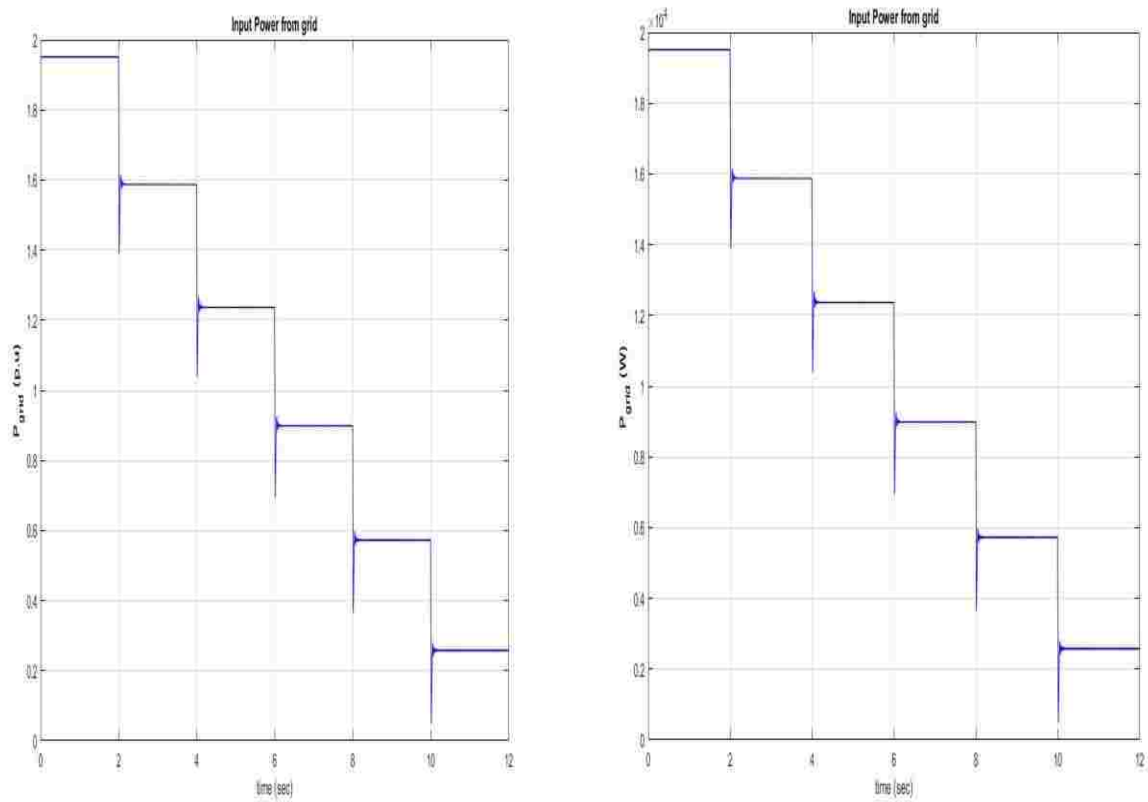

Figure 38. Input Power from Grid when P_{load} = 20kW

5.5 COMMUNICATION BETWEEN GRID AND GENERATORS

The communication between the different units connected to the grid is important to maintain the stability in the power network. Here the communication between the grid and converter is checked by using different delays to the two converters connected in parallel. The stability of the system's communication is checked by stepping down the signals in the converters at two different times. The signals are stepped down within a 0.1 second delay as the stability time of the proposed model is analyzed to be 0.1 second. The signal of the converter 2 is stepped down when the converter 1 is still in unstable period. The signal of converter 2 is stepped down after a 0.1s delay than the signal of converter 1. From the output power measured, it can be seen that the system still maintains the stability even after the delay in the signal. The delay signal is considered to be the communication signal for the parallel units.

The output power waveforms are shown below. In the converter 1, the signal is stepped down from full load to half load after 5 seconds and in the converter 2, the signal is stepped down from full load to half load after 5.1 seconds. This shows a delay of 0.1 second between the stepping down of the signals in converter 1 and converter 2. Here, the communication signal is sent to each converter manually. However, in practical applications even with the external communication link, the system can be operated with higher and improved efficiency with any changes to any of the converters. The same communication can be set up for a system with higher number of distributed generators as well.

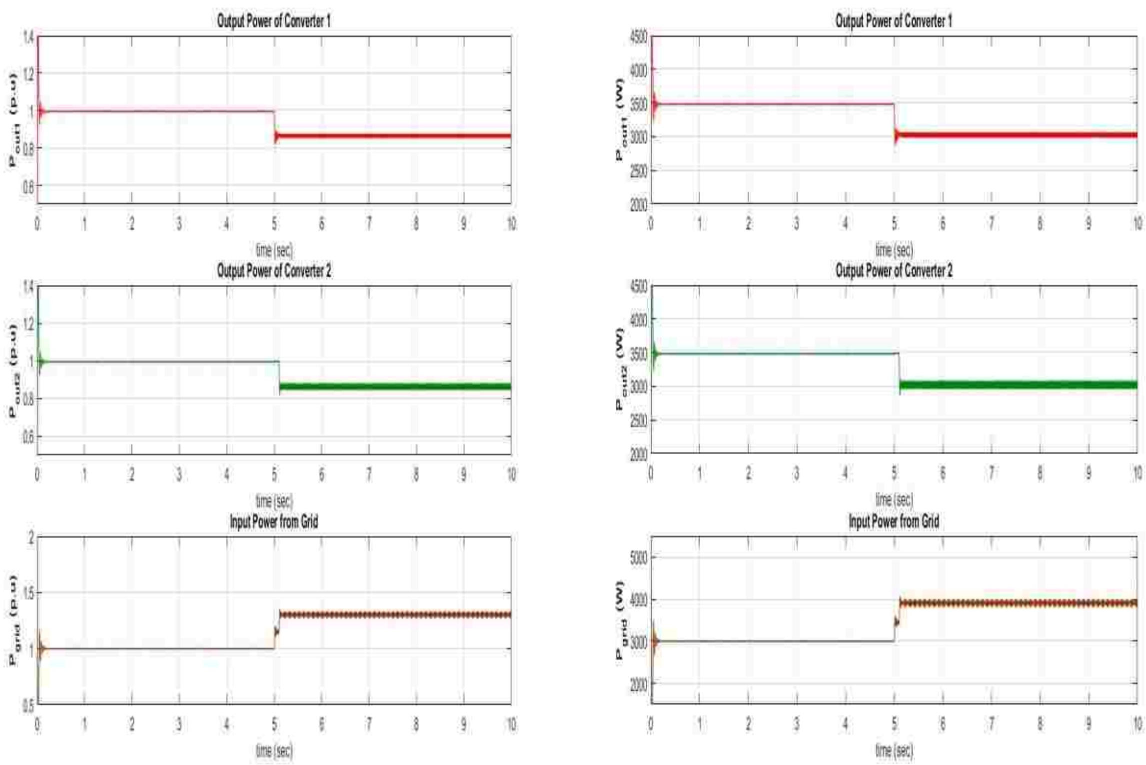

Figure 39. Output Power during Communication Delay

From the above figures, it can be seen that even when the stepping time is just 0.1 seconds, the system is stable and performs the stepping down of the output power between the converters efficiently. The converter 1 and the converter 2 is maintained at full load capacity till a period of 5 seconds. At t=5seconds, the converter is dropped to half load capacity and the power output of the converter 2 changes from 1.0p.u to 0.85p.u. At this time, the grid power increase from 1.0p.u to 1.15p.u. After 0.1 seconds, the converter 2 is dropped to half load capacity and now the grid power in turn increases with an additional 0.15p.u. The system is unstable during the 0.1 seconds and still the system maintains stability by efficient power sharing between the converters and the grid to the load. This shows the system efficiency and optimization even during the period of instability and the interruption caused by the communication delay in the system.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 CONCLUSION

The power sharing between the distributed generators connected in a DC microgrid system is performed and analyzed. The working of the system is monitored by performing the steady state and the dynamic analysis for the system. The tests are performed for various values of the coupling resistance. This leads to a conclusion that the system efficiency and performance is not affected and also the system is optimized when the coupling resistance value is maintained above 0.3p.u. This helps in maintaining the rated system voltage of 400V throughout the working of the system by using the droop controller installed in each converter. Since the voltage is maintained constant, the power control can be easily carried out by controlling the output current from each converter. The system works with external and internal communication signal given to each converter by maintaining the stability within the limited range provided. This helps in eliminating the effect of instability and occurrence of blackouts. Theoretically, this novel power sharing control can be generally applied to any DC generators for their output power regulation.

6.2 FUTURE WORK

The future work focuses on adding more converters to the system and analyzing the stability performance in power sharing and also by using other renewable energy resources as the primary source of energy for different distributed generator system. The hardware implementation of the proposed model is also to be implemented to analyze the performance and efficiency of the system.

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Rotaract Club Secretary for the year 2014-2015.

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