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Power Dispatching of Active Generators using Droop Control in Grid connected Micro-grid

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Abstract

Renewable energy promises a green energy future for the world. However, many technical problems still have to be solved. Almost all renewable energy sources require power electronic converters for power processing and therefore inverter control systems and power dispatching strategies are significant in renewable energy applications. The existing electricity grid architecture is based on centralized power generations while most renewable power generations are distributed and connected to lower or medium voltage networks. Some of important renewable energy resources such as solar and wind power are intermittent in nature. This is a challenging issue for grid integration of renewable energy into the grid and raises difficulties for power system operational control and maintaining power quality. In practical integration of renewable energy systems, these problems must be addressed and solved.

In this research, grid integration methods and inverter control methods for the renewable resources have been studied. First task of the study was development of a Voltage source Converter (VSC) system. Active and reactive power control systems for power dispatching have been implemented in the VSC and so that it can work as an active generator. The power dispatching policy of the active generator is based on combination of droop and PI control method. A micro-grid model has been proposed in order to achieve high penetration of renewable energy. In the proposed 500 kW micro-grid system, it is considered that 250 kW of the power is come from the central grid and the remaining power is provided by local distributed generations. Micro-grid has been connected to the main grid via back-to-back converter topology. Frequency droop is originated from the back-to-back converter, where any power deviation from base power level (250 kW), causes ± 0.002 Hz/kW deviation from base 50 Hz frequency. In this micro-grid, there is a combination of dispatchable generations and an intermittent power generation. Dispatchable generation include a solid oxide fuel cell (SOFC) and a central energy storage system where both systems can work as active generators. Active power flow of each DG unit is based on frequency variation originated by the back-to-back converter and reactive power flow is based on the voltage variation of coupling points of each active generators. In the propose control system, power flow of local micro-grid renewable power sources are controlled for maximum utilization of available power within the micro-grid and minimize the power flow from the main-grid. In this implementation, the main-grid and micro-grid can work as two different AC power system areas where frequency and voltage are isolated through an intermediate DC path.

The model has been simulated in Matlab Simulink and stable operations have been observed where micro-grid frequency, voltage and power quality were within acceptable ranges. This shows the usability of the proposed model for achieving high penetration of renewable power into micro-grids.

Key words: Distributed generation (DG), Droop control, Active generators, Voltage source converters (VSC), Micro-grid, Renewable energy, Grid integration

Preface

First I would like to express my gratefulness for Professor Mohan Lal Kolhe for motivating me in this research area and continuously providing necessary supervision to success this study. It was great pleasure to work with him for the entire study period.

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Abbreviations

DG	Distributed Generation
DER	Distributed Energy Resources
VPP	Virtual Power Plant
VSC	Voltage Source Converters
IGBT	Insulated Gate Bipolar Transistors
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
PCC	Point of Common Coupling
AC	Alternative Current
DC	Direct Current
THD	Total Harmonic Distortion
SOFC	Solid Oxide Fuel Cell
CHP	Combine Heat and Power
PV	Photovoltaic
LC	Inductor Capacitor
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
DFIG	Double Fed Induction Generators
FACTS	Flexible AC Transmission System
SVC	Static VAR Compensation
PF	Power Factor

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Chapter 1

Introduction

This chapter presents the research problem, background and motivation for this research study. Moreover, research objectives and solution strategy are discussed. The report outline is introduced in final section.

1.1 Background and Motivation

Renewable energy sources provide an attractive alternative power generation method over fossil fuels with many merits in environmental, economic and political concerns. Even though renewable sources have merits for green power generations, the major drawbacks such as power intermittent and distributed nature of resources introduce difficulties in integrating these systems to the electricity grid. Traditionally electricity grid was developed with the idea of centralized controllable power stations which are transmitting the electricity from source to consumers. However distributed generations also getting more popular with the recent development of renewable energy technologies and micro-grid concepts. Distributed generation (DG) also includes both small scale non-renewable (oil, gas) electricity generation stations and renewable sources (solar, wind, bio-energy, fuel cell etc.). In addition, energy storage systems can be included in this class and it can be considered in wider context as distributed energy resources (DER). The integration of distributed renewable energy sources like wind power, solar power, bio-energy and fuel cell to the power grid is an important topic. A lot of research is going in grid integration of these sustainable electricity generations.

Traditionally, when managing the electrical system stability, utility companies uses several services from the base synchronous generators. Synchronous generators have active power dispatching based on grid frequency and voltage stability function by varying reactive power delivery. Also they have particular ramp rate (MW/Min), the ability to change the power level as required. Also generators have a system inertia that will ensure constant power delivery for several seconds even with the input power changes and provides the stability of the grid for disturbances. Further, by changing energy source input (hydro inlet gate in hydro generators, gas or steam inlet value in gas or steam turbines) the power can be dispatch according to the demand. However most of available renewable DGs are connected through passive inverters and they don't have these capabilities. But to achieve high penetration of renewable energy, our power converters should be intelligent and able to provide not only the power but also the grid control capabilities for stable power system operation.

Most of the DER are integrated at low or medium voltage network as low penetration fashion where DER are connected as passive systems and they are not involving grid voltage controlling, frequency controlling and stability activities [1]. However, there are difficulties when controlling and coordinating the high penetration of DER in the grid. Most renewable power systems are not directly connected to the grid, but via power electronic interfaces between the grid and the renewable sources where the final stage comprises DC/AC inverters. These interfaces can be modified to work as active generators so that DER can participate in the frequency, voltage and system stability control activities of the grid.

In present situations, in many countries the regulations says that when the frequency, voltage level exceed the given thresholds or in fault conditions, the inverter (DG unit) must be disconnect from the grid for safe operations. However with large penetration of distributed generations, it is not possible to disconnect many DGs from the grid but supporting for grid regulation purpose. For example, to achieve this task, Germany has changed their DG interconnection regulations in 2012. With this new regulation they are expect some primary grid control services such as active power, reactive power control from grid connected inverters. However the stability and controllability of these systems could cause a problem as large number of small units directly connecting to the main grid and participating to the grid control activities. Smart micro-grid architecture is proposed to solve those problems and it is required to control the DG units within the micro-grid.

In future smart-grid architecture, micro-grids will play an important role for achieving high penetration of distributed generation and integration of RESs. These RESs will be connected within a Micro-grids and Micro-grid controller will provide the control capabilities within the micro-grid. The other important concept is virtual power plant (VPP) where VPPs consist of an aggregation of DERs to operate as a traditional generation system with respect to controllability and market participation. Especially, the intelligent mixed asset VPPs are promising as they deliver scaling benefits and enclose different types of resources [2]. In many cases combination of above two methods in hierarchical method may give better results [3]. However in achieving those objectives, the capabilities of the DG inverters are critical and inverters should be smart to handle the real time dynamic conditions of the grid.

Voltage source converters (VSC) are significant in many DG inverter applications. VSC includes solid state power electronics switches such as insulated gate bipolar transistors (IGBTs) or metal oxide semiconductor field effect transistors (MOSFETs) and control system to control these switches. In AC power systems, the output waveform should have power frequency and inductor-capacitor (LC) filters are required to remove the harmonics. Further these VSCs can be improved by providing active, reactive power control capabilities and kind of inertial power delivery capability with energy storage systems [4]- [5]. Therefore controlling the required power dispatching in grid connected renewable generation is essentials in achieving large penetration. It is required to have dq0 transformation for active and reactive power control [6]. Dq0 transformation is used to transfer 3 phase voltage or current sequence to a 2 axis (I_d, I_q) rotating coordinate system and it consist with 2 transformation steps, namely Clark transformation and Park transformation.

If DG units are operated as dispatchable sources such as micro-turbines, diesel generators, fuel cells or batteries, then the normal operation method of conventional generators can be extended to the DG inverters. In this case DG will participate for voltage, frequency control with proper dynamic capabilities and DG will work as an active generator. The implementation of such a systems in a grid connected micro-grid will be a method for achieving high penetrations of renewable resources and systems will be capable of compensation the intermittent nature of non-dispatchable sources such as PV and wind power generations. In addition if the micro-grids connect to the main grid via back to back converter unit, micro-grid can control as a separate Power system area.

This research study is focused on grid connected micro-grid system for VSC control, power dispatching and power flow management. The practical important of the study is that, environmental friendly dispatchable renewable resources will work as active generators to balance the intermittent power within the AC micro-grid power system while maximizing the local power generation.

1.1 Thesis Definition

The main focus of this research is to implement a grid connected micro-grid for increasing the penetration of renewable energy resources. Power dispatch strategies of active generators are the key to achieve this task. The research objectives are defined as follows.

1. To develop and implement a simulation model for a voltage source converter (VSC) for controlling active and reactive power dispatching based on frequency and voltage droop characteristics.
2. To develop and implement simulation model of a back-to-back converter for a grid connected micro-grid operation which operates as a separate AC power system through a DC interconnect.
3. To analyse a grid connected micro-grid for achieving high penetration of renewable energy resources and proper load sharing among different renewable energy sources within the micro-grid.

1.2 Solution Strategy

In a micro-grid, there will be many DGs and those DGs have to operate in synchronizing to each system. Some of DGs such as wind or PV may not be in position to operate as controllable power generation. But in some DGs power dispatching may controllable and may be improved to work as active generators. In this study SOFC and central battery unit will be used as controllable DGs. The micro-grid will be interconnect through back-to-back converter to the main-grid. Frequency droop method will be implemented in micro-grid side of the back-to-back converter, and active generators in micro-grid have to change their power dispatching based on this frequency droop. In this micro-grid, four inverters will be operate in parallel to provide power for the micro-grid loads where back-to-back converter provides the based load power. The Rest of power will be provided by the SOFC, battery and intermittent power source. Intermittent power will be injected uncontrollable way to the micro-grid while fuel cell and battery inverters control their output power to maintain micro-grid frequency and voltage within standard levels. VSCs and their control system are analysed for implementing in effective integration of distributed generators. Active and reactive power dispatching strategies based on the droop characteristics of the micro-grid. Dq0 transformation and PI control systems will be included in several sub systems of this simulation model. Complete simulation model will be developed by MATLAB/Simulink [7].

1.3 Contribution

In this study, a novel concept is introduced to increase the penetration level of renewable energy (from both types dispatchable and non-dispatchable) in an AC micro-grid. Power dispatching and sharing between DGs are based on primary control without additional secondary information. This is achieved by implementing frequency droop control together with proportional integral (PI) and voltage droop control systems. In proposed model, a SOFC and a central battery storage system can be used to compensate the all intermittent nature of DGs and hence system efficiency can be increased while reducing the cost of storage within the micro-grid. Other than pure hydrogen, several types' of fuels can be used for SOFC. The SOFC fuel cell system can be used to work as combined heat and power (CHP) mode to increase the efficiency. The usage of back-to-back converter gives additional benefits where main-grid and micro-grid can operate as two different power systems while, connected through back-to-back converter.

Renewable energy research community and the power utility companies benefit from the findings of this research study.

1.4 Report Outline

The next chapters of this report are organised to present the details information of each objectives, models and results of the study. **Chapter 2** presents the conventional power system operations, where the topic of integrating renewable power system in the electricity grid is also discussed by focusing the importance of active generators. **Chapter 3** gives the mathematical formulation for VSCs and active generators which are focused on dq0 transformation and AC network power flow. In **chapter 4**, the active generator and back-to-back converter simulation models and results are discussed in details. The detailed information of the proposed micro-grid model and its results are discussed in **chapter 5.** Finally the conclusions of the research study is given in **chapter 6**.

Chapter 2

Integration of Renewable Energy in Power Systems

The detailed background technical information of the research problem is discussed in this chapter. First the electricity grid and its operational control methods are presented. Then the existing grid frequency and voltage control mechanisms are discussed. Finally the frequency and voltage control issues and available solutions for integrating the renewable energy into the electricity grid are discussed in details.

2.1 Introduction

The Electricity grid is an interconnected system of electricity generation stations, transmission and distribution systems. Control systems and protection systems are used to maintain stable operation of the network. The alternative current (AC) electricity grid was developed during the end of the 19th century and is still evolving to match the ever-changing customer requirements, technological innovations, economical operations and environmental issues.

2.1.1 Evolution of the Electricity Grid

The evolution of electricity grid according to the IEA is shown in Figure 2.1.

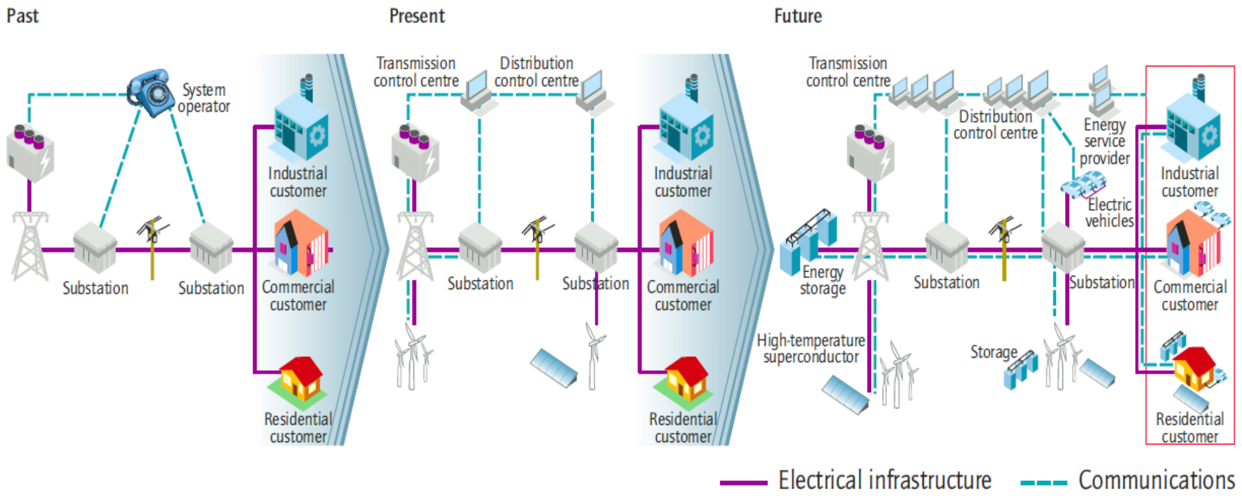


Figure 2.1: Past, present and future electricity grid [8]

Traditionally, the electric grid includes centralized high capacity generation stations, high voltage transmission networks and medium and low voltage distribution networks as well as control systems to control the grid. Power flow is unidirectional from centralized station to the customer premises. Conventionally coal, gas, oil power stations and hydro power stations are being used for power generation. In early electricity grid, Limited primary control technologies and the telephone network had been used to control the electricity grid. With this limited control and information, the grid had been less reliable, and less efficient. With the development of technology, changes of customer demand and other factors, the electricity grid also has evolved to meet the legal requirements and consumer preferences.

In the present situation centralized power station include coal, gas, nuclear and large scale renewable plants such as hydro power stations, wind power farms, high capacity PV power plants and bio-energy plants. Centralized plants are connected to the transmission network and its control is relatively easy. However, with the development of renewable systems, there is also an increasing number of power stations in the distribution network. In the present situation, this penetration level of renewables in power system is low. Also, DG units do not involve in grid frequency, voltage and other control activities, but transferring such control to centralized power plants. But some countries like Germany and Denmark have achieved 20 % or more energy from intermittent energy sources such as wind and PV. Therefore the present electricity grid include more sophisticated control systems in transmission network and low/moderate control over its distributed networks. This is not sufficient and more controls activities over distribution network are required.

Moreover, in future this distribution generation can be expected to increase further and a high penetration of renewables is expected. The smart-grid will be the solution to manage this large penetration of renewable energy. In future micro-grids, energy storage systems, electric vehicles and demand response management, will play important role in power systems management [9].

2.1.2 Characteristics of the Generators used in Electricity Grid

This section briefly review the generator used in electric grid with their characteristics. Synchronous generators, asynchronous (induction) generators and power electronic converters with DG sources are the main types of electric generators.

Synchronous Generators

Synchronous generators are used in traditional power stations and these machine provides the major contribution for electricity generation. There are several advantages with synchronous generators. Their excitation control system can be used to control the grid voltage. Also governor control systems ensure the grid frequency stability. Also the prime movers of the bulk synchronous generators are the main source of inertial /primary frequency response of the grid. Coal, gas and nuclear and hydro power stations are based on synchronous generators. In addition, bio-mass based micro turbine systems and some wind turbines are based on synchronous generators.

Asynchronous Generators

Asynchronous (Induction) generators are used in many small power production facilities. Asynchronous generators are very popular in Wind power applications. It is low cost and has ability to compensate the rapid wind speed changes via the slip function. Also these machines are capable of providing the inertial capability to the grid with its large rotating inertia. But due to variable nature of the wind, electric output become varies and modern control systems isolate the variable nature of mechanical power by using the power electronics converters (DFIG (Type-3) and full convertor (Type-4)) in wind turbines. Therefore it loses its inertial capabilities.

Power Electronics Voltage Source Converters (VSC)

Almost all major renewable energy sources use power electronic converters. It provides the facility to synthesis the required power waveform according to the applications. However, major drawbacks compared to synchronous generators are limited dynamic capabilities and harmonic presents in output waveform.

Renewable source can be classify into two major areas, dispatchable sources and non-dispatchable sources. PV and wind are non dispatchable as energy sources varies over time. However hydro power, Fuel cells and bio-energy based micro-turbines are dispatchable as these systems are associate with stored energy source. Therefore inverter control systems are designed according to the nature of renewable energy sources. Figure 2.2 shows the application areas of VSC in renewable generations.

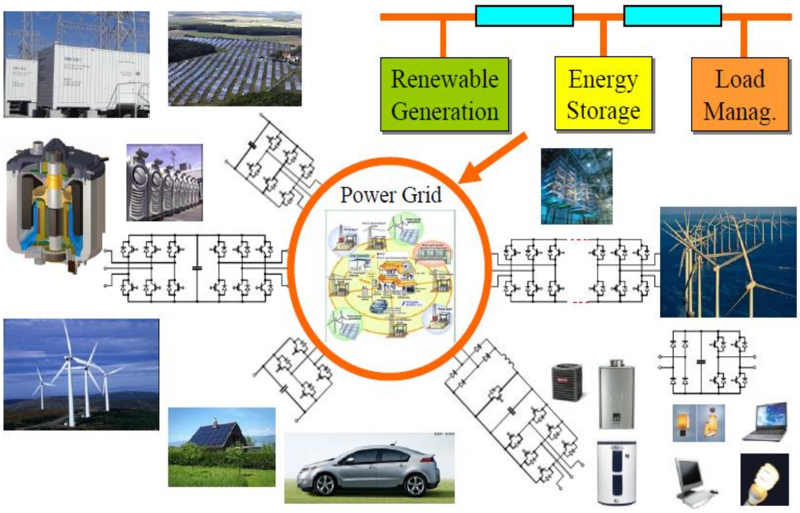


Figure 2.2: Power Electronics devices in Renewable energy applications

PV systems contains MPPT circuits and PWM based VSC to provide power. Traditional small PV invertor injects only the active power. But large PV solar power stations, should have the capability to provide both active and reactive power by participating in frequency control activities and voltage regulations.

There are several types of wind turbine designs. In type-1 systems, asynchronous machines are used and wind turbine designed to operate fixed speed. These systems are directly connected to the grid without use of power converters. Type-2 systems are capable of providing variable speed near synchronous speed via changing the rotor resistance. These systems are inefficient when deviate from synchronous speed and they do not use power electronic converters. In wind power systems, type-3 DFIG and type-4, systems are using the power electronics convertors to regulate power flow of the wind turbines. These systems are capable of working in variable turbine speed and use advance control systems to capture maximum available wind power [10].

In micro-turbine application, it has to use power electronics since the turbine have high speeds than grid frequency. In this case, frequency reduction is required. Fuel cell systems also requires the power electronics convertors as these systems are generating DC currents which need to boost and convert into AC. From these generators, power is dispatchable according to the demand.

2.2 Electricity Grid Operations

The operation of electricity grid is a complex task. Several control systems and supporting systems are used to make a stable grid operation. The major control of grid operations include frequency control, voltage control, and protection and fault management.

2.2.1 Power Balance and Frequency Control

One of main task of grid operation is real time power management of the grid. This is achieved by controlling the electricity production and the consumptions. Most of electricity generators are synchronous generators and they run in synchronous speed which is the grid frequency. In Europe and most of countries, 50 Hz grid frequency is used. USA and other several countries 60 Hz frequency are used. Any mismatch of electricity generation and consumption, will effect to deviate the grid frequency and automatic generator control systems ensure the real-time balance of electricity supply and demand. Therefore grid frequency is accurate measure of balance between electricity supply and demand.

The European frequency control standards are defined in ENTSO-E Operation Handbook [11] where Load-Frequency Control and Performance section describe the requirements. Transmission operator is required to maintain grid frequency between 49.8 and 50.2 (± 0.200) and this is the normal operating range. However in long term deviation should be ± 0.180 Hz. Grid control systems are not activate in ± 0.020 Hz range and if deviation exceed this limit then turbine governing systems are activated in the range of ± 0.020 Hz to ± 0.200 Hz. In this primary control systems, the generators detect frequency droop and change their mechanical power input and control its generator speeds to allowable range. However in large scale faults ± 0.800 Hz frequency deviations are allowed. Further changes in frequency will cause to activate protection relays and some customers will be dropped from the grid to maintain the frequency and if this is not successes complete power system black-out may happen.

Reserved Power

In grid operations, some generators are used in maximum capacity to provide the base load. But there are many conventional generators are not operate in full capacity level and maintain some level of power reserve to facilitate the power balancing and grid frequency control activities. However in renewable generations, they normally set to operate in maximum capacity level, so that they cannot involve in grid frequency control activities. However as a concept energy storage systems can be included with renewable energy sources, and some level of reserve power can be maintained.

Ramp Rate

Ramp rate is the rate that generators can change its output. The unit used to measure the ramp rate is MW/minute. Ramp rate is very important in grid frequency management process. In conventional generators, ramp rate is known and controllable according to the requirements. But with renewables the ramp rate is highly depend on availability of intermittent power (Wind and solar) it become a random variable. Ramp rate controlling of renewable generations is an important research area in renewable energy context.

2.2.2 Reactive Power and Voltage Control

In Europe distribution voltage is maintain at 230 V ±10% with 50 Hz frequency. As in frequency control case, the grid voltages are not same in all points of the network. Therefore voltage control is become a kind of distributed control. Synchronous generators can control their bus voltage by changing its excitation. Voltage droop mechanism is used in these excitation systems. In addition major voltage control mechanism is implemented in the transmission network using Flexible AC Transmission system (FACTS). Low cost devices for voltage control are thyristor controlled Capacitor/inductor banks. In addition STATCOMS, SVC are used as advance devices. In distribution network, voltage regulation is achieved by automatic-tap changing transformers located in substations. For long distance distribution lines pole mounted automatic-tap changing transformers also used. In addition, fixed tap-changing transformers also used as the requirements.

2.2.3 Protection Systems

The protection systems are very important in grid operations and this is usually related to the fault current level. Sophisticated automatic protection system operation is essential for safe grid operation. In conventional power system, power flow is uni-directional. But with DG sources, the grid power flow become bi-directional and the protection system operations become a challenging task.

2.2.4 Power Quality Management

In addition to frequency and voltage controls, there are strict regulations for power factor (PF) correction, Total harmonic distortion (THD) level of the grid waveforms. Further the degree of variation of supply frequency and voltage of the network is a measure of quality of the grid. To achieve large penetration of renewable energy, the electricity grid should be a strong enough to compensate voltage, frequency and PF variations as quickly as possible.

2.3 Integration of Renewable Energy into the Electricity Grid

In previous sections the basics of existing electricity grid and its operations are discussed. In this section our main focus area is how renewables can be connected to the grid. Grid integration of renewables are discussed in three major cases namely low penetration with existing grid, high penetration with existing grid and high penetration with future smart-micro-grid architecture. My main research focus is achieving high penetration of renewables with micro-grid architecture by proper power dispatching strateries.

2.3.1 Low Penetration with Existing Grid

In this case, grid operators are responsible for managing the grid stability and DG operators can send the maximum power available with them, without major consideration of grid operations. In most of countries these method is practically used as renewable portion is small compared to the central dispatchable generations which has reserve power to control the grid.

Grid Integration Strategies

The DG operators have to deliver the power based by grid synchronization via PLL systems with correct phase sequence. Further proper protection system should be included in the DG units to disconnect the units in case of fault or unfavourable grid conditions.

Frequency Control

In low penetration case the distributed generators are not involving in frequency control activities. Grid operator is doing the task. Most of PV panels and Wind generators can inject the maximum available power into the grid. Whenever grid frequency is exceeded the allowable limit the Inverters are required to disconnect from the grid.

Inertial Response, Reserve Power and Ramp Rate

DG units do not have inertial response capabilities and it depends on grid. DG are operate in maximum power condition and therefore it do not have reserve power. Also ramp rate is uncontrollable and unpredictable as it deliver power when renewable sources are available.

Voltage Control

In low penetrated networks, DG units do not involve in voltage control activities of the PCC point. Instead it operates in PF correction mode, where PF keep closer to unity. Most of PV units and Wind generators work in this way. Since most of Renewable sources are connecting to low/medium voltage lines, voltage control of distribution network is real issue to overcome by network operators when integration of renewable sources. The amount of DG units connecting to particular distribution network are limited by the voltage control margins of that distribution network. Automatic tap control transformers, SVC and STATCOM are used by operators to control the network voltage.

2.3.2 High Penetration with Existing Grid

As shown in figure 2.3, when increasing the renewable energy penetration, the portion of existing dispatchable power plants may get reduce and intermittent power portion become considerable level. Therefore in such type of situation intermittent sources cannot work as passive generators, but they have to actively participate in grid frequency and voltage control activities.

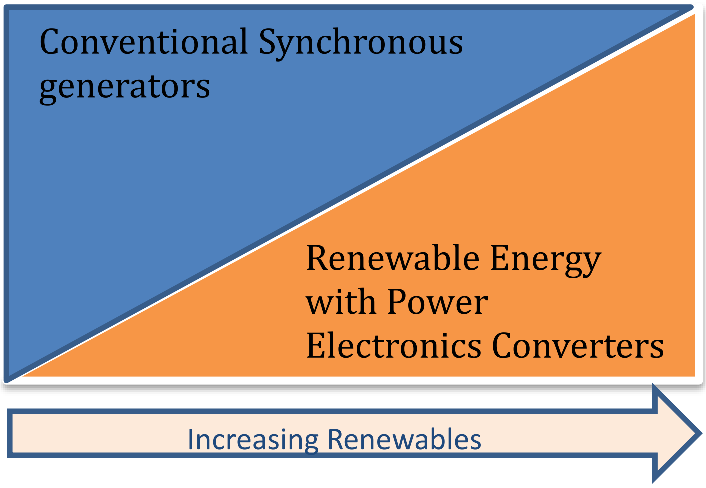


Figure 2.3: Electricity generators and increasing the renewable energy in the grid

For example, countries like Germany and Denmark uses some of these control strategies as they have achieve around 20% of energy from intermittent renewable energy sources and on future the renewable penetration is expected to grow further. For example Germany has introduced new grid code which focuses the stable operation of solar inverters by actively involving the grid stability managing. According to new VDE-AR-N-4105 regulations, all solar inverters should fulfil with following requirements. Output power control, reactive power control, frequency-based power reduction, inverter reconnection conditions and Phase balancing [12].

Grid Integration Strategies of VSCs

In addition to grid synchronization, phase sequence matching and protection system controls, the inverters should be more intelligent. Since the power delivery amount is considerably effect to the grid stability, Phase balanced operations and proper invertor reconnection strategies have to implement in the VSCs. In this way VSC will intelligently response to the grid conditions. Also ramp rate controls is important and have to be implement in the inverters.

Power and Frequency Control

To achieve frequency control through renewable sources, several methods are possible. Following list shows some important methods for achieving power flow control and frequency control.

1. If renewable energy source is dispatchable source such as SOFCs, bio-energy based micro turbine, Hydro it can participate in power and frequency control activities.
2. Non-dispatchable renewable sources (PV, Wind) can be converted as dispatchable with energy storage systems. Batteries, super capacitors or pump hydro methods can be used as energy storage medium.
3. Change the power delivery point of intermittent renewables from its maximum operating point and run them with some reserve power margin. In this method renewables (PV, wind) will not capture maximum available power from sources and which leads to economic challenges of the operations. With this methods renewables can also participate in frequency control same as conventional synchronous generators.

4. Demand side management where non critical loads schedules can be shift to a time period where the grid has excess power.

Reactive Power and Voltage Control

As discussed in low penetration case, most existing VSC are operating in power factor correction mode (zero reactive power). Additional voltage control loop can be included in VSC inverters to provide the necessary reactive power to the grid (Volt-VAR control). However inverter have to operate within defined power factor range (usually -0.95 to +0.95). With this methods VSC will have the capability to control the grid voltage at the PCC point. Distribution network voltage control important when increasing the penetration of DG units. Especially it is required to manage voltage rise effect of distribution network which is occurs when DG units generate more power in the distribution network and low power demand in the network.

2.3.3 High Penetration of Renewable DG with Smart Grid Concepts

As explained earlier, integrating few distributed renewable systems to the grid can be achieved with available technologies. However, if the contribution from DG has to be maximized while maintaining the stability and reliability of the network, then solution may be using smart grid concepts such as micro grids, large scale energy storage systems, smart homes with demand response management etc.

As seen in Figure 2.4, future smart grid networks will provide a real-time, multi-directional flow of energy and information. This will help to better communication and coordination between all the stakeholders in the electricity business such as power plant operators, network operators and the end-consumers. Smart intelligent equipment's with modern digital controls are used in entire electricity grid from central control office to end customer levels.

According to International Energy Agency, "a smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability" [8].

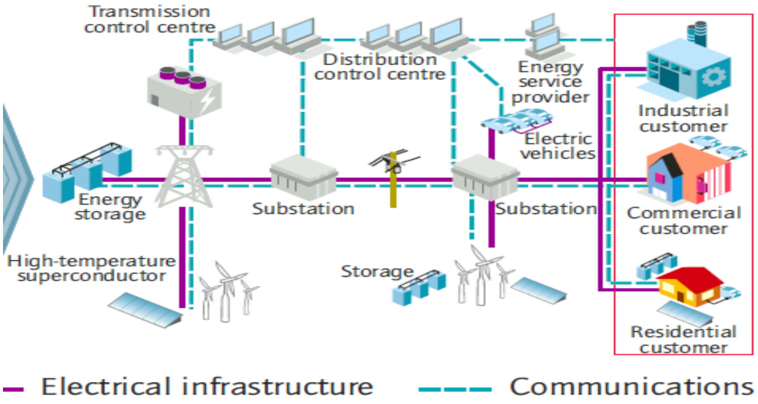


Figure 2.4: Future electricity grid - Source: The International Energy Agency (IEA) [8]

Defining a scope for smart grid technologies is important as it will give overall understanding and boundaries of main concerned areas. Following list shows a smart grid scope defined by US department of energy in 2012 [13].

- Integration of DG Systems /renewable energy sources and energy storage systems
- Automation of transmission and distribution network with self-healing and intelligent control capabilities.
- Energy efficiency, System coordination and situational assessment
- Smart buildings with demand respond management
- Electric vehicle, charging and storage issues

Smart Micro-grids

The smart micro-grid concept can be used to integrate distributed generation in a smarter way. A micro-grid is independent electricity networks isolated from the main grid and includes self-sufficient local generators, storage devices and loads. Figure 2.5 illustrates this concept.

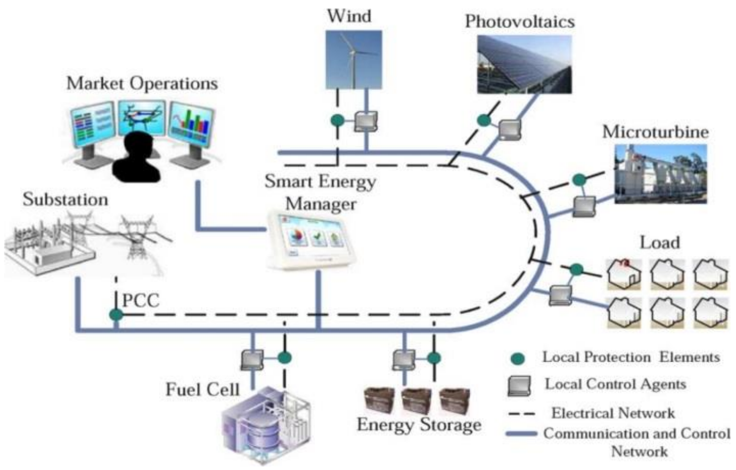


Figure 2.5: The Micro grid concept [14]

Environmentally friendly renewable technologies such as hydro power, wind turbine, photovoltaic and energy storage systems provide the power to the micro-grid as distributed manner. This will help to reduce the greenhouse gas emission. Also reduce the transmission and distribution losses of traditional grid by eliminating long distance power transmission. With this concept all stakeholders of the network can become active users.

As shown in the figure 2.5, Smart micro-grid provides two way energy distribution and communication networks and consumers can communicate with market operators to reduce their energy cost (Demand Response management). On the other hand operators have the facility to optimize customer's power consumption by measuring the real-time user demand. Generally grid connected micro-grids are always synchronized with the grid via point of common coupling (PCC) and if there is a failure in main grid, micro-grid can operate as isolated and self-sufficient manner without major disturbances to the network and customers. When main grid returns to normal the micro-grid can resynchronize with main grid which make more reliable electricity supply to the customers.

Energy Storage Systems

Since most of available renewable power outputs become fluctuate, intermittent and random, Advance energy storage systems can be integrated to renewable power systems so that power output can be made smooth.

Numerous energy storage technologies are available but the challenge is to make them more practical, reliable and economically feasible. Current widely used storage technologies is pumped hydroelectric storage. Compressed-air energy storage also possible, but it required specific environments to implement and it is a costly solution.

Producing large scale (MW Scale) batteries are hot research topic and technologies based on Lead (lead-acid, lead-carbon), sodium sulphur (NaS), lithium-ion are under research. Present, Japan grid scale batteries can supply power to its grid with about 300 MW for up to six hours [15]. As electric vehicles becoming more popular, the batteries used in electric vehicles can also be used as an energy storage medium when vehicles are stationary and parked in home or office. Further hydrogen is very useful energy carrier and which can be integrated with Electrolysis/Fuel cell system to store energy and reproduce electricity.

Super capacitors also emerging new technology for short time storage which can use stabilize voltage of renewable systems. For example Photovoltaic systems producing fluctuating power due to effect of clouds which can be regulate using super capacitors as it can store power within short periods. Flywheel storage systems are also commercially available and are useful for regulating the frequency of a power grid. It can reliably deliver modest amounts of power for seconds or minutes and absorb surplus power as quickly.

2.4 Summary and Discussion

In this chapter, the technical background for integrating renewables into the power systems have been discussed. The chapter starts with discussing the electricity grid structure and its operational control. Then methods for integrating renewables in the grid is discussed in details. With this knowledge, it is clear that smart-micro grid is the best way to achieve high penetration of renewables.

In this research micro-grid method is focused, which has been discussed in 2.3 section. To achieve this task, power electronics interfaces required to be equipped with smart control systems which means they should work as active generators. Therefore the understanding of VSC and its control systems is essential to make a stable micro-grid.

Chapter 3 covers three-phase voltage source converters (VSC) and their control systems. Three-phase VSCs are the actual interface of renewables and can be modified to work as conventional generators to provide primary load sharing capabilities, frequency control and voltage control via reactive power delivery etc. Therefore the overall system can be defined as an active generator.

Chapter 3

Mathematical Formulation of AC network Power Flow and Active Generators

The main focus of this research work is implementing active and reactive power dispatching strategies for active generators in micro-grids. The aim is to achieve high penetration of renewable energy. An active generators includes VSC and their control systems. Moreover, the active generators have the power flow (active and reactive) management capabilities based on frequency, voltage droop characteristics. The power for active generators can be extracted from renewable sources and proper integrated storages.

3.1 Introduction

Many of the renewable energy sources such as Photovoltaic systems, SOFC are DC in nature. Therefore it requires a DC to AC inverter for integrating them to the AC grid. Further, micro-turbines generators are operated much higher frequencies than grid synchronous speed and hence back-to-back (AC to DC to AC) conversion is required to match the grid frequency. Although old type-1 and type-2 Wind turbines can connect to the grid without Inverters, most of modern variable speed type-3 (DFIG) and type-4 (Full converter) are connected to the grid via power electronics inverters. When consider the energy storage systems, such as batteries they deliver the stored energy as DC and DC/AC conversion is required to utilize the energy in AC Grid. Therefore it important to study the operation and underline mathematical concepts and control system for VSCs. Before study about the VSCs, it is essential to understand the traditional AC network theories with synchronous generator operations which are discussed in Section 3.2 and these concepts will be extended to VSCs in further sections.

3.2 General AC Network Power Flow Theories

Small length transmission line ($0 < 80$km) active and reactive power delivery from source to the load (Fig 3.1) can be written as follows.

$$P = \frac{V_s}{(R^2+X^2)}[R(V_s - V_R\cos\delta) + XV_R sin\delta] \tag{3.1}$$

$$Q = \frac{V_s}{(R^2+X^2)}[-RV_R sin\delta + X(V_s - V_R\cos\delta)] \tag{3.2}$$

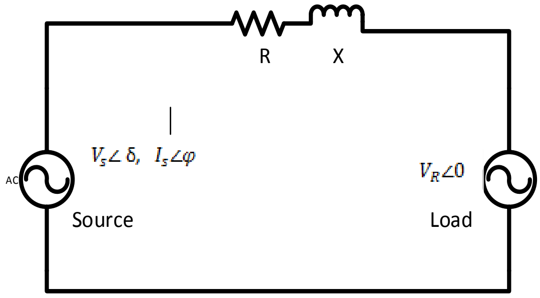


Figure 3.1: AC Network Power Flow with small length transmission line

Where

R, X = transmission line resistance and inductance
P,Q = active and reactive power delivery
V_S, V_R= source and load voltage
δ = power angle

For high voltage transmission lines R/X ratio is small and R can be neglected. Therefore,

$$P = \frac{V_s V_R sin\delta}{X} \tag{3.3}$$

$$Q = \frac{V_s^2}{X} - \frac{V_s V_R \cos\delta}{X} \tag{3.4}$$

For small δ values, sin δ can be approximate to δ (in radian) and cos δ can be approximated to 1. Therefore,

$$P = \frac{V_s V_R \delta}{X} \tag{3.5}$$

$$Q = \frac{V_s(V_s - V_R)}{X} \tag{3.6}$$

This means by changing power angle, active power can be controlled. Same way by controlling magnitude of voltage difference, the reactive power can be control. In synchronous machines power angle can be controlled by changing the input mechanical power through turbine governing system and output voltage can be control by changing the excitation of field windings.

3.2.1 Voltage and Frequency Droop Control

Consider a synchronous generator (figure 3.2) is placed in source side. When load increase (P increase), generator has to provide more power to the load. To increase P injections to the grid, the power angle has to increase. This is achieved controlling the input value of the turbine, based on grid frequency droop.

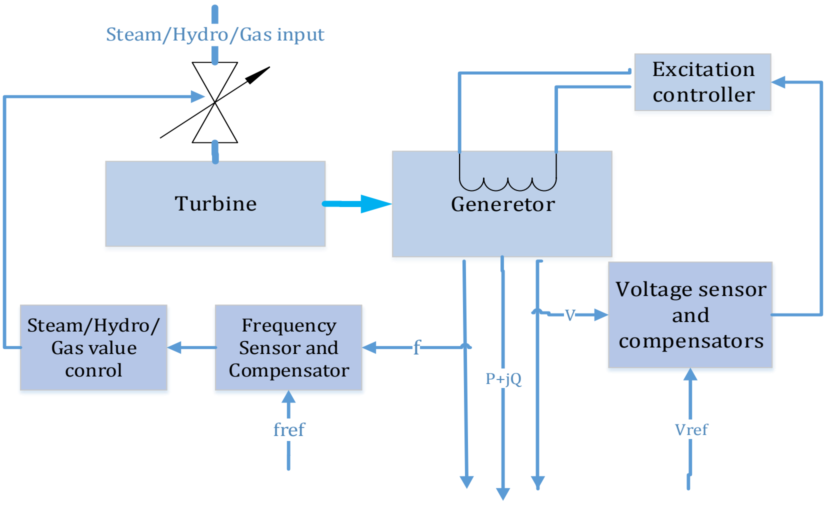


Figure 3.2: Load frequency and excitation voltage regulator of a turbo-generation

Frequency droop is defined in equation 3.6. Typical frequency droop values (k_p) for grid scale synchronous generators are 5 %.

$$k_p = \frac{Change\ of\ frequency from\ normal\ frequency}{Change\ of\ Power\ from\ set\ point} \tag{3.7}$$

$$f = f_0 + k_p(P - P_0) \tag{3.8}$$

Further changing reactive power means, the voltage of coupling point changes. This can be achieved by changing the excitation of the generator. A simple relationship of this droop behaviour can be shown as equation 3.9.

$$V = V_{grid} + k_q(Q - Q_0) \tag{3.9}$$

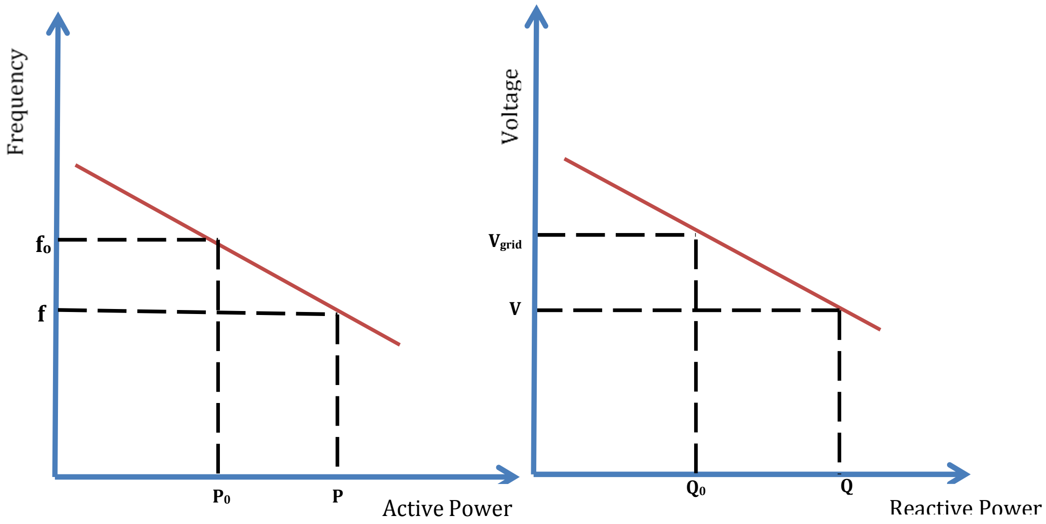


Figure 3.3: Droop control Method: (a) Frequency droop, (b) Voltage droop

The frequency droop characteristic above can be interpreted as follows: when frequency falls from rated f_0 to f, the power output of the generating unit is allowed to increase the power dispatching value fromP_0 to P. A falling frequency indicates an increase in loading and a requirement for more active power. In same way when the coupling point voltage of synchronous generator decreases from V_{grid} to V, generators are allowed to increase its reactive power from Q_0 to Q level.

3.2.2 Parallel Operation and Load Sharing

In a case of two generators providing the power to a load. The active power sharing between each generator depend on load angle and reactive power depends on magnitude of voltage deference.

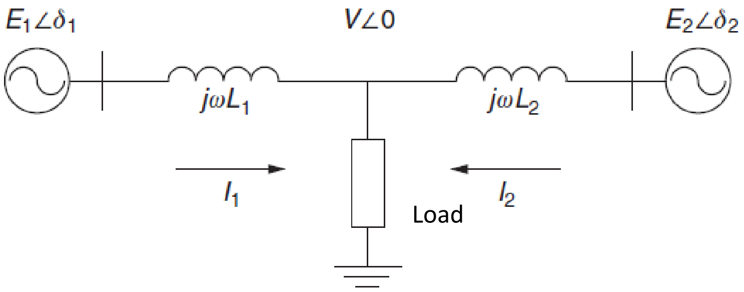


Figure 3.4: Parallel operation of Power generators

When several generators are operate in parallel, and for load changes each generator can automatically change their power levels, based on frequency droop characteristics. This is useful as generators response load changes by taking the frequency variation as input signal and droop function as power calculation method. For example when load increases, which results a frequency reduction in the system, generators will increase their power levels according to the droop curve and hence the system frequency will increase again. However droop control mechanism is a proportional control system and it cannot control the frequency for selected set point value and always there exist a steady state error. Therefore secondary control mechanism is used for accurate frequency control.

3.3 Active and Reactive Power Control of VSCs

To get an independent controllability of active and reactive power in the VSCs, it is necessary to get two control variables for each. Dq0 transformation can be used to get independent two current components, I_d current to control active power and I_q current to control reactive power.

3.3.1 Dq0 Transformation

Dq0 transformation is used to transfer 3 phase voltage or current sequence to a 2 axis (I_d, I_q) rotating coordinate system and it consists with two transformation steps, namely Clark transformation and Park transformation. For balanced symmetric three phase systems, dq0 transformation can be simplified to dq transformation and zero current component can be neglected. In this study symmetric dq0 transformation is considered and hence only dq components are used instead of dq0 components.

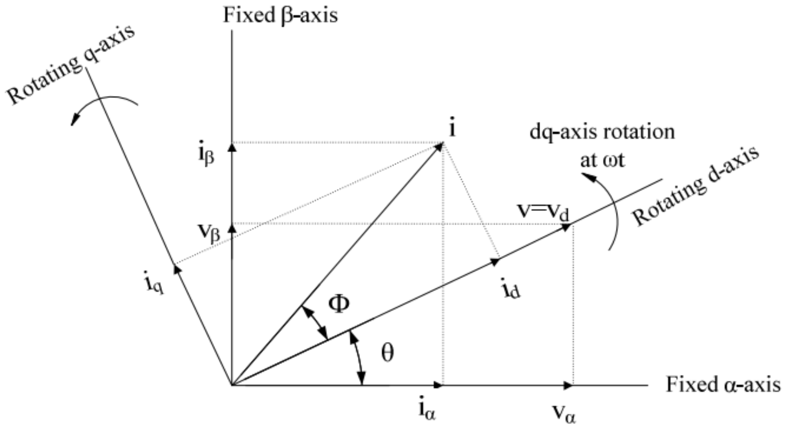


Figure 3.5: Clark Transformation and Park Transformation

Clark transformation

Clark transformation help to transform 3 phase voltage or current sequence (V_{abc} or I_{abc}) to stationary voltage or current reference frame (V_α,V_β or I_α,I_β). Mathematical this process can be shown as following.

$$\begin{bmatrix} v_{\propto} \\ v_{\beta} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (3.10)$$

Park transformation

Park transformation is used to transform stationary voltage or current reference frame (V_α,V_β or I_α,I_β) to a rotating voltage or current reference frame (V_d,V_q or I_d,I_q) and mathematically shown as following equation .

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} cos\ \theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_{\propto} \\ v_{\beta} \end{bmatrix} \qquad (3.11)$$

Consider symmetrical there phase system example where;

$v_a = \mathrm{V}\cos(\theta)\,, v_b = \mathrm{V}\cos(\theta - 2\pi/3)\,, v_c = \mathrm{V}\cos(\theta - 2\pi/3)$

By applying Clark transformation and park transformation

$$\begin{bmatrix} v_{\propto} \\ v_{\beta} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} {}^{2}/_{3} \,.\, \mathrm{V}\cos(\theta) \\ {}^{2}/_{3} \,.\, \mathrm{V}\sin(\theta) \end{bmatrix}, \qquad \begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} V \\ 0 \end{bmatrix}$$

Here v_q become zero and $v_d = V$

3.3.2 Independent Control of Active and Reactive Power of VSC

Consider a three phase VSC system, where DC power is converted to AC and transferred to infinite AC bus. Each IGBT transistors are controlled by a PWM system to generate the required AC waveform.

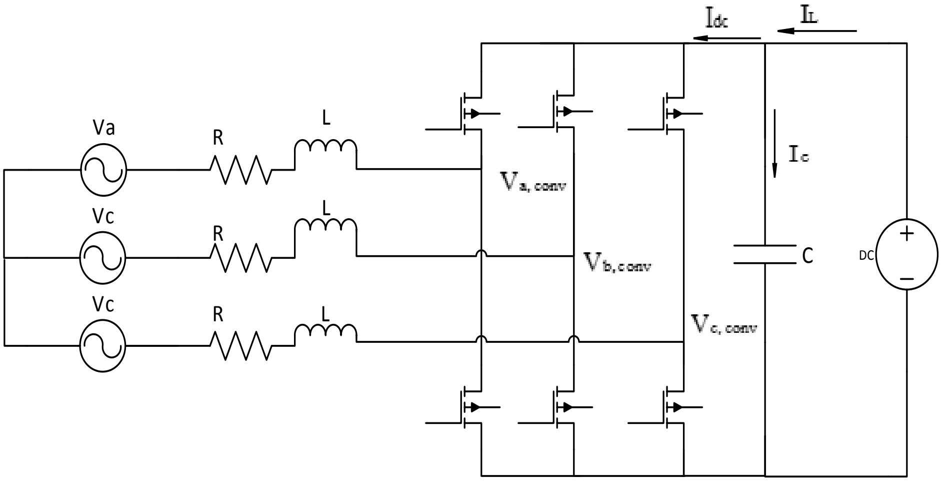


Figure 3.6: Basic VSC converter system

The voltage balance equation (Consider current flow DC side to AC) for above system can be written as;

$$v_{abc,conv} = v_{abc} + Ri_{abc} + L\frac{di_{abc}}{dt} \qquad (3.12)$$

$$\begin{bmatrix} v_{a,conv} \\ v_{b,conv} \\ v_{c,conv} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad .$$

By taking Dq Transformation;

$$\begin{bmatrix} v_{dconv} \\ v_{qconv} \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \end{bmatrix} + R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$v_{d,conv} = v_d + Ri_d + L\frac{di_d}{dt} - \omega Li_q \qquad (3.13)$$

$$v_{q,conv} = v_q + Ri_q + L\frac{di_q}{dt} + \omega Li_d \qquad (3.14)$$

Considering dc voltage side;

$$I_L = C\frac{dv_{dc}}{dt} + I_{dc} \qquad (3.15)$$

The power balance equation is given by;

$$\frac{3}{2}\left(v_d i_d + v_q i_q\right) = V_{dc}I_{dc} \qquad (3.16)$$

Now considering grid voltage along d axis and then grid voltage= v_d and v_q=0. Therefore instantaneous active (p) and reactive (q) power relationship is;

$$p = \frac{3}{2} v_d i_d \tag{3.17}$$

$$q = -\frac{3}{2} v_d i_q \tag{3.18}$$

This means active and reactive power can be controlled independently with i_d and i_q current components.

3.4 Three-phase VSC Power Flow Control

In PWM based VSC systems, PWM is used to generate required AC waveform and there can be used several methods to achieve power flow control. However control schemes are varies according to the nature of renewable power source and control requirements. This section discussed some of available control techniques found in literature.

1. The load angle control method can be used same as synchronous generators. The power angle of reference waveform can be calculate based on active power requirement and the magnitude of voltage can be calculate using reactive power requirement.

   $$\delta = \frac{\mathrm{P.X}}{V_S.V_R} \tag{3.19}$$

   $$V_s = V_R + \frac{(Q.X)}{V_s} \tag{3.20}$$

   When renewable power source work in unity power factor mode, Q is set to zero and$V_s = V_R$. An implementation of this method for synchronous permanent magnetic wind turbine control can be found in [16].
2. DFIG Wind power generator control systems, two converters namely, rotor side converter and grid side converter are used. To control rotor side converter, dq transformation based method is normally used. Id component of rotor current is used to control output voltage (reactive power) and Iq component is used to control the generator torque (active power). The output of this stage is DC current and which is used as input to the grid side converter [10].
3. In most of PV power systems, fuel cell and grid side converter of wind turbines, dq0 transformation is used to get two independent current components, I_d, I_q.

Active power flow can be controlled by changing the I_d and reactive power can be controlled by changing the I_q components.

3.4.1 Three-phase VSC Operation in Current Mode Control

In this research the power flow of each active generator is controlled by the third method discussed in above section. Here dq0 transformation and its associated I_d, I_q current components are used for power flow control. There can find many implementation methods in this category. But in all inverters, internal current control method and grid synchronization with PLL are common, while other external control designs modified according to the nature of renewable power source. The system used in figure 3.7 can be used for grid connected solar inverter or grid side converter of wind turbine.

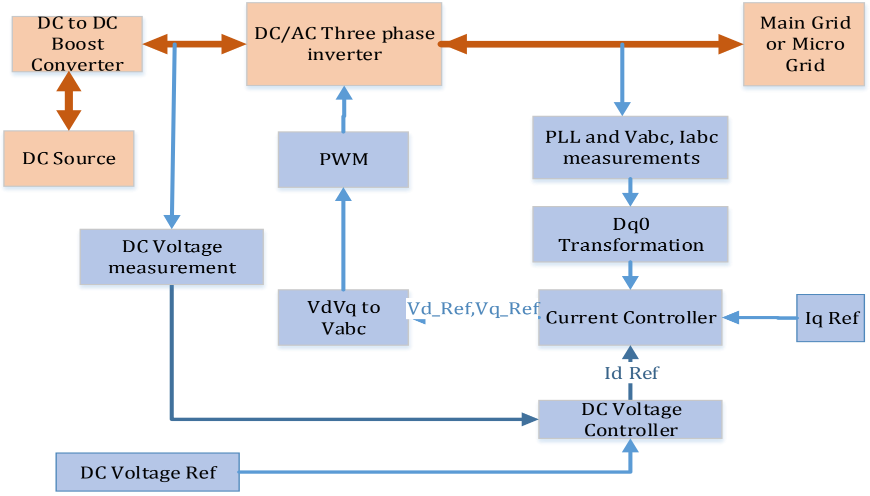


Figure 3.7: Current mode control for intermittent renewables

When this system use as solar inverter, PV array work as DC current source and DC to DC boost converter should work in maximum power point tracking mode by controlling the its output voltage. The objective of DC voltage controller is maintaining the constant DC bus voltage by controlling its active power output (Id current component) [6].

In wind turbine case DC source can be achieved by the AC to DC conversion, which is generally associated with the rotor side control system. Generally DC to DC boost converter is not used in DFIG wind turbines and rotor side converter is controlled to get required DC voltage. However in type-4 full converter wind turbine case DC to DC boost converter with diode rectifiers can also be used [10].

Figure 3.8 shows the inverter control system, where DC voltage control is done by boost converter. This method is suitable for Battery and Fuel cell type power sources. Constant DC voltage is assured by boost converter, I_d, I_q can be control as active and reactive power requirements respectively.

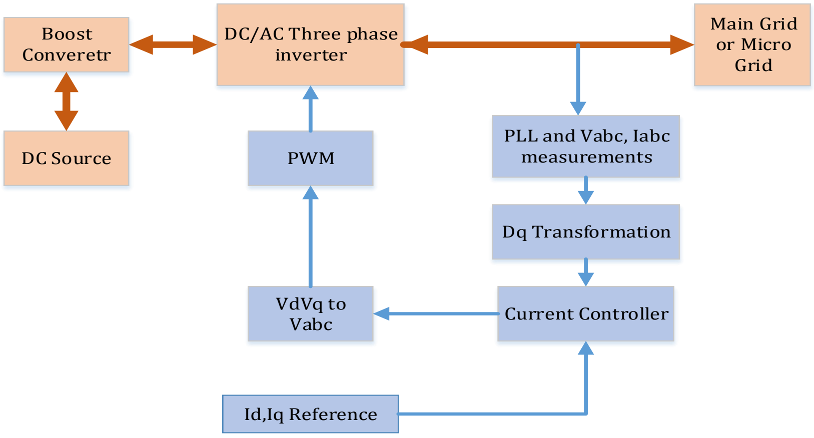


Figure 3.8: Current mode control for dispatchable renewables

3.4.2 Three-phase VSC Operation in Voltage Mode Control

When VSC is used to provide the power to an isolate load (not to the grid), PLL system cannot use. Unlike grid connected case there cannot use a measured waveform to synchronize. Therefore VSC unit has to generate its own waveform based on reference amplitude, frequency and phase. Figure 3.9 shows such a VSC implementation.

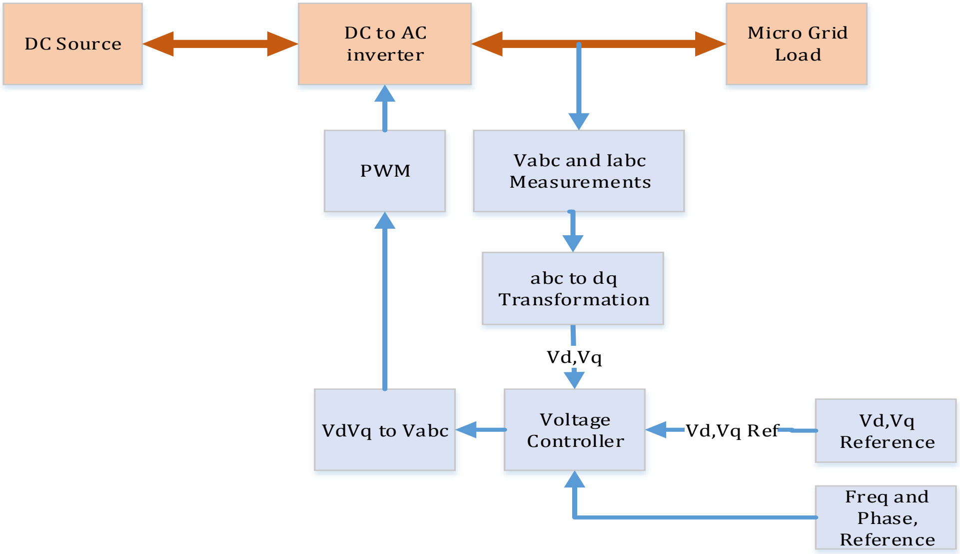


Figure 3.9: Voltage mode control of a VSC

In this implementation only voltage controller is used and it is simple implementation. But for advance operations, inner current controller and outer voltage controller implementations can be found in the literatures. In this study, the voltage mode control of VSC system is implemented in the micro-grid side of back to back converter.

3.5 Active Generator Operation with Droop Control

In the above sections, AC network power flow control and VSCs control systems are discussed. To converter a VSC to an active generators, droop control system have to be implemented in the VSC control system. In the VSC with current mode control, the active and reactive power dispatch can to be modified with following equation. This system will work as an active generator with controllable power dispatching capabilities.

$$P = P_0 + k_f(f - f_0) \qquad (3.21)$$

$$Q = Q_0 + k_v(V - V_{grid}) \qquad (3.22)$$

Where;

P = Active power output
P_o = Active power set value of the generator
K_f = frequency droop setting
f = measured frequency
f_o = standard grid frequency set point

Q =Reactive power output
Q_o = Reactive power set value of the generator
K_v = voltage droop setting
V = voltage of coupling point
V_o = standard grid voltage set point

The simulation model implementation of active generator is discussed in chapter 4.

3.6 Summary and Discussions

In this chapter, the mathematical formulation of active generators are discussed. First, AC network power flow theories and VSC operation methods are discussed. It is observed that with dq0 transformation, it is possible to do independent control of active and reactive power with I_d and I_q current components. With PI control systems this power flow can be controlled. Then the active generator operation with droop control is discussed which can be included in control systems to generate power references. These active generators can be used in the same way as conventional generators in the micro-grid environment.

In the next chapter the implementation details of the active generator simulation models are discussed. This includes VSC control system and droop control implementations.

Chapter 4

Active Generator and Back-to-back Converter Models and Simulations

In previous chapter, basic mathematical formulation for VSC and active generators are considered. In this chapter, MATLAB/Simulink implementation of active generator and back-to-back converter are presented. Furthermore, droop control techniques are implemented and analysed for power dispatching. In chapter 5, complete micro-grid model will be simulated by combining back-to-back converter and several active generators.

4.1 Introduction

Basically VSCs can be controlled as current mode control, where VSCs have to synchronize with the grid voltage waveform and can provide power to the grid by controlling its current output. However when VSCs are not connected to the grid but directly to a load, it has to produce its own AC waveform to operate its loads. In this case inverters has to generate and control its output voltage waveform and works in voltage control mode. Since proposed micro-grid will be connected to the main-grid via back to back converter, grid waveform is not transferring to the micro-grid and voltage mode control is required in proposed micro-grid. All other inverters can synchronize with this waveform and can be worked in current mode control.

4.2 Active Generator Power Dispatching Simulation Model

Figure 4.1 and 4.2 show simplified block diagram view and Simulink implementation of the Active generator model. The power converter systems used in figure 4.2 included the typical VSC and LC filter, delta–wye transformer unit and control systems. The main sub units of the system and its purpose is as follows. More details of each unit is discussed in next sections. The system parameters are given in appendix A.1.

1. Three Phase Bridge and PWM unit: The universal bridge which is controlled to achieve bi-directional active and reactive power delivery based on PWM signal.
2. PLL and grid synchronization: PLL is used to get the grid frequency, voltage and phase angle information, which is used in the control system

3. LC Filter: LC Filter used to reduce the harmonic of output waveform
4. ΔY Transformer and Grid connection: Delta–wye transformer used to change the potential levels and electrical isolation.
5. DC source: Providing the required power to the system.
6. Control System: Current controller implement the independent control of active and reactive power delivery of inverter, based on PQ reference and V, f reference.

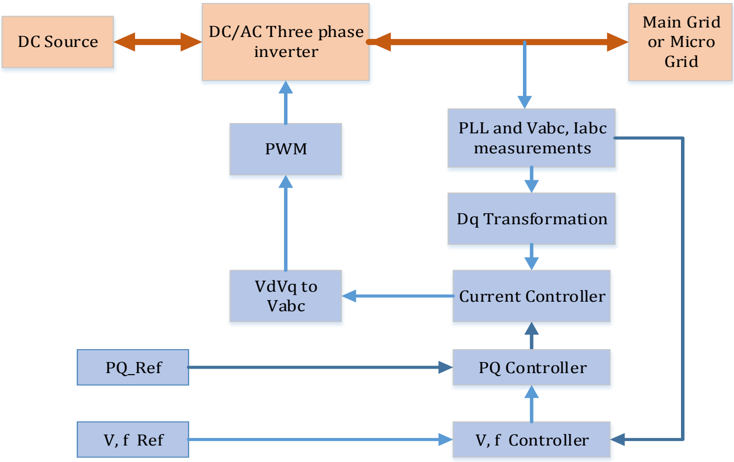


Figure 4.1: Active Generator model for current mode control

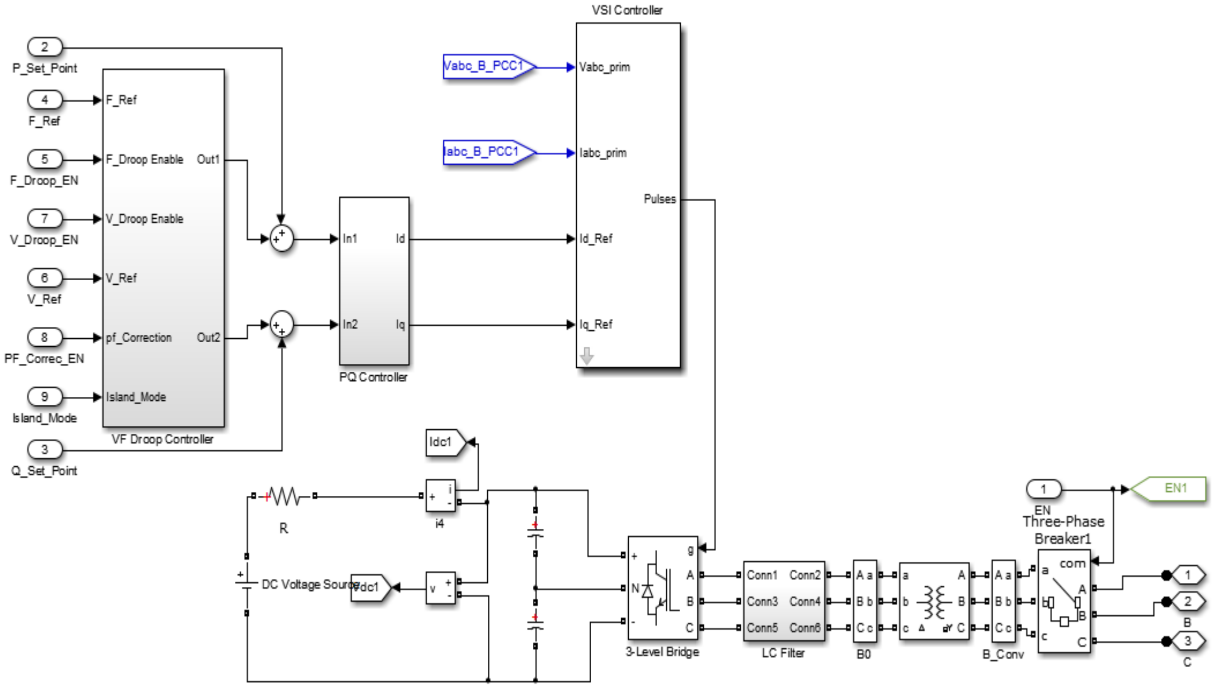


Figure 4.2: Simulink implementation of Active Generator model for current mode control

4.2.1 DC Power Source

In this initial study phase, an ideal DC voltage source is used. However in the micro-grid implementation, other DC power sources such as Battery and SOFC with a DC-DC converter (for DC voltage regulation) are used and will be discussed in chapter 5.

4.2.2 VSC Control System

VSC control system generate the required PWM signal for the inverter bridge based on reference I_d, I_q current components and V_{abc}, I_{abc} measurements. Figure 4.3 shows the Simulink implementation of VSC Control and there include three major sub systems. The main sub units are shown in following list.

i. PLL based measurement sub system
ii. current controller
iii. Pulse width modulation signal generation

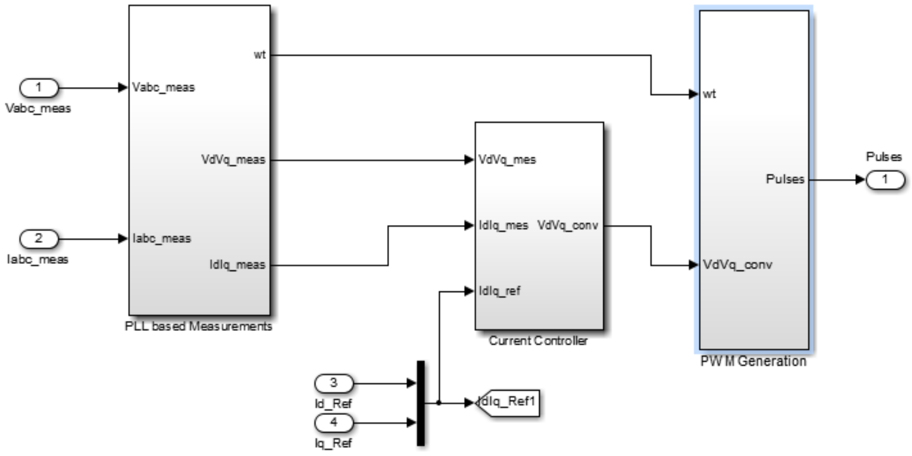


Figure 4.3: VSC Control sub system

PLL based Measurement sub system

Feedback control system is used in the inverter, where output voltage and current are measured and other required data for control system are generated. More details are shown in figure 4.4. V_{abc} is measured and is given input to PLL unit. PLL output gives the phase angle (ωt) of the grid and this phase ωt signal is used for synchronization purpose.

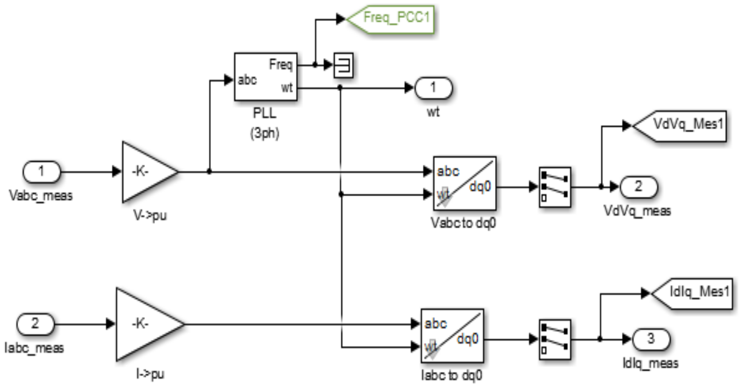


Figure 4.4: PLL based Measurement sub system

Next task of this sub system is to convert V_{abc} and I_{abc} waveforms to V_d, V_q and I_d, I_q components and these measurements are sent to the current controller.

Current controller

Figure 4.5 shows the implementation of current controller. The error between I_d, I_q reference and I_d, I_q measured are sent to the PI controller and PI Controller gives the output for V_d, V_q reference and it is used as the PWM block reference voltage.

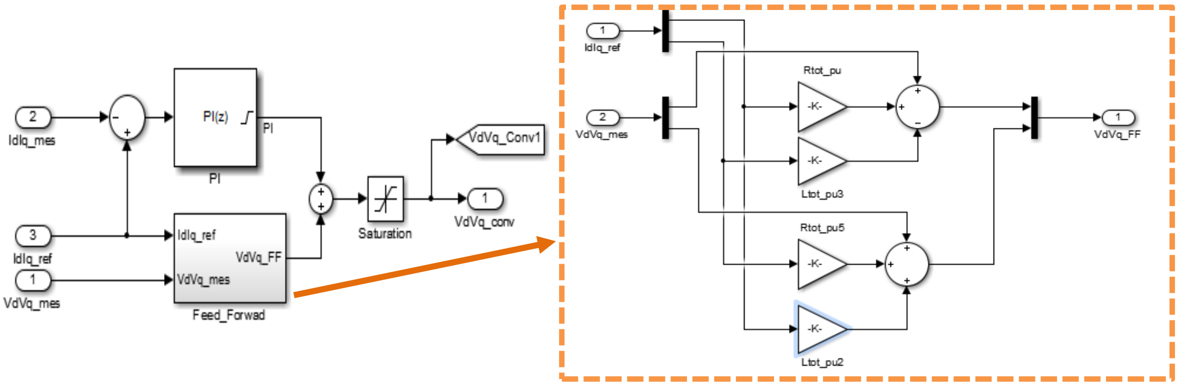


Figure 4.5: Current Controller

In addition, as discussed in section 3.3, the feed forward system is used to implement the 3.13, 3.14 equations which can decouple the dq components of current and voltages.

$$v_{d,conv} = Ri_d - \omega L i_q + L\frac{di_d}{dt} + v_d$$

$$v_{q,conv} = Ri_q + \omega L i_d + L\frac{di_q}{dt} + v_q$$

Voltage reference signal generation and PWM

Inside the PWM block, the required reference sin waveform is generated based on V_d, V_q signal and measured phase angle of the AC system. V_d, V_q signal is normalized by following factor.

$$\text{Vd, Vq signal normalized factor } = \frac{0.5V_{dc}}{V_{sec} * sqrt\ (2/3)}$$

Where V_{dc}=800V and V_{sec}=260V rms.

Then this reference voltage signal is sent to the regular PWM unit and it generate the required pulses for the inverter bridge. Since ΔY transformer is the included in VSC system, there is a -pi/6 radian phase shift in the voltage, which has to be corrected.

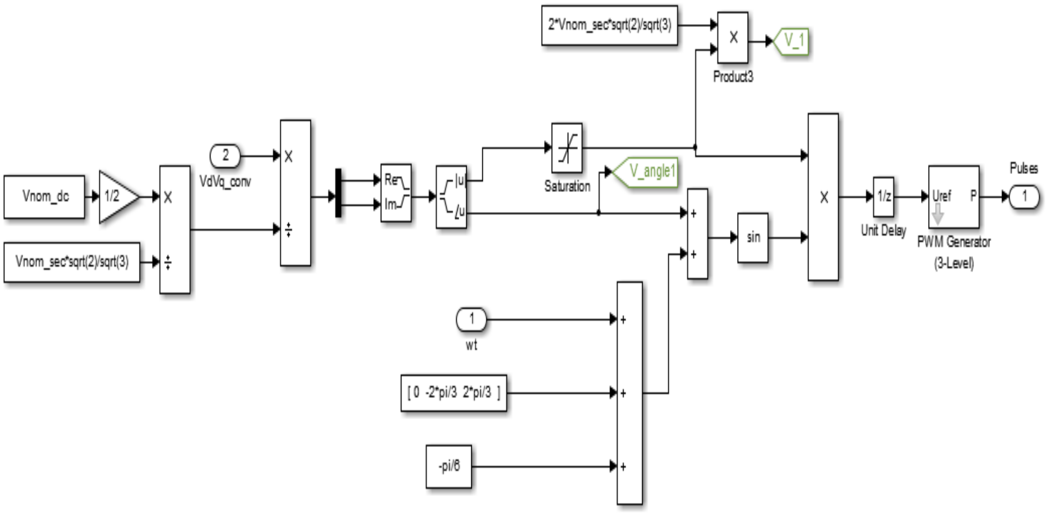


Figure 4.6: Voltage reference signal generation and PWM

4.2.3 Active and Reactive Power (PQ) Controller

In grid or micro-grid connected mode, VSC output voltage is defined by the grid and VSC has to follow grid voltage. But VSC can send the available DG power to the grid by controlling its I_d and I_q current components.

Output power were measured and compared with reference active and reactive power. The error signal for power (P and Q) feed to the PI controller. The maximum power output of the converter is limited by the saturation limit. The Simulink implementation is shown in Figure 4.7.

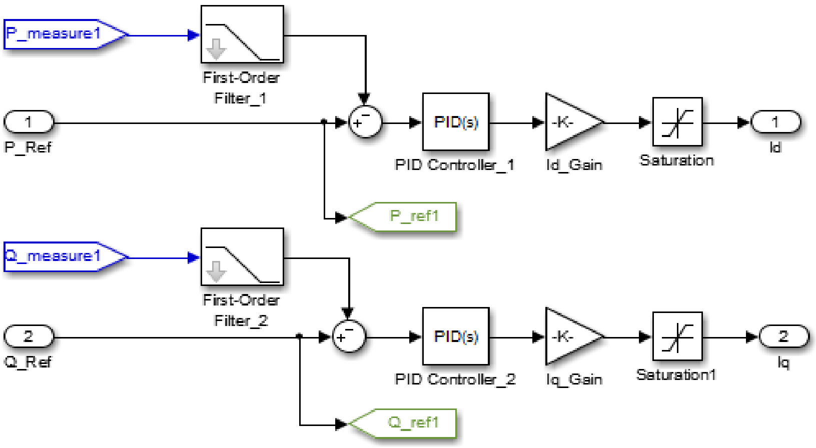


Figure 4.7: Active and reactive power (PQ) controllers

4.2.4 Frequency and Voltage Controller

Frequency and voltage control logics are implemented in the VSC system and therefore the system can work as an active generator. The Flow chart of control logic is shown in figure 4.8 and Simulink implementation is shown in Figure 4.9.

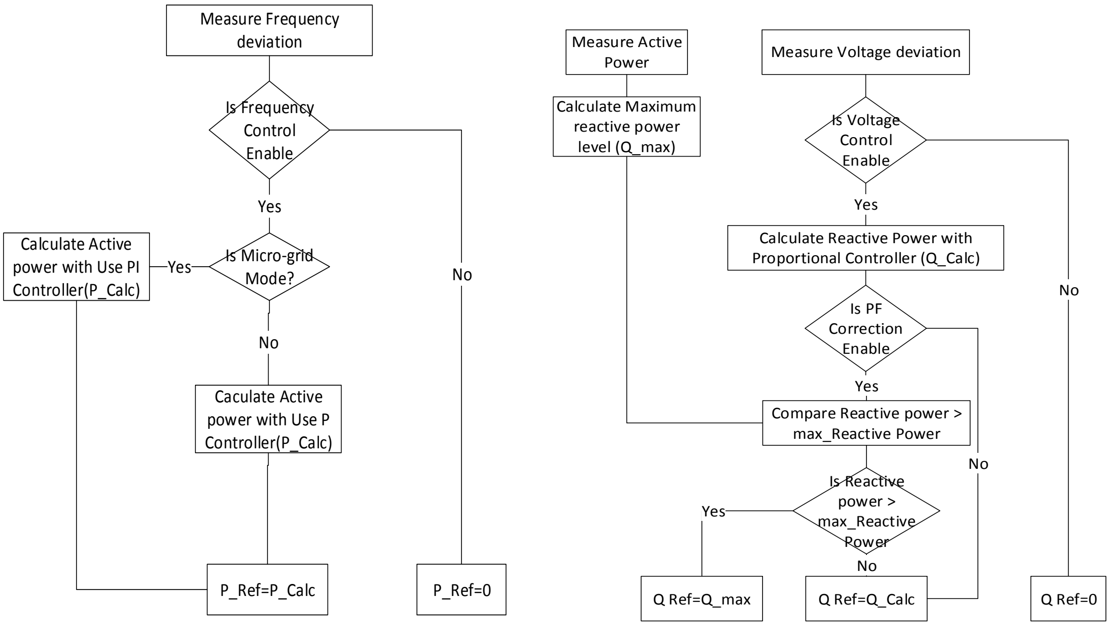


Figure 4.8: Frequency and Voltage droop control logics

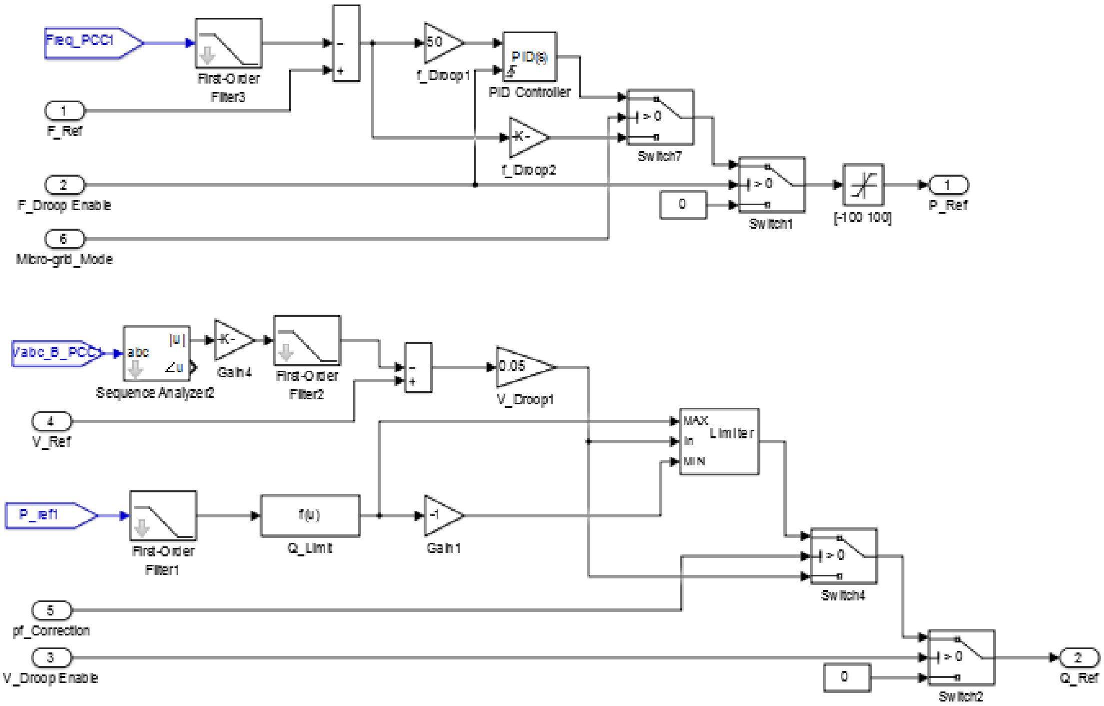


Figure 4.9: Frequency and Voltage controllers

Initially, active and reactive power can be set to the required value. However some additional active power can be delivered according to the frequency deviation of the grid. If frequency droop is enable, this additional power requirement reference is calculate based on the error signal of reference and measured frequency values. If system is in micro-grid mode, PI controller is used as controller. However if system is not in micro-grid mode, then only proportional control is used. This system implements the frequency droop capabilities within the VSC and system can act as an active generator. The output of this control system gives the additional power reference.

Voltage control is based on changing the reactive power delivery by changing the I_q current component of the system. Initially, reactive power delivery point can be set to the required value. Additional reactive power can be delivered based on the voltage deviation of PCC of the active generator. If voltage control is enabled, the error signal of reference and measured voltage is sent to the voltage controller which generate the required reactive power. Further if power factor correction is enabled, the maximum reactive power is calculated based on maximum power factor (0.95) and the reactive power level is constrained by this limit.

4.2.5 Simulation Model

Active generator has been connected in grid with a load and tested for performance. Figure 4.10 shows the implementation. 11 kV, 50 Hz grid is modelled by taking three-phase voltage source and the load is set to 250 kW active power and 50 kVar reactive power levels. Three short distance transmission lines (0.3 Ω/km, 1mH/km) each has 1 km length were used for interconnections. Power reference was given by a signal builder model available in the Simulink. Other model parameters are same as shown Appendix A.1.

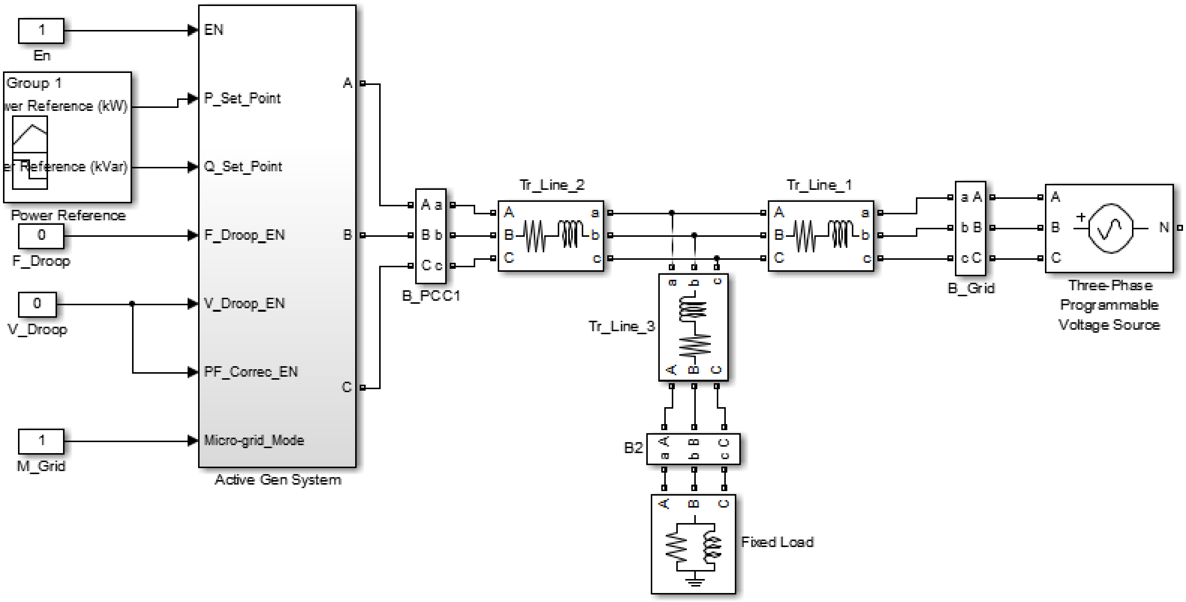


Figure 4.10: Simulation model of Active generator, load and the Grid

4.2.6 Simulation Results

Active, reactive power flow and AC network parameters such as voltage, frequency, current and THD at the load point have been tested.

Active and Reactive Power flow Control

Active and reactive power references and measured values are shown in figure 4.11. Voltage and frequency droop controllers have been deactivated in this test. Simulation The time 0.5 s has been selected as the simulation start time. Active and reactive power references were selected to test different power injection scenarios of the active generator. In 1.0-1.5 s time period the active power input is ramp signal while reactive power input remain 0. In 2.0s step response of active power is tested. Active generator performances are well accepted for both ramp and step inputs. However little oscillation of reactive power observed for 50% step down of active power, but soon after reactive power become stable.

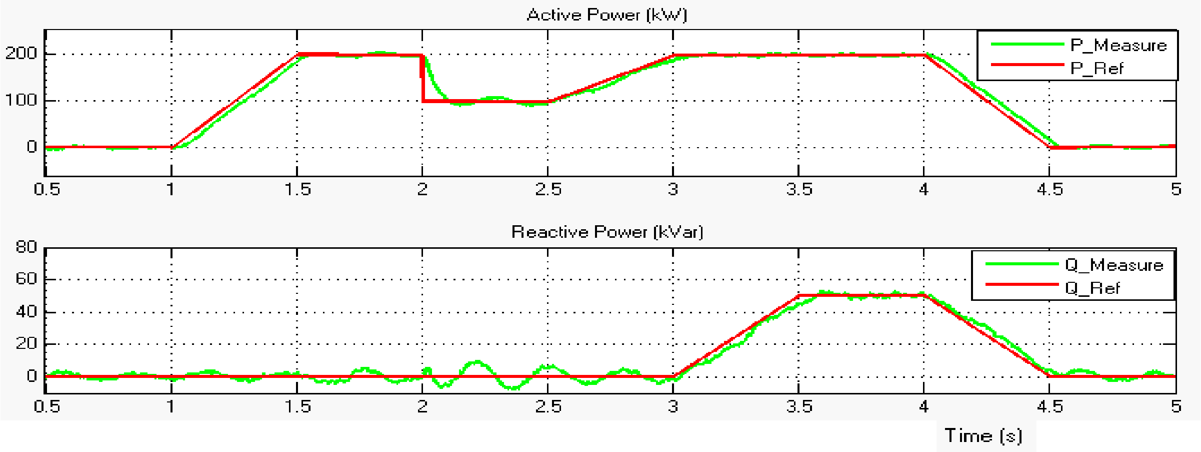
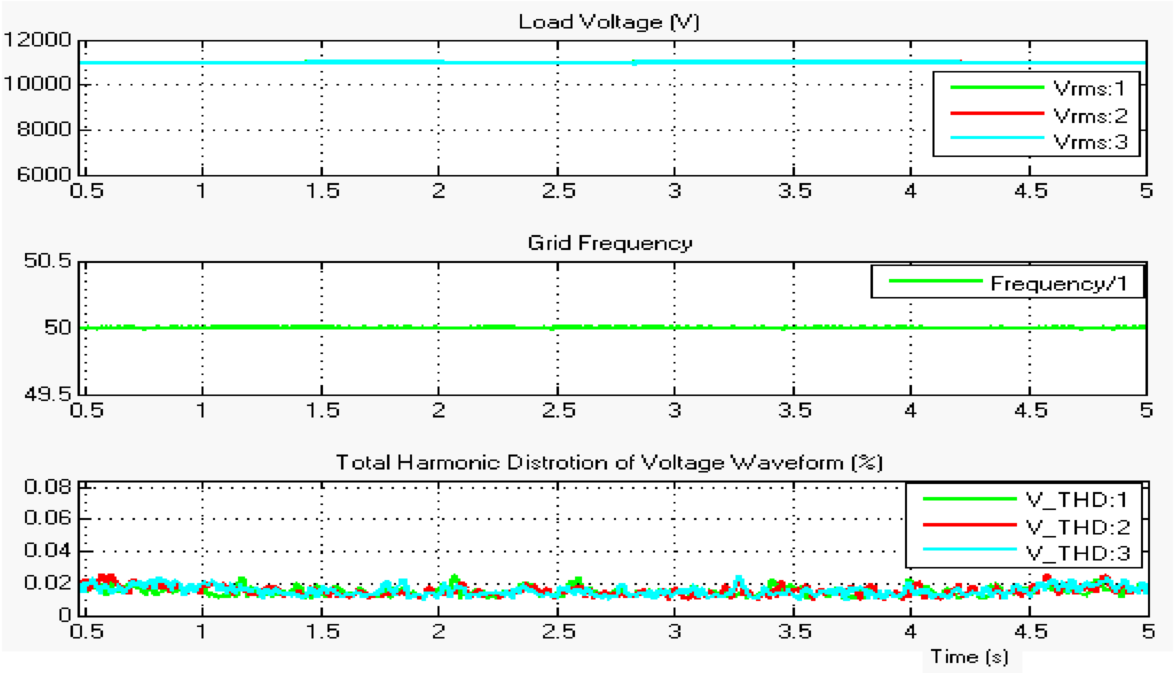
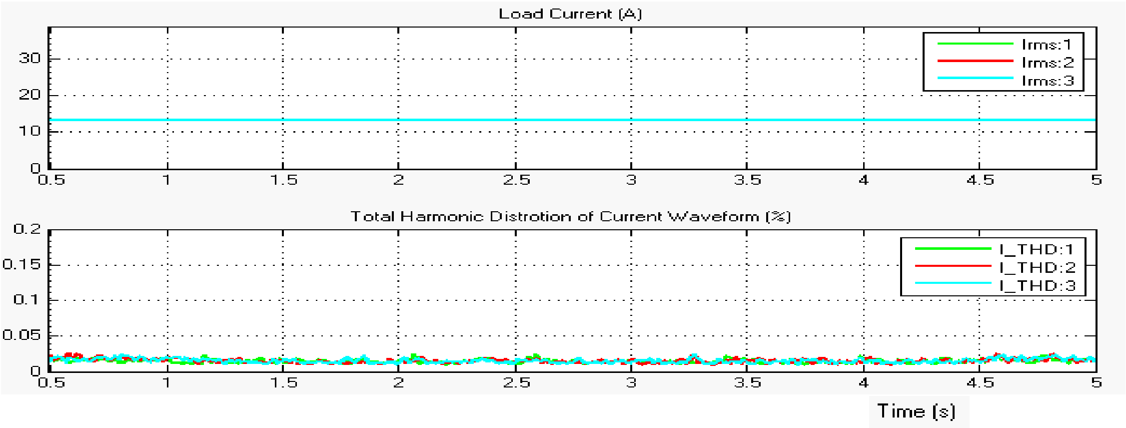


Figure 4.11: Active Generator Active and Reactive Power dispatching.

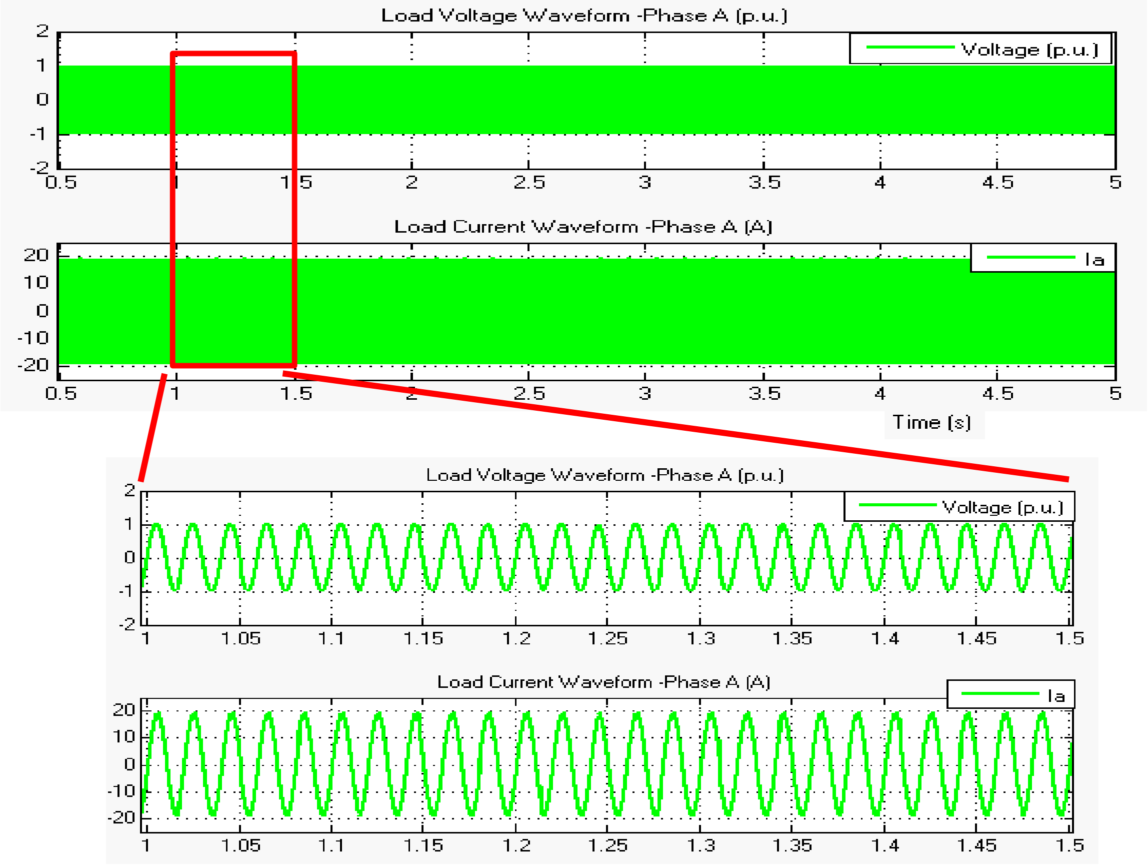
Figure 4.12 shows the voltage, frequency, and current and harmonics percentage at the load. The load voltage, is stable in all the time and frequency is remain at 50 Hz. The total harmonic distortion of load voltage and current waveforms are very small values.



(a) Load voltage, frequency and THD



(b) Load current and THD



(c) Load voltage and current waveform

Figure 4.12: Voltage, frequency, current and THD and load.

Active Power flow with Frequency droop Control

In this test, the active generator power settings were set to 200 kW and 0 kVar. Frequency and voltage control were enables. Simulation start time has been selected at 1.0 s and gird normal frequency is set to 50 Hz. From 1.5s to 2.5s grid frequency increased as ramp signal and remain at 50.5 Hz.

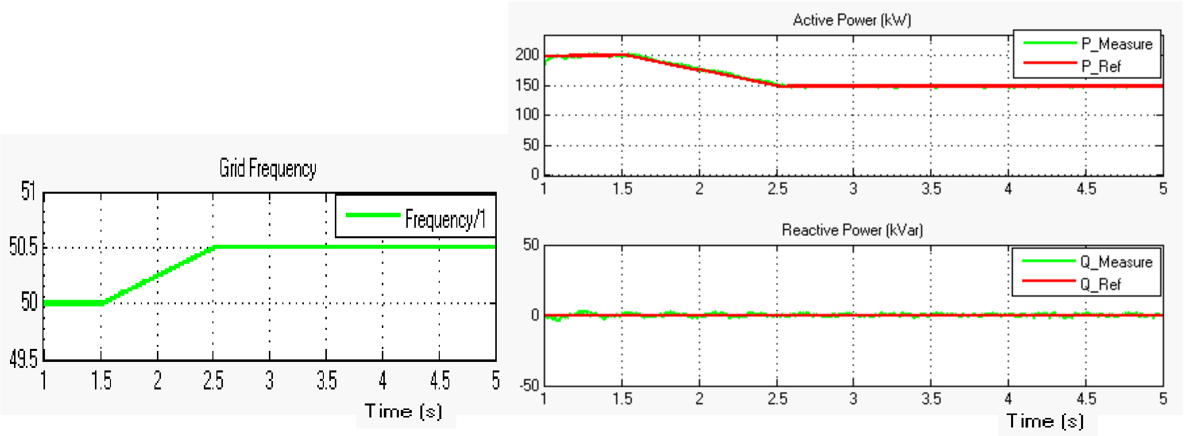


Figure 4.13: Frequency based active power delivery of active generator

Active generator response to this frequency variation, by reducing its power output. Since droop setting is 100 kW/Hz, the power reduction is 50 kW (0.5 Hz*100 kW/Hz). Only droop control used in this test. In micro-grid application, droop control together with PI control will be used and it is discussed in Chapter 5. In real micro-grid, it is expected a reduction of the grid frequency to the normal value with this additional power.

Reactive power flow with Voltage droop Control

In this test the active generator power settings were set to 200 kW and 0 kVar. Frequency and voltage control have been enabled. Simulation starts at 1.0 s steady state and frequency is 50 Hz. From 1.5s to 2.5s grid voltage was decreased as ramp signal until is become 0.95 p.u (10450 V). Active generator responses by increasing its reactive power delivery until 27.5 kVar (11000 V *0.05* 0.0.05 kVar/V). The results are shown in Figure 4.14.

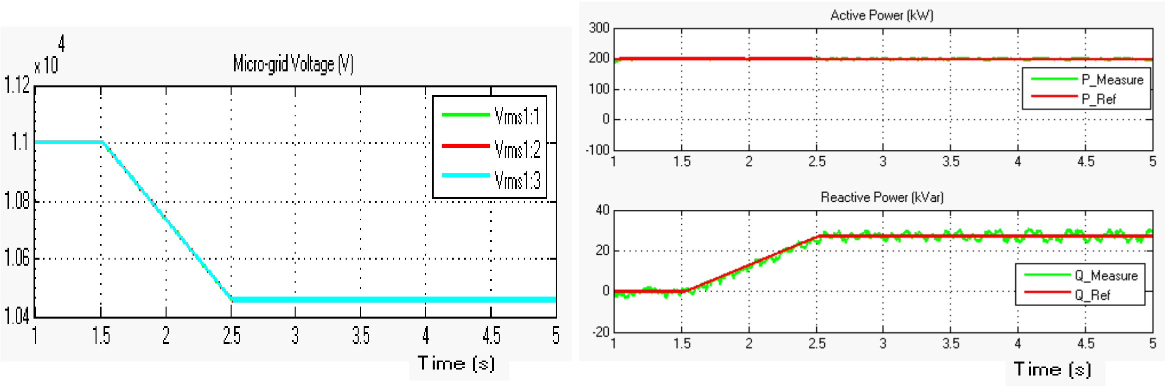


Figure 4.14: Voltage base reactive power delivery of active generator

4.3 Back-to-back Converter Simulation Model

In the proposed micro-grid, 250kW of power is planned to get from the grid and rest of power expected to get from both dispatchable and non-dispatchable renewable sources so that 50 % of renewable energy form DGs can be achieved. Back to back converter topology is implemented to get 250 kW power from the grid. This method give additional benefits as listed in following.

1. Power flow path includes intermediate DC link so that separate droop characteristics can be used for micro-grid operation.
2. Frequency variations of the micro-grid side will not effect to the main grid.
3. The reactive power flow from main grid to micro-grid can be set as zero and micro-grid may works in unity power factor for the main-grid.

Figure 4.15, block diagram shows the implementation of back to back converter topology. It includes two power transformation stages.

1. In first stage, AC power is converted to the DC and DC bus voltage is maintained at a constant level. The reactive power flow from grid is set to zero.
2. In second stage, VSC has to generate required AC waveform for the load. In this case VSC controls its output voltage.

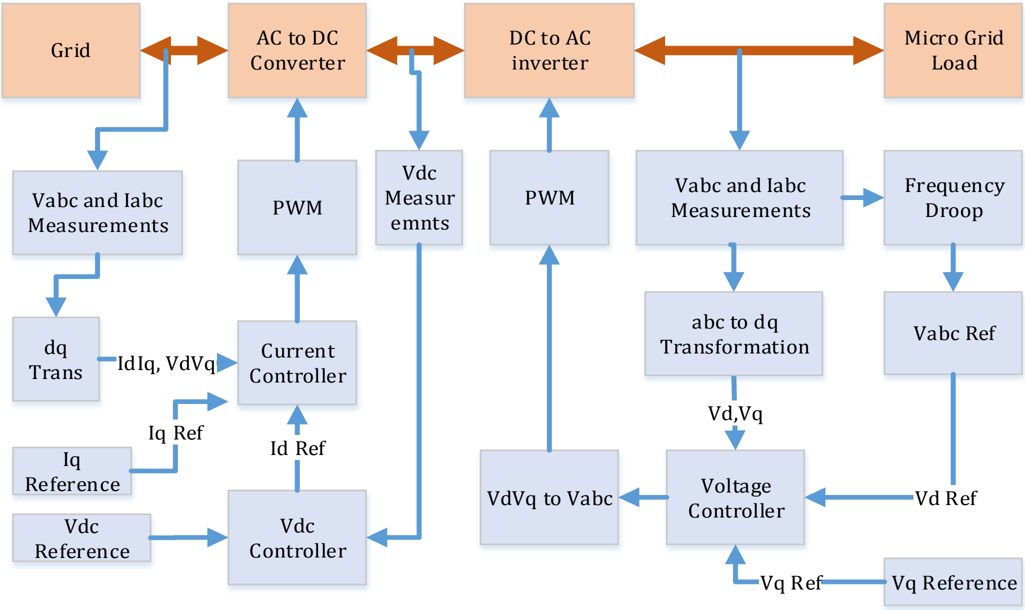


Figure 4.15: Block diagram of Back to back converter

The Simulink implementation of back to back topology is shown in the Figure 4.16. More details are given in appendix A.2.

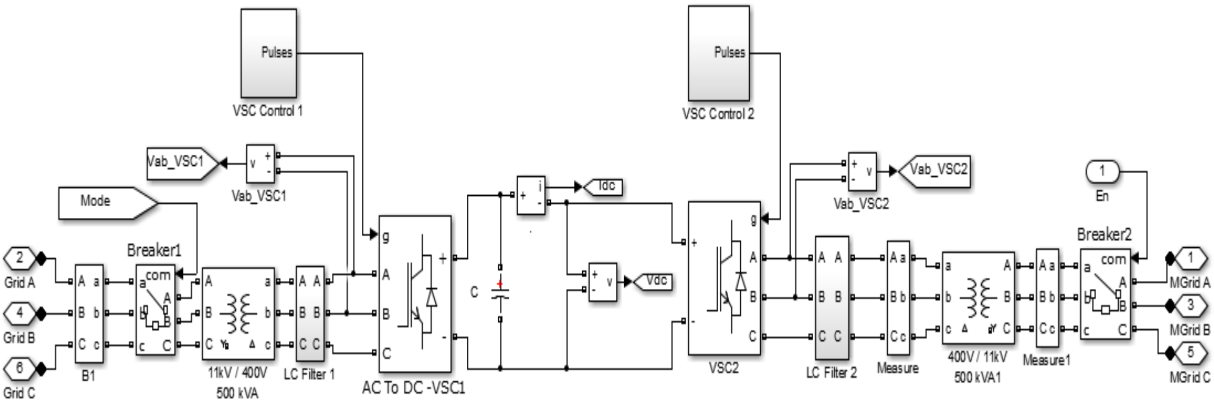
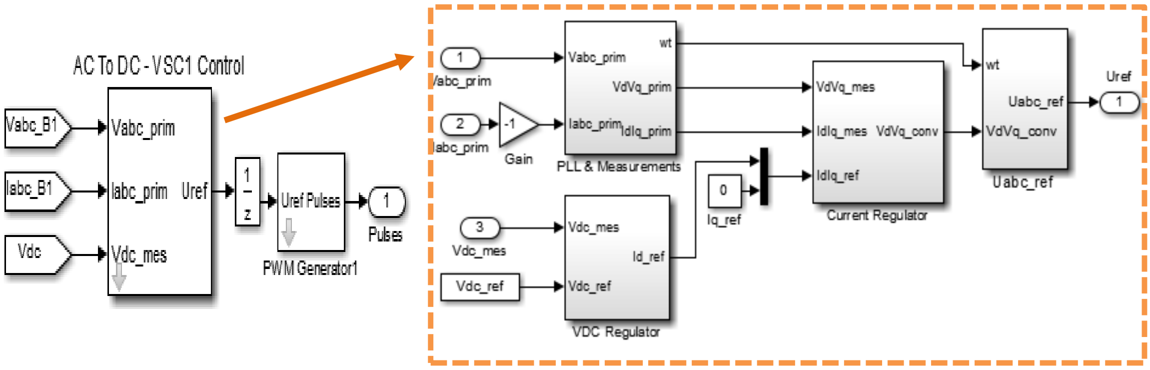


Figure 4.16: Simulink implementation of Back to back converter

4.3.1 AC to DC Conversion and Control Strategies

In the first stage AC voltage is converted to DC voltage. 11kV to 400V transformer and LC filter unit used for voltage step-down and remove the harmonics. The control objectives in this stage are maintaining constant DC bus voltage and unity power factor operation. In PLL measurement unit, the input voltages and current measurements are taken and converted to the Id-Iq, Vd-Vq components and input to the current controller. The current controller calculate the error between current references and measurements and PI controller is used to compensate the error. The current reference Iq is set to zero to get unity power factor operation and Id is generated from DC voltage controller output, where DC voltage control task is achieved. PI controller is used in DC voltage controller to compensate the DC voltage errors. Figure 4.17 shows the Simulink implementation of AC to DC converter control system.



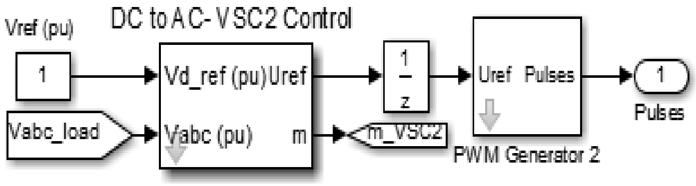
(a) VSC Control 1 system (b) Inside units of AC to DC VSC1 Control block

Figure 4.17: Simulink implementation of AC to DC converter control system

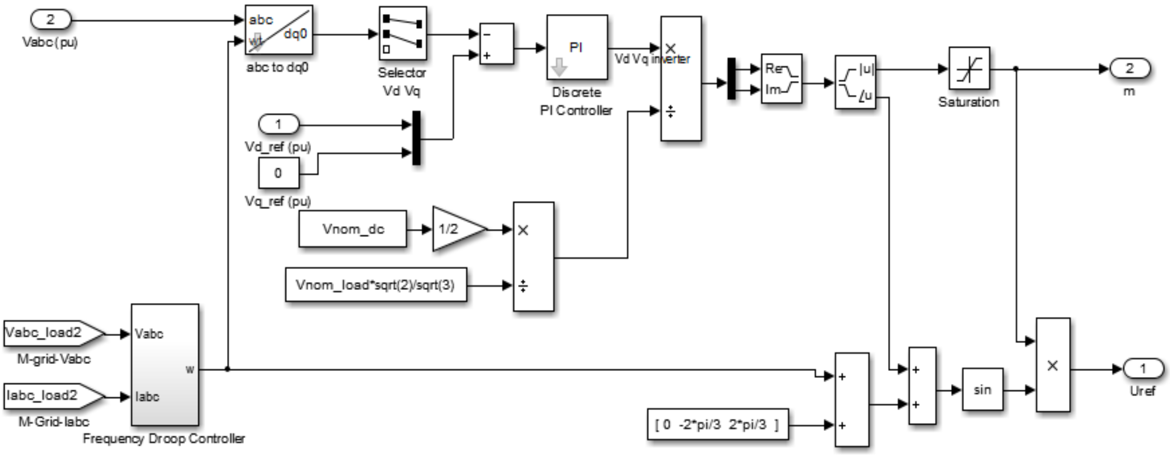
The output of control system is feed to PWM generator and PMW unit generates the control signal for universal bridge operation.

4.3.2 DC to AC Conversion and Control Strategies

In this stage the control objective is generating the required AC waveform for the micro-grid operation. Since main grid is isolated via intermediate DC link, the micro-grid can operate in different voltages or frequencies as the requirement. However in this study, the micro-grid voltages and frequency values are set to same values. But micro-grid uses different frequency and voltage droop method and works independently. Figure 4.18 shows the control system used for the DC to AC converting with Simulink implementation



(a) VSC Control_2 System



(b) Inside units of DC to AC VSC2 Control block

Figure 4.18: Simulink implementation of DC to AC converter control system

The output voltage is set to 1 p.u (400 V) reference voltage, where V_d=1 p.u and V_q=0. Output voltage is measured and V_{abc} p.u. and compared with the reference voltage waveform. The error signal is feed to PI controller. Then the reference sinusoidal waveform is normalized and feed to PWM unit. The required phase angle (ωt) is generated in Frequency droop controller block and the implementation is shown in

Figure 4.19. Based on power delivery, Frequency droop is generated. This frequency reference is used to generate ωt of V_{abc} reference waveform and reference signal is sent to the voltage controller. For safely purposes, the maximum frequency variation of the system is set to ± 0.5 Hz.

$$\mathrm{f} = \mathrm{f}_{base} - \mathrm{K}_f(\mathrm{P} - \mathrm{P}_{base}) \tag{4.01}$$

$$\mathrm{V}_{\mathrm{abc\_ref}} = VSin(\omega t + \phi) \tag{4.02}$$

Where K_f = 0.002 Hz/kW, f_{base} = 50 Hz, ω= 2* pi * f , V and ϕ are the amplitude and angle components of V_d +i V_q outputs of the voltage controller

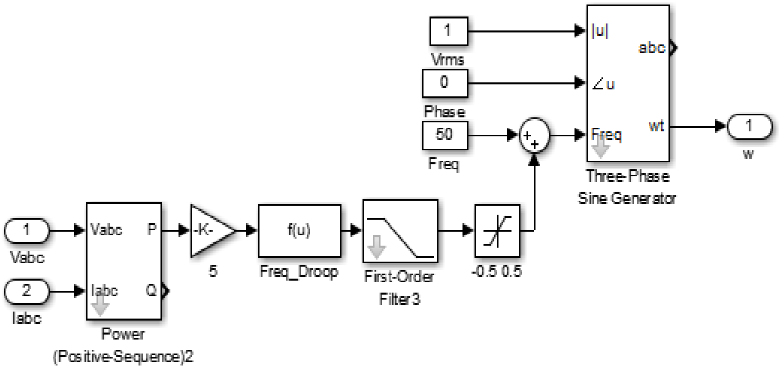


Figure 4.19: Simulink implementation of Frequency droop in back-to-back converter

4.3.3 Micro-grid Simulation Model with Back-to-back Converter

The main task of back-to-back converter is interconnecting the micro-grid via DC link for power transfer and work as isolated two different AC systems (Main-grid and micro-grid). The implementation of Simulink test system is shown in Figure 4.20.

The system consist with two different AC grids the main grid and micro-grid. Micro-grid is connected to the main grid via micro-grid controller. Micro-grid controller can work in two deferent mode. In Mode-0, micro-grid is directly connected to the main grid and in mode-1 micro-grid connect to the main grid via back to back converter. The implementation of micro-grid controller is shown in Figure 4.21.

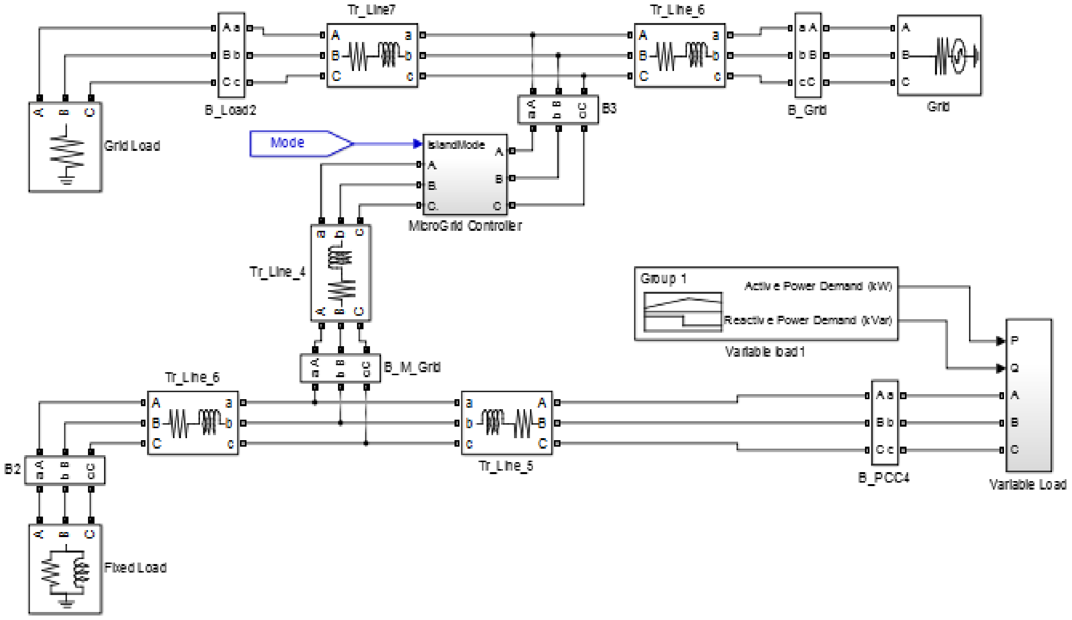


Figure 4.20: Simulink Model with Back to back converter

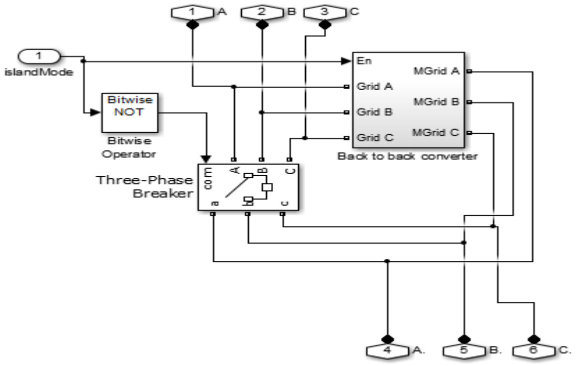


Figure 4.21: Simulink Model of Micro-grid controller

There are two types of loads in the micro-grid, the fixed load which is set to 250kW, 50 KVar value and variable power unit is implemented as in Figure 4.22.

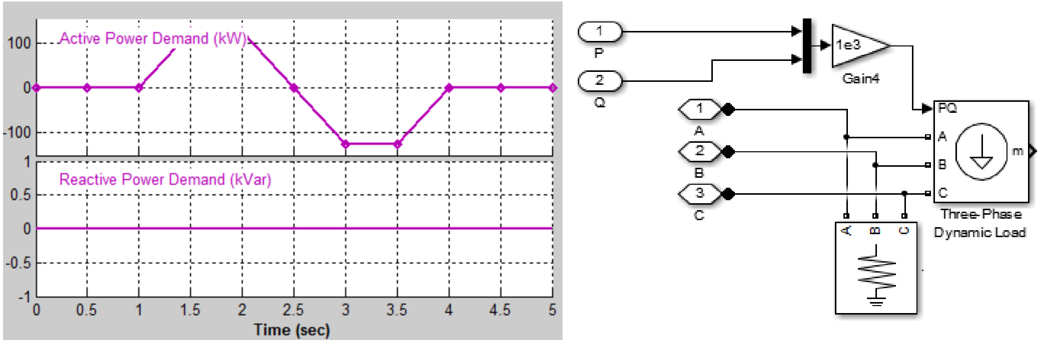
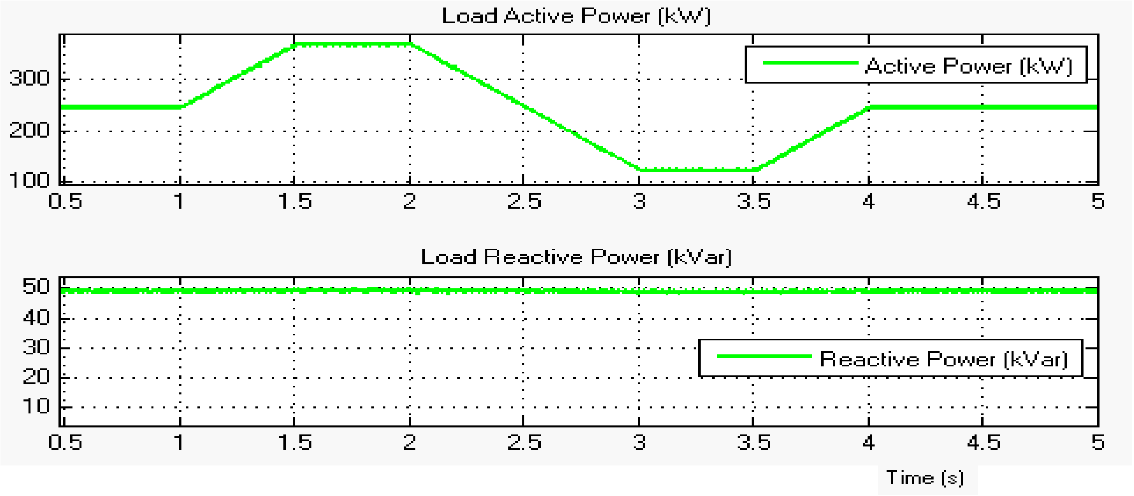


Figure 4.22: Simulink Model for variable power unit

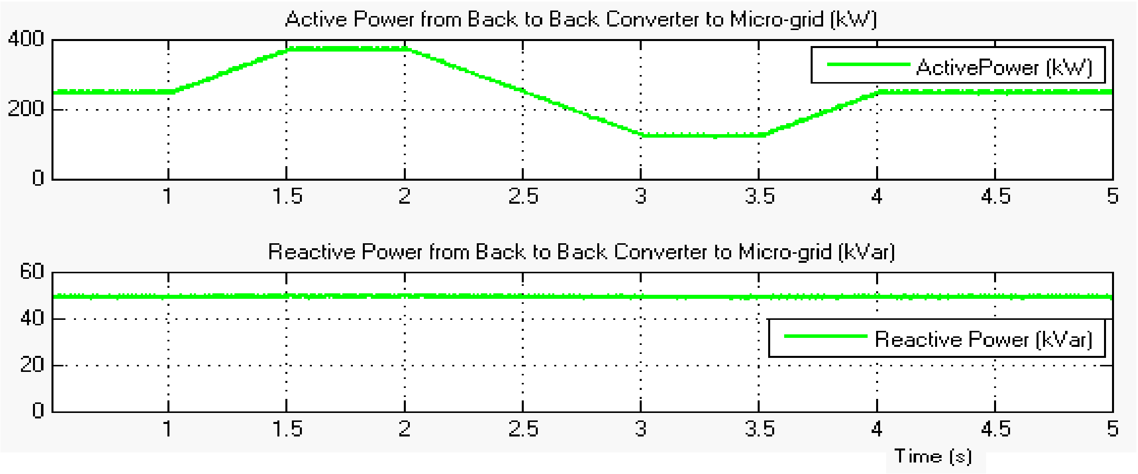
Variable power units can work either in power consumption (load) or generation (generator) mode. Therefore the power demand can be in the range from -125 to + 125 kW. With this setup, micro-grid total load is varied from 250 ± 125 kW, 50 kVar power range and micro-grid voltage, frequency and harmonics were measured. Ode45 solver with variable steps was used as main solver and Tustin solver with fixed step size 1e-5 was used as powergui solver of the simulation model. In the simulation results, 0.5s has been selected as the starting point and 0.5 to 5.0 s time period are selected for the analysis.

4.3.4 Simulation Results

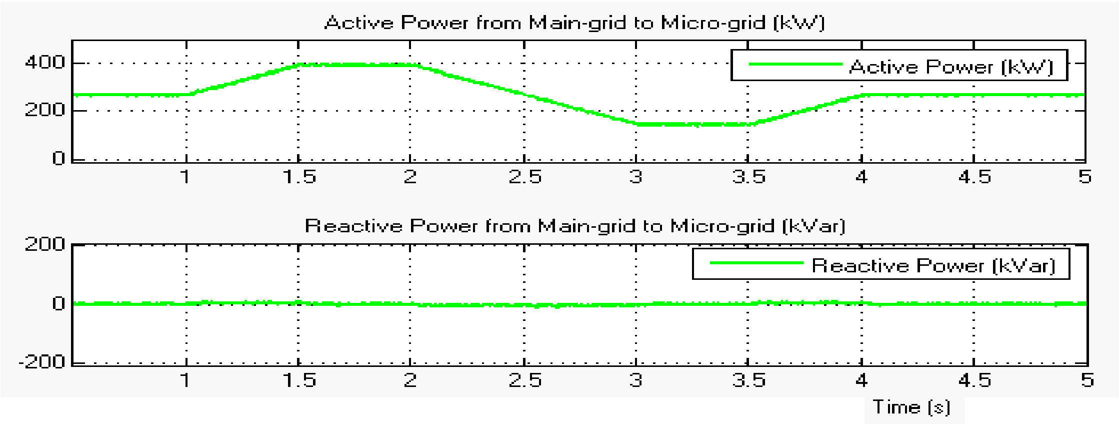
The Power flow among each units are shown in Figure 4.23. Total active power demand from back-to-back converter varies in 250 ± 125 kW range and reactive power is 50 kVar.



(a) Total Load (Fixed and variable) Power flow



(b) Power flow from back-to-back converter to micro-grid

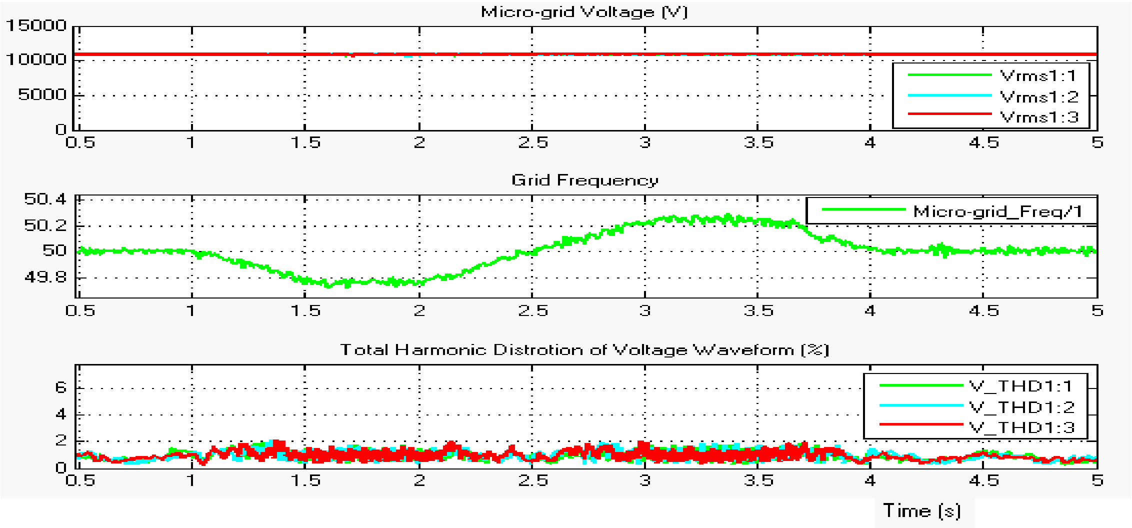


(c) Power flow from main-grid to micro-grid

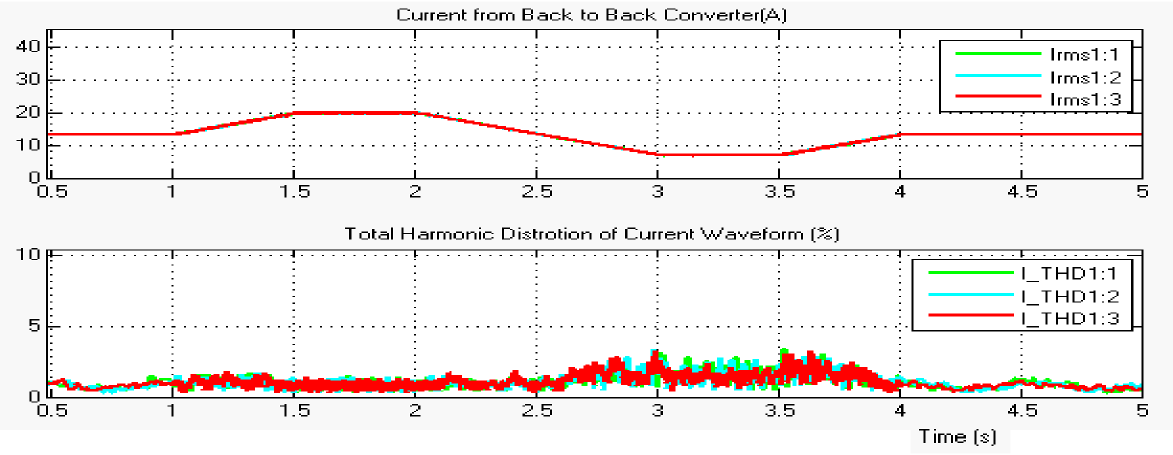
Figure 4.23: Micro-grid power flow

Back to back converter provides this power requirement. However the active power from main grid varies 250 ± 145 kW, this additional power can be considered as the power loss through the back-to-back converter and it is approximately 5% loss. Reactive power flow from grid side set to zero.

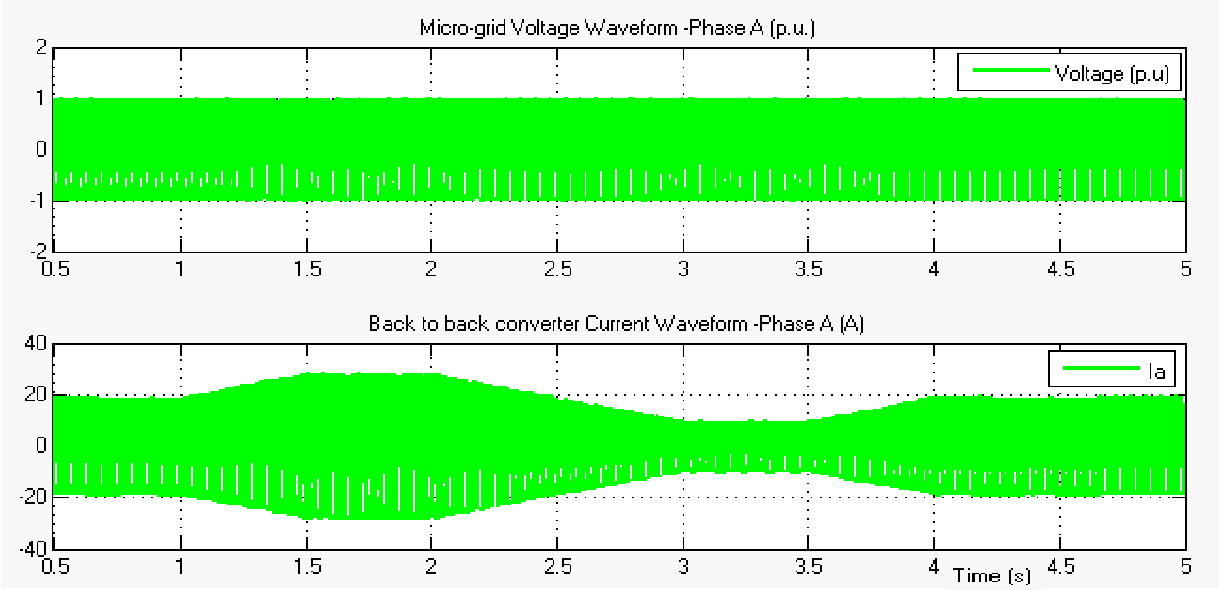
Micro-grid voltage, frequency, current and harmonics values are shown in Figure 4.24. Micro-grid voltage is stable around 11kV rms level and grid frequency is varied according to the eq 4.01. The THD of voltage waveform is below 2.5 % in all the time and the current harmonics is remain less than 5 % in all the time. However, due to the DC link, the main grid is isolated from micro-grid and the simulation results for main grid is given in Figure 4.25.



(a) Voltage and frequency and THD of Micro-grid

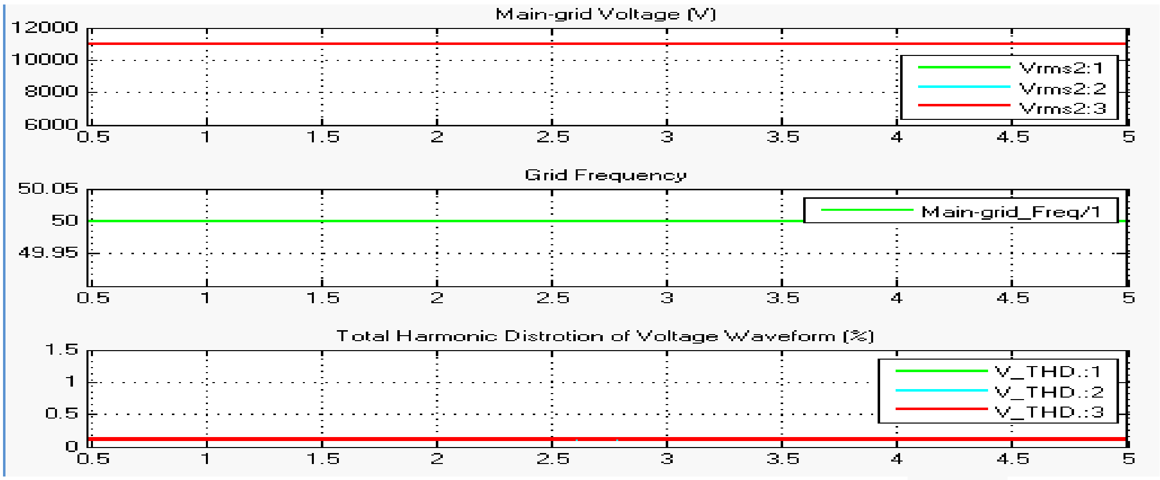


(b) Current and current THD of Micro-grid

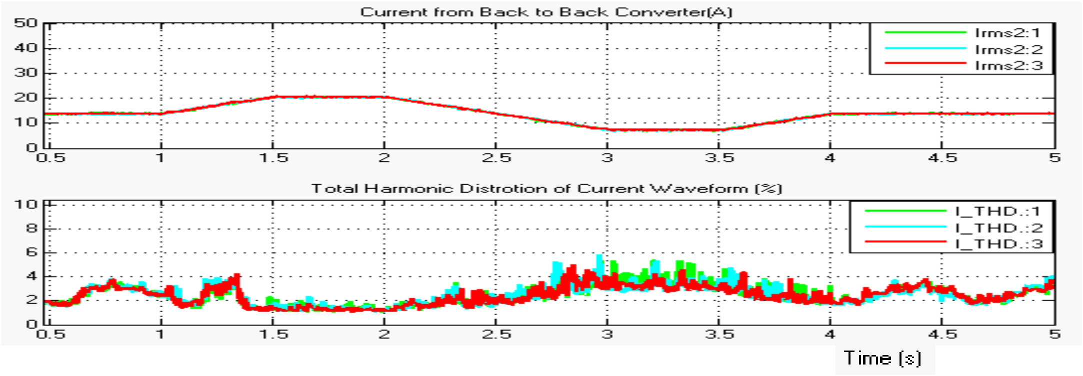


(c) Micro-grid Voltage (p.u) and Current waveform

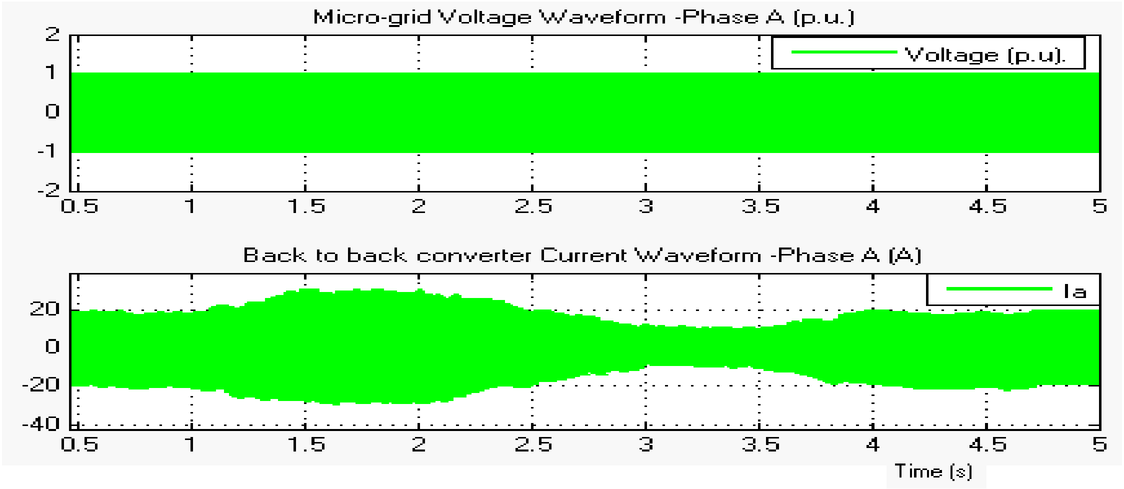
Figure 4.24: Micro-grid Voltage, frequency, current and THD measures



(a) Voltage and frequency of Main-grid



(b) Main-grid Input current and THD



(c) Main-grid Voltage and current waveform

Figure 4.25: Main-grid Voltage, frequency, current and THD measures

It is clear that the two AC grids are isolated from each other. Voltage, frequency and currents at back-to-back converter terminals are summarized in table 4.1.

Table 4.1: Comparison of AC Network parameters

AC Network parameter	**Main Grid Side**	**Micro-grid Side**
Frequency	50 Hz	49.75- 50.25 Hz
THD in Voltage waveform	Less than 0.25%	Less than 2.5 %
THD in Current waveform	Less than 5 % for rated current	Less than 5 %

Main-grid frequency remain 50 Hz, while micro-grid frequency range from 49.75-50.25 Hz, which is as defined in droop equation of back-to-back converter. Both voltage and current harmonics in micro-grid is in acceptable range. The total harmonics presents in main grid is less than the micro-grid and this is a very favorable result. The current harmonics presents in both main-grid and micro-grid is remain in low values.

4.4 Summary and Discussions

In this chapter, two types of VSC systems were implemented, simulated and results were discussed. Current mode controlled VSC with active, reactive power control and frequency-voltage control were discussed. This active generator has the capability of providing requested active or reactive power reference. It also has the capability to change their active power level based on the grid frequency and the reactive power delivery based on voltage differences.

A Small micro-grid has been implemented with a back to back converter. With this architecture, the main-grid and micro-grid are work as two different AC power system areas, while power transmission through a DC link. When the power flow from back-to-back converter change 250 ± 125 kW range, the frequency of back-to-back converter output voltage changes from 49.75 to 50.25 Hz range. However in actual micro-grid application, other active generators will react for this micro-grid frequency change by adjusting their output power. It was observed that the two power system areas are worked with two different frequency, voltage and THD contents. The main-grid frequency has not been effected by the micro-grid frequency changes. Also the effect for main-grid voltage, by micro-grid voltage harmonics are very low. The current harmonics in both micro-grid and main-grid remain 5 % percentage.

In next chapter, the complete micro-grid with the back-to-back converter for main-grid connection and other active generators in the micro-grid will be implemented and will be tested for different loads and intermittent power demand-supply levels of the micro-grid. The control objective is for utilizing the maximum local DG power sources while minimizing the power input flow from main-grid to the micro-grid.

Chapter 5

Grid Connected Micro-grid Model and Simulation

Renewable distributed generations are promising a green energy future. However many techno-economic challenges need to overcome, lot of research work is focusing to solve those problems. This research address one key challenging area on grid integration of renewable energy systems. Grid connected micro-grid topology is used in this research study and power dispatching of active generators has been focused.

5.1 Introduction

One of main technical problem of renewables power systems is their intermittent nature (eg: PV and Wind) and hence power level become uncontrollable (non-dispatchable) according to the demand. However there are some DGs, they are controllable (SOFC, bio-energy associated micro turbines, hydro power and energy storage systems). Then uncontrollable DGs can compensate the intermittent nature of PV and Wind outputs. The main challenge in micro-grid is to increase the penetration of DG renewable generation while minimizing the dependence of central generation (main-grid), which is based on non-renewable energy sources in many countries. In this research, a micro-grid simulation model has been implemented and simulated for dispatching power from DGs by using f, v droop characteristics of the micro-grid. This Chapter presents the implementation details and results of the simulation study.

5.2 Micro-grid Model

To achieve high penetration of renewable energy, micro-grid can provide a reliable solution. Renewable generation has to be maximise within the micro-grid and the remaining power of the micro-grid can be taken from grid via back to back converter. With this topology power pollutions of micro-grid can be isolated via DC link between grid and micro-grid. Major portion of micro-grid power demand has to be supplied by dispatchable renewable sources (SOFC, mini hydro, and micro-turbine) and central energy storage systems can be integrated to make a stable and reliable power system. All renewable generations used in this study connected through voltage source converters where controlling of inverters are the key to the power management strategies.

Figure 5.1 shows the proposed simulation model. The simulation scenario includes 500kW capacity micro-grid and it is expected that 50% of power get from the grid through back to back converter. Intermittent power source is operated in maximum power mode and it going to provide power directly to the micro-grid. Remaining power is expected to get from a SOFC and a central energy storage system which are a dispatchable sources and work as active generators. Fuel cell and battery system compensate the intermittent power by changing their power output.

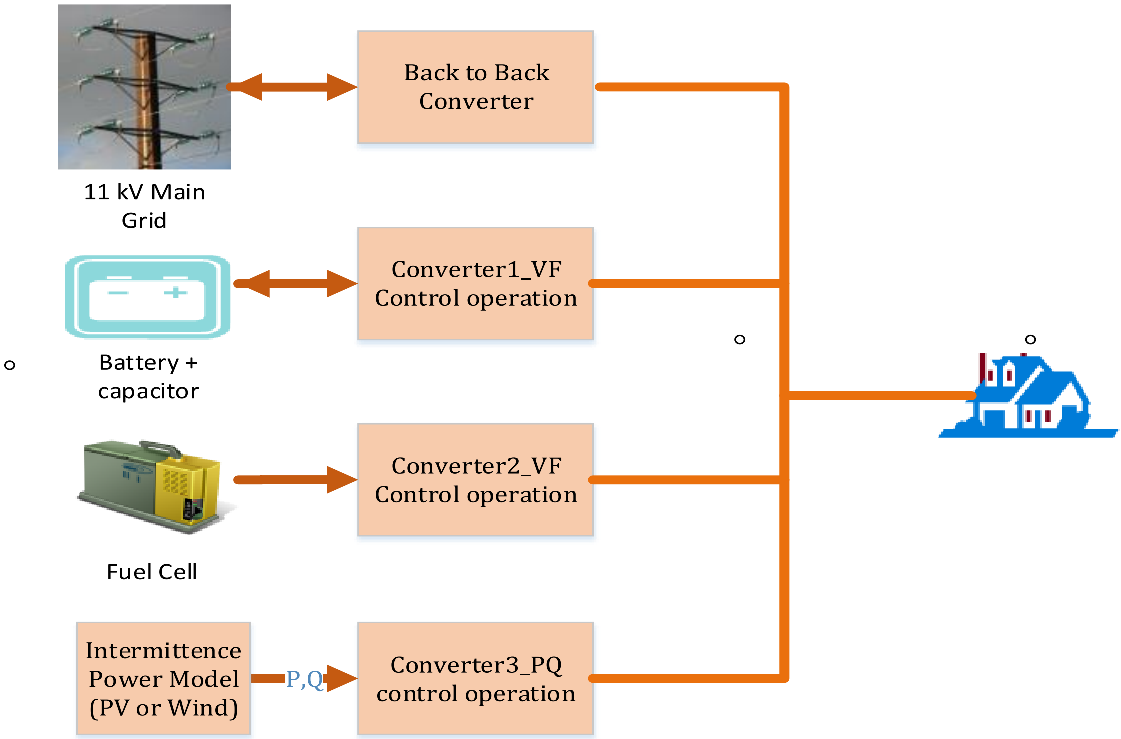


Figure 5.1: Proposed Micro-grid Simulation model

Figure 5.1 shows the block diagram of proposed micro-grid. The model of micro-grid has been developed by Matlab/Simulink and shown in Figure 5.2. SimPowerSystems tool box is used to model the micro-grid. Each power sources inter-connected using short distance 11 kV transmission lines. The complete parameter list of the Simulink model is given in Appendix B. Implementation details, control strategies and simulation results of the model are discussed in rest of the sections.

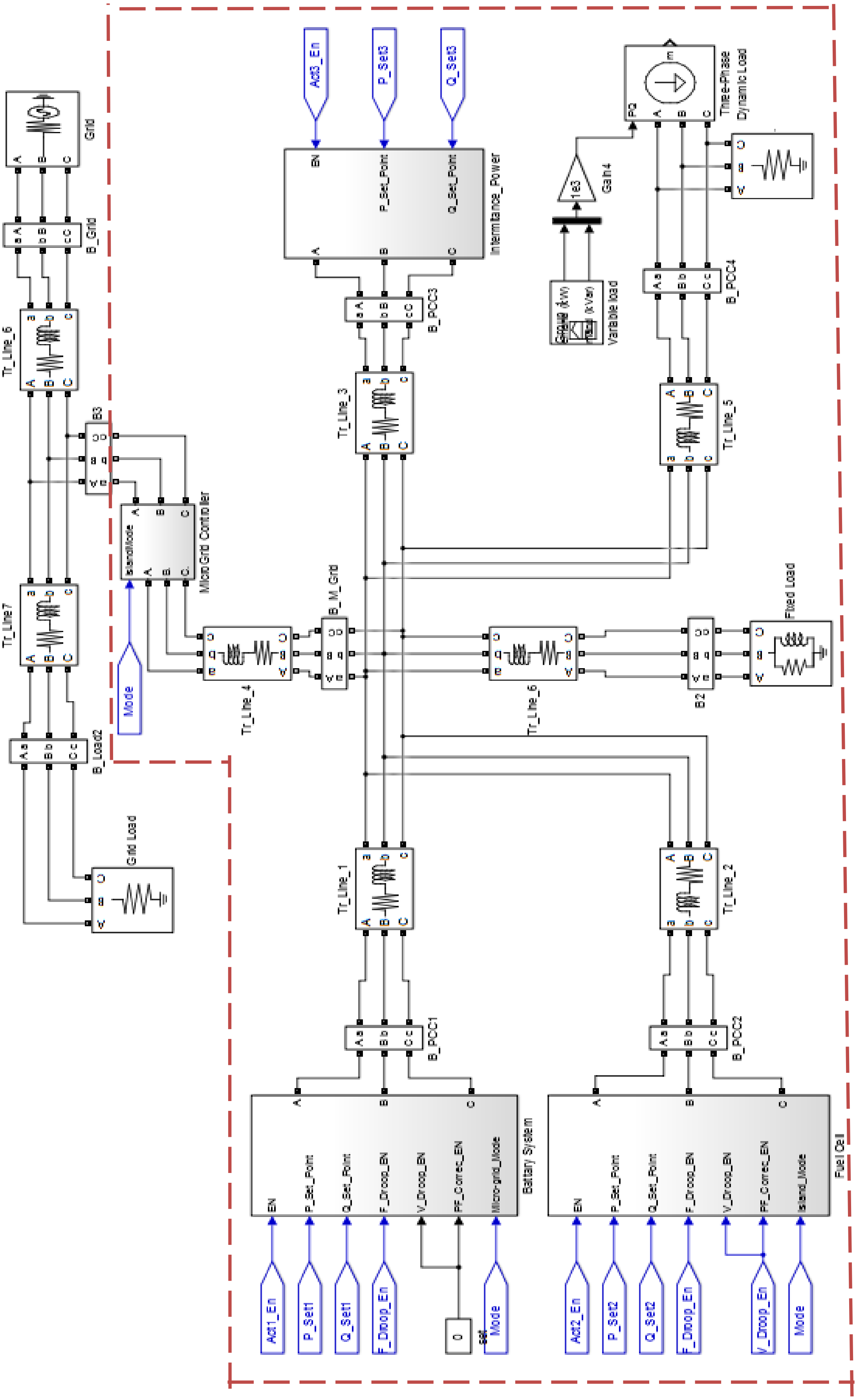


Figure 5.2: Simulink implementation of Micro-grid Simulation model

5.3 Power Sources and Load Models

Power sources and their power conditioning devices, controllable and non-controllable load models are developed in MATLAB/Simulink. Central energy storage system, SOFC, intermittent power source, main grid and loads were modelled as sub systems and interconnected to the 11 kV micro-grid through power conditioning devices.

5.3.1 The Central Energy Storage Model

Batteries are the most familiar electro-chemical devices used to store the electrical energy. The dynamic electrical response of batteries can be improved by combining super capacitors for fast delivery of energy. There are many types of battery technologies, Lead-acid, Lithium-ion, Nickel-cadmium, Nickel-Metal-Hydride and Flow batteries are most important battery designs. In modern renewable energy systems, energy storage systems are very important and many new types of battery technologies are under development.

However, in this research a Lead-acid battery model include in Matlab library has been used. DC to DC bidirectional synchronous converter is used to keep constant battery output voltage for the VSC power interface. With this design, battery can work in both charging and discharging modes. Figure 5.3 shows the Simulink model implementation. The model parameters and other details are given in appendix B.

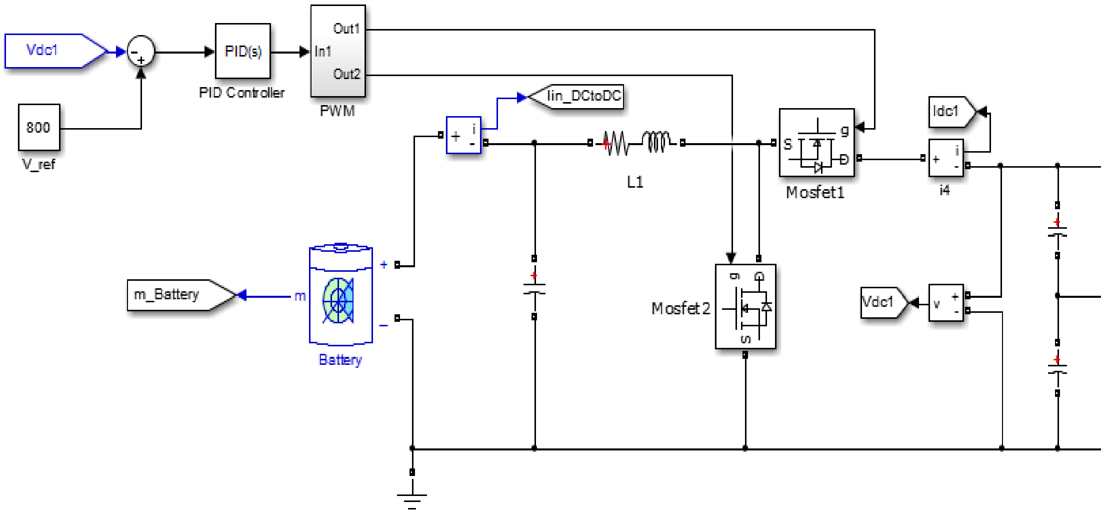


Figure 5.3: Simulink implementation of central Energy storage System

5.3.2 Solid Oxide Fuel Cell Model

Applications of fuel cells are increasing due to their environmental friendly behaviours and the capability to work in combine heat and power (CHP) operations. Fuel cell and batteries are based on electro-chemical technologies. However batteries are energy storage devices and can work only through stored energy, while fuel cell can work long as fuel is supply is available and can be used as a reliable power source. There are many types of fuel cell systems. The most common technologies are polymer electrolyte membrane fuel cells (PEM fuel cells), alkaline fuel cells (AFCs), solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs) and molten carbonate fuel cells (MCFCs). Main advantages of fuel cells are, no moving parts, various hydro carbons can be used as fuel which can be derived from different renewable energy sources. The fuels for fuel cells range from hydrogen, methanol, methane and other reformed hydrocarbons etc.

Solid oxide Fuel cells work at high temperature and it is an attractive device in medium to high range power production. Further when it is used as combine heat and power generation, the overall system efficiency can be increased significantly. Therefore 2 units 100 kW SOFC models has been used in the micro-grid model [17]. DC to DC synchronous converter has been used to maintain constant DC voltage output from the fuel cell system. The Matlab implementation is shown in Figure 5.4. The model parameters and other details are given in appendix B.

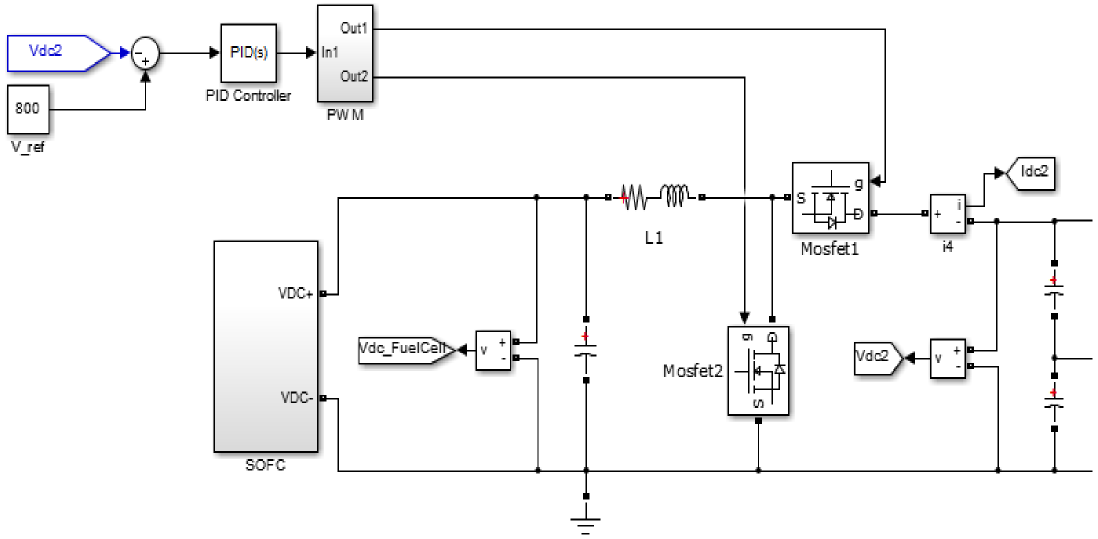


Figure 5.4: Simulink implementation of SOFC Power System

5.3.3 Intermittent Power Source Model

Intermittent power input has been modelled using the general VSC model developed in Section 4.2. Figure 5.5 shows the implementation of intermittent power system model. The model parameters are given in appendix B. In this model active power output has been set to vary between 0-150 kW while reactive power delivery is set as zero. This intermittent power source can be used to represent either PV or wind source where output power can be changed according to the solar irradiance or wind speed variations.

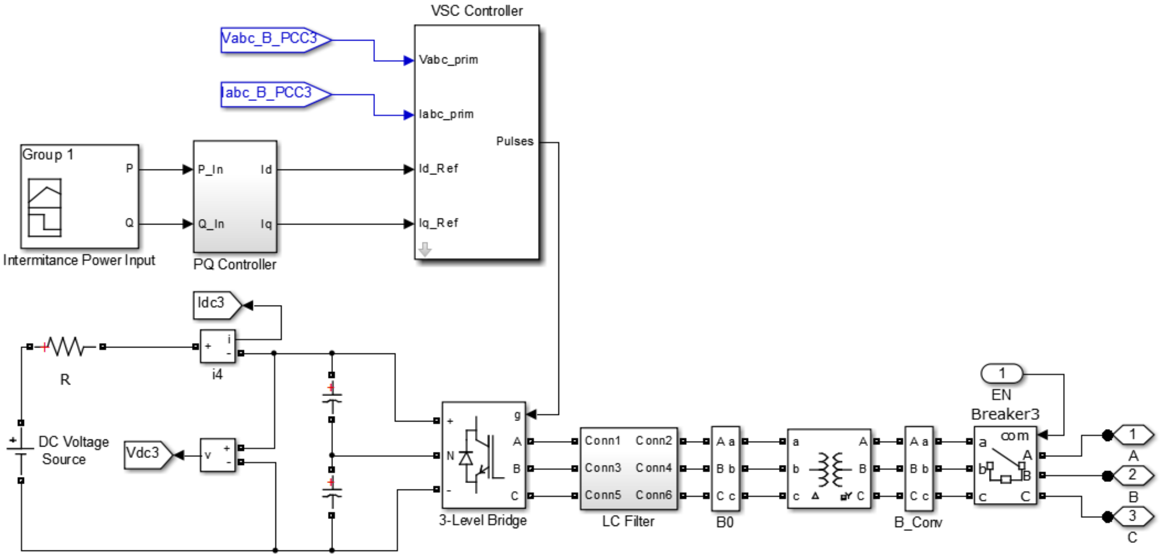


Figure 5.5: Simulink implementation of intermittent power source

5.3.4 Main-grid Model

Main grid is considered as a voltage source, transmission lines and a load. The micro-grid is connected to the main grid via back-to-back converter. Simulink implementation is shown in Figure 5.6 and the model parameters are given in appendix B.

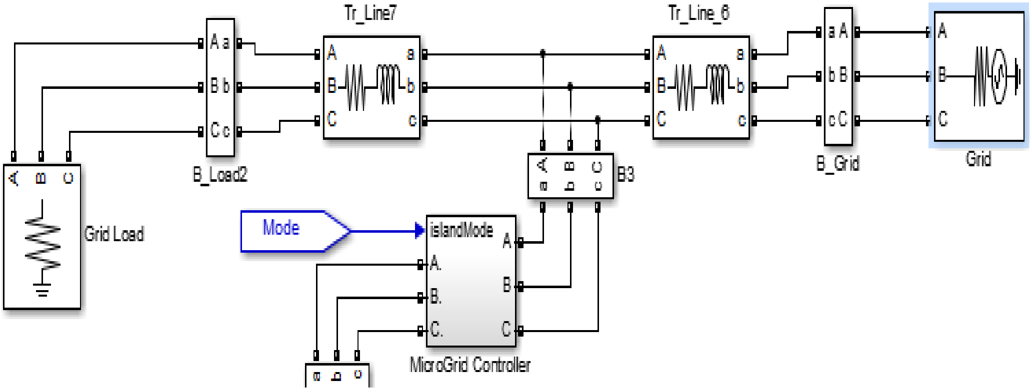


Figure 5.6: Simulink implementation of Main-grid

5.3.5 Micro-grid Load Model

Two types of loads are considered (fixed and variable). Fixed load can represent the base load of the micro-grid. 250kW, 50 kVar load values used for the fixed load. Matlab inbuilt dynamic load has been used as variable load and the load values has been varied to simulate the load variation in the micro-grid. Figure 5.7 shows the Simulink model implementation.

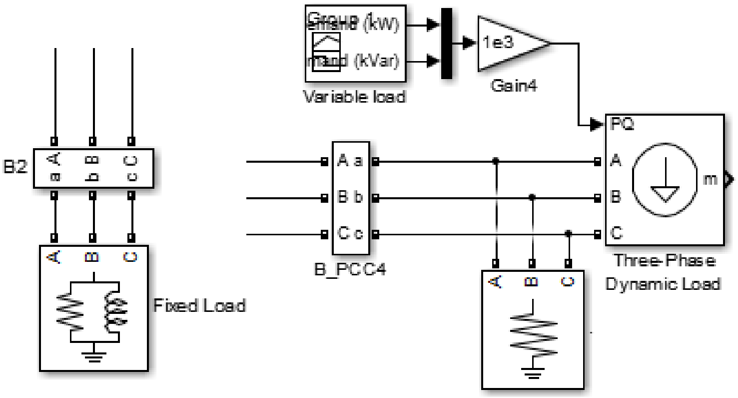


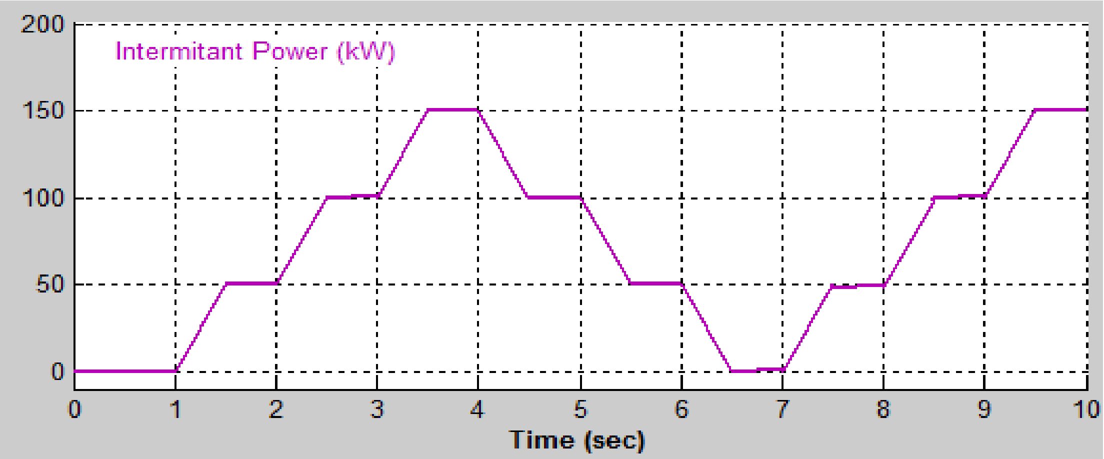
Figure 5.7: Simulink implementation of Micro-grid loads

5.4 Micro-grid Simulation Scenario and Inverter Control strategies

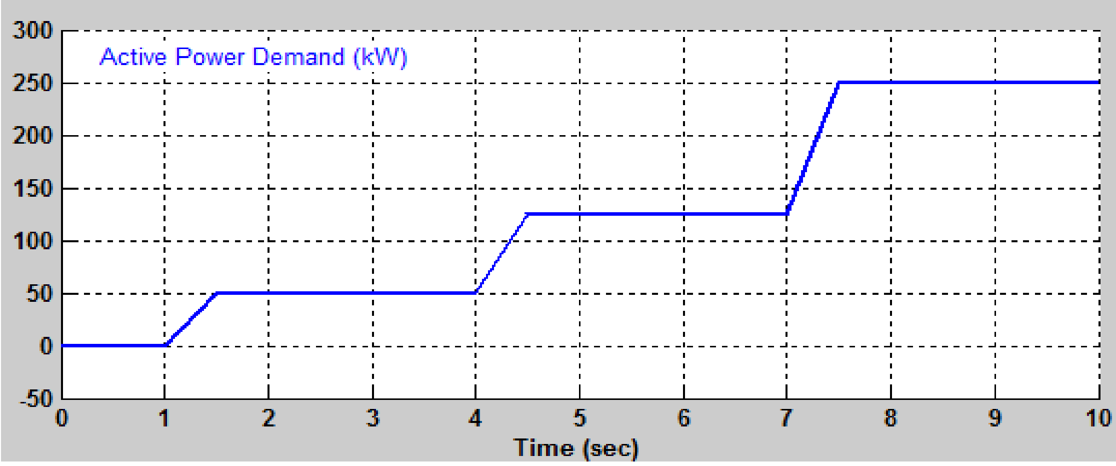
5.4.1 Simulation Scenario

In this scenario, the control objective is to maximize the utilization of intermittent power sources (PV or wind) with proper load balance, frequency, voltage regulations and power quality. SOFC cell and battery systems work as active generators to accommodate this task. The load sharing capability of these sources are depended on the frequency droop characteristics defined in each active generator. In this case maximum of 50% of renewable energy is used in the micro-grid and system is capable to manage 50% of intermittent power within the system.

In this simulation, micro-grid consist of two loads. First load is a fixed load and the capacity is assumed 250kW/50kVar (0.98 power factor), Second load is a variable load which can vary from (50-250 kW) active power and reactive power (10-50 kVar). Intermittent power input is varies from 0 to 150kW and it inject the available power into the micro-grid in uncontrollable manner. The Micro-grid power demand and intermittent power input into the micro-grid is shown in Figure 5.8.



(a) Intermittent power input



(b) Micro-grid variable load

Figure 5.8: Intermittent power input and Micro-grid load variation used for Simulation

Different possible power combination in the micro-grid has been considered in this simulation scenario, where total micro-grid power varies from 300 to 500 kW and intermittent power varies 0-150 kW range with 0 to 50 % intermittent power contribution in the micro-grid. Table 5.1 shows the different combinations.

Table 5.1: Power level combinations tested in the simulation

Intermittent Power Supply (kW)	**0**	**50**	**100**	**150**
Micro-grid Power Demand (kW)	**Intermittent Power utilization (%)**			
300	0	16.67	33.34	50
375	0	13.34	26.67	40
500	0	10	20	30

5.4.2 Inverter Control Strategies

In the micro-grid, back to back converter is used for interconnection to the main-grid. It is expected to get 50% power (250 kW) from main grid through back to back converter. As discussed in Section 4.3, any deviation from 250kW power level influence to change the reference frequency of micro-grid (±0.5 Hz for ±250 kW). The other active generators provide the power into the micro-grid by synchronizing to the voltage via phase locked loop. Dq transformation based active and reactive power control is implemented in these active generators and frequency and voltage droop based controllers are used to generate the PQ references. Droop control with PI control is implemented for accurate power dispatching and reduce the steady state error of micro-grid frequency. Voltage droop characteristics used for reactive power delivery and voltage control. Table 5.2 shows the control strategies of each power units.

Table 5.2: Inverter control strategies

Power Unit	Active power control strategy	Reactive power control strategy
Active Generator 1 (Battery via VSC)	Charging or discharging to compensate micro-grid dynamic power requirement based on frequency droop. Reference power output at rated frequency = 0 kW	Reactive power delivery = 0 kVar.
Active Generator 2 (SOFC via VSC)	Maximum capacity 200 kW. Can change power levels from 10 to 200 kW range based on frequency droop. Reference power output at rated frequency = 50 kW	Provide reactive power based on voltage droop at common coupling point.
Main Grid via Back to back converter	Providing 50% of micro-grid power 250 kW. Deviation from 250 kW power level introduces frequency change in micro-grid 0.5 Hz per 250 kW (0.002 Hz/kW)	Share the reactive power demand with SOFC. Provide balance reactive power to the load.
Intermittent power source via VSC	Provide available active power	Reactive power delivery = 0 kVar.
Loads	(i) Fixed load = 250 kW (ii) Variable active power (50 to 250 kW).	(i) Fixed load= 50 kVar (ii) Variable reactive power (10-55 KVar)

5.5 Simulation Results

From the simulation, active and reactive power demand and supply of each inverters units have been observed. Further, in micro-grid and main-grid operating parameters such as frequency, voltage and THD have been analysed.

5.5.1 Micro-grid Active Power Sharing between each Power Sources

Figure 5.9 shows the active power sharing among different power sources of micro-grid. The load power demand varies between 300 to 500 kW range and intermittent renewable energy power varies from 0 to 150 kW.

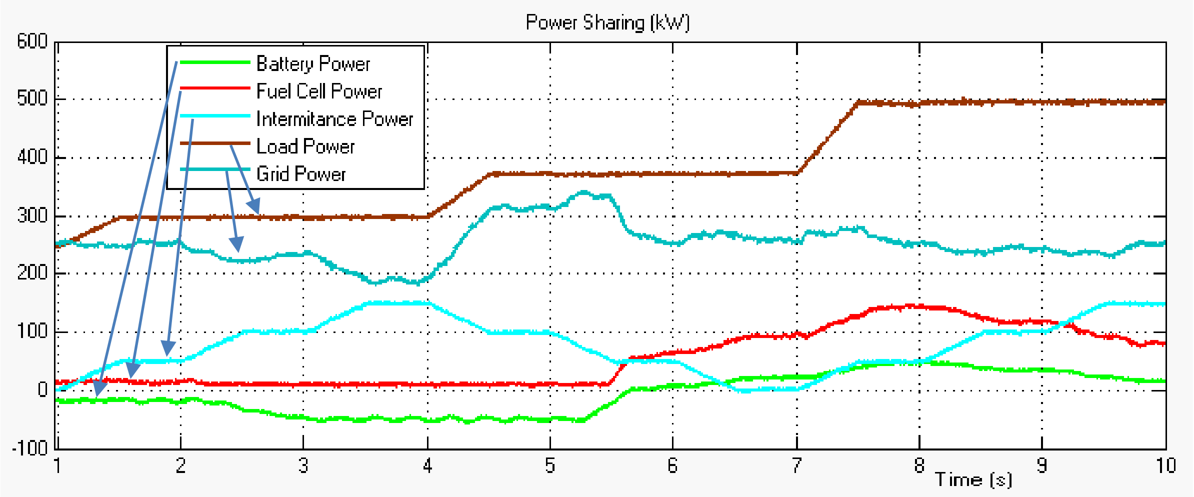


Figure 5.9: Active Power sharing among different power sources in micro-grid

Simulation start time is selected at 1 s time. Initially at 1s time, load is 250 kW and 10 kW power is delivered by SOFC while battery charge at 10 kW rate. Then load become 300 kW and until 4s, the intermittent power increases until 150 kW. In this range, battery consume power at its maximum rate of 50 kW and power from main-grid reduces until 180 kW and SOFC deliver its lowest power level 10 kW. In the time period of 4 to 7 s, the load increase until 375 kW and intermittent power reduces until 0 kW. In this time range, SOFC power level is gradually increases until 100 kW, and battery change from charging mode to discharging mode. This power changes are based on combination of frequency droop with PI control methods. From 7 to 10 s period, micro-grid load increases until 500 kW and intermittent power also increases. The power balance is shown in the Figure 5.9.

5.5.2 Micro-grid Reactive Power Delivery from each Power Sources

In the proposed micro-grid system, most of reactive power is provided by back-to-back converter and the remaining is provided by the SOFC. Reactive power delivery from SOFC is based on the voltage drop of its common coupling point without using the PF correction and rest of reactive power is delivered by back-to-back converter. Reactive power from other sources were set to zero. Figure 5.10 shows the real time reactive power demand and supply.

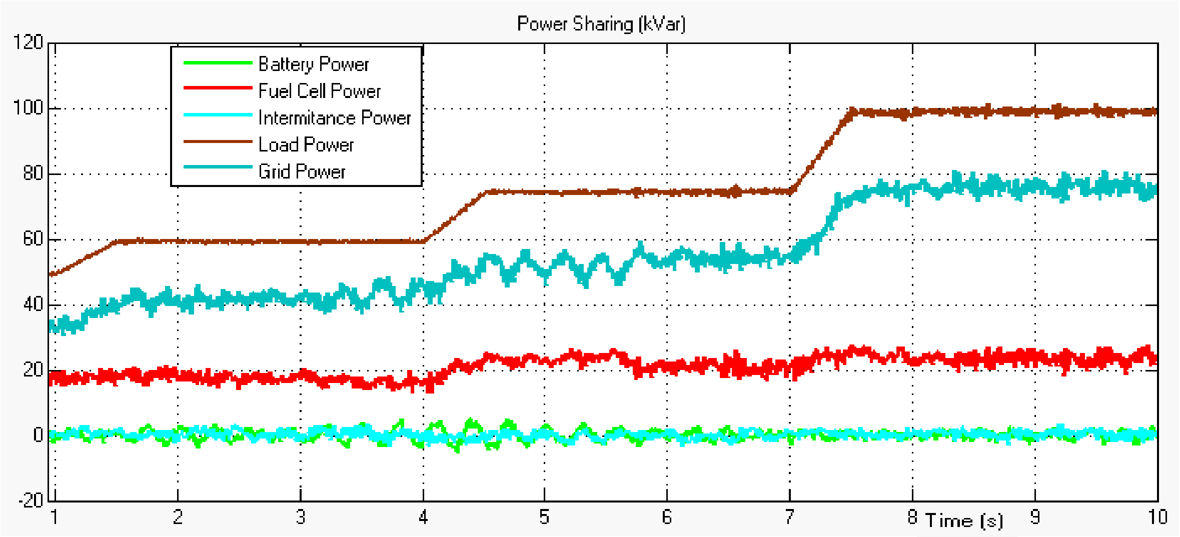


Figure 5.10: Reactive Power Delivery from each power sources in micro-grid

Reactive power from SOFC is 15 to 25 kVar range and rest of reactive power is delivered by the back-to-back converter. It is observed that, there is some fluctuations in the reactive power delivery of each units of this model. However, the reactive power management is achieved from this developed model.

5.5.3 Intermittent Power Input to the System

Power reference and measured values of intermittence power source in the VSC system is shown in Figure 5.11. The active power of VSC is selected as varying signal in the range of 0 to 150 kW and reactive power set to zero. Here power reference can be considered as power availability at PV or wind source and measured value can consider as the power injection from converter to the grid.

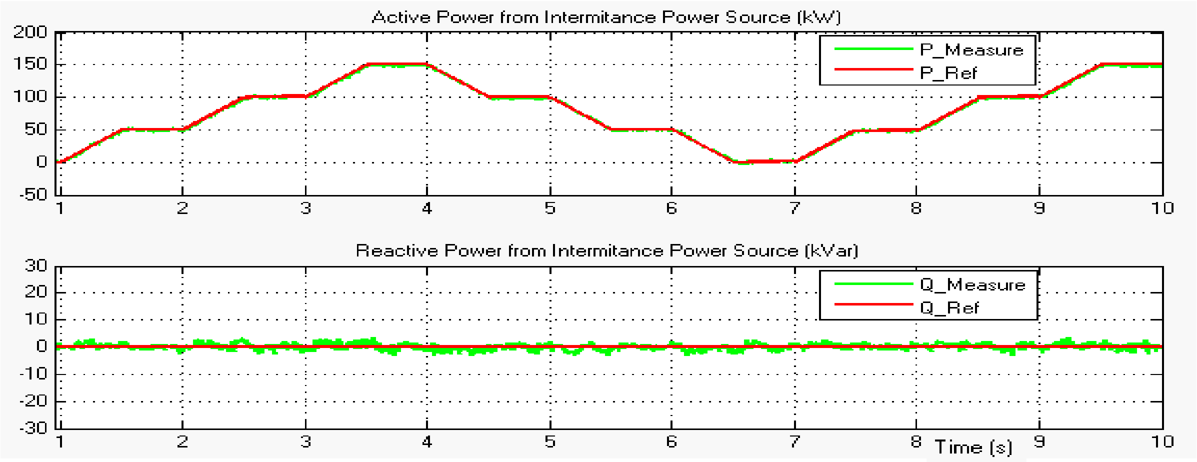


Figure 5.11: Power reference and measured values of intermittence power source

5.5.4 Battery System Power Delivery

Battery system power reference and measured values are shown in Figure 5.12. Battery system is working in both charging and discharging mode. In 0- 5.5 s period, battery is in discharging mode and after that battery is in charging mode.

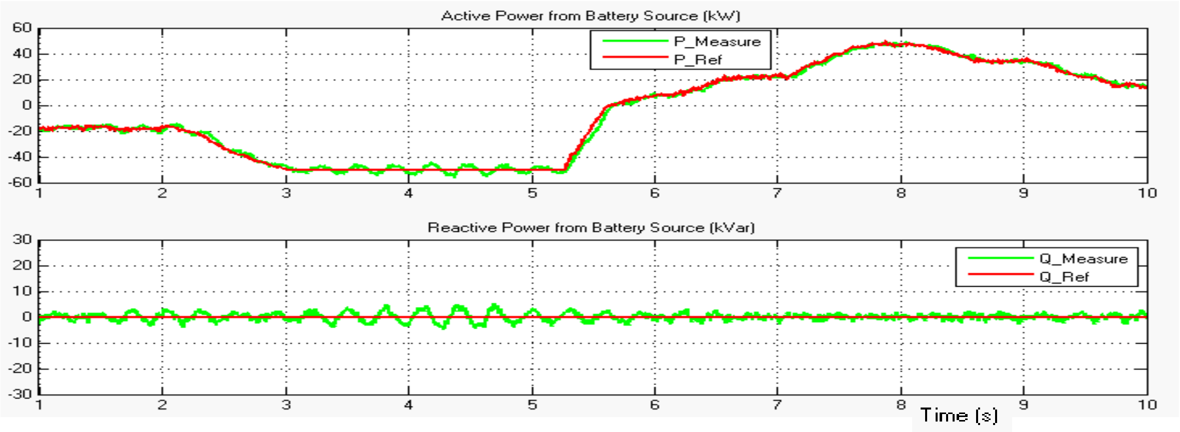


Figure 5.12: Power reference and measured values of Battery system

The reference and measured values of active power components shows accurate control results. But, for reactive power, a little fluctuation around control values are observed. However, ever all system results are at acceptable level.

5.5.5 SOFC System Power Delivery

SOFC power output is vary to compensate the intermittent power and balance the system power demand. Fuel cell system is used as the main dispatchable renewable power source.

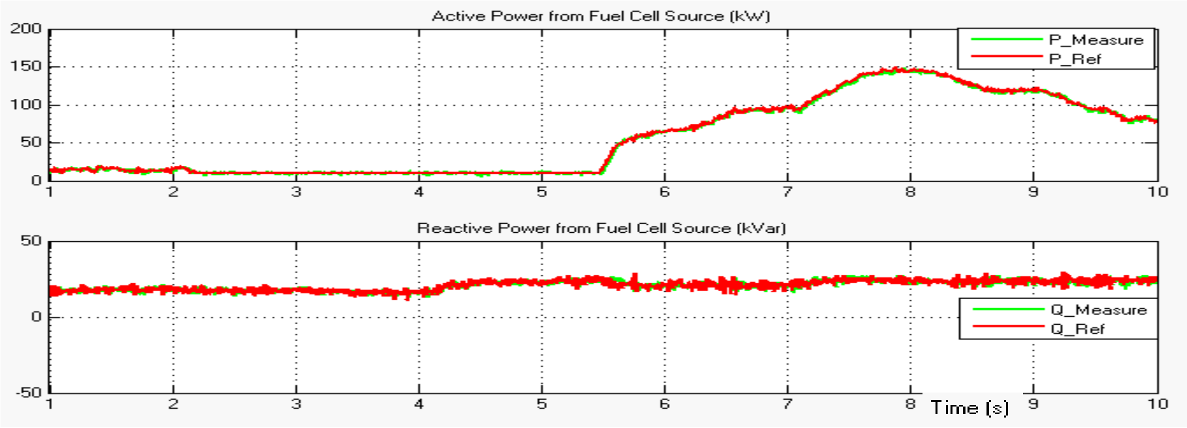


Figure 5.13: Power reference and measured values of SOFC system

The power limits of SOFC range from 10-200 kW. Both active and reactive power can be provided by the SOFC and Figure 5.13 shows the simulation results. It is observed that the both active and reactive power dispatching shows very good performance as expected for fulfilling the power demand.

5.5.6 Power from Back-to-back Converter to Micro-grid

In this micro-grid, it is expected that 250 kW of its power requirement come from main grid. Deviation from 250 kW power level introduces frequency change in micro-grid 0.5 Hz per 250 kW (0.002 Hz/kW). Other active generators (i.e. SOFC and battery) responses to this droop characteristics by changing their power dispatching.

The required reactive power is generated in locally by the back-to-back converter. From the Figure 5.14, it is clear that the power flow through back-to-back converter varies around 250 kW level, which reflect that the additional power requirement in micro-grid is supplied from local available renewable power sources.

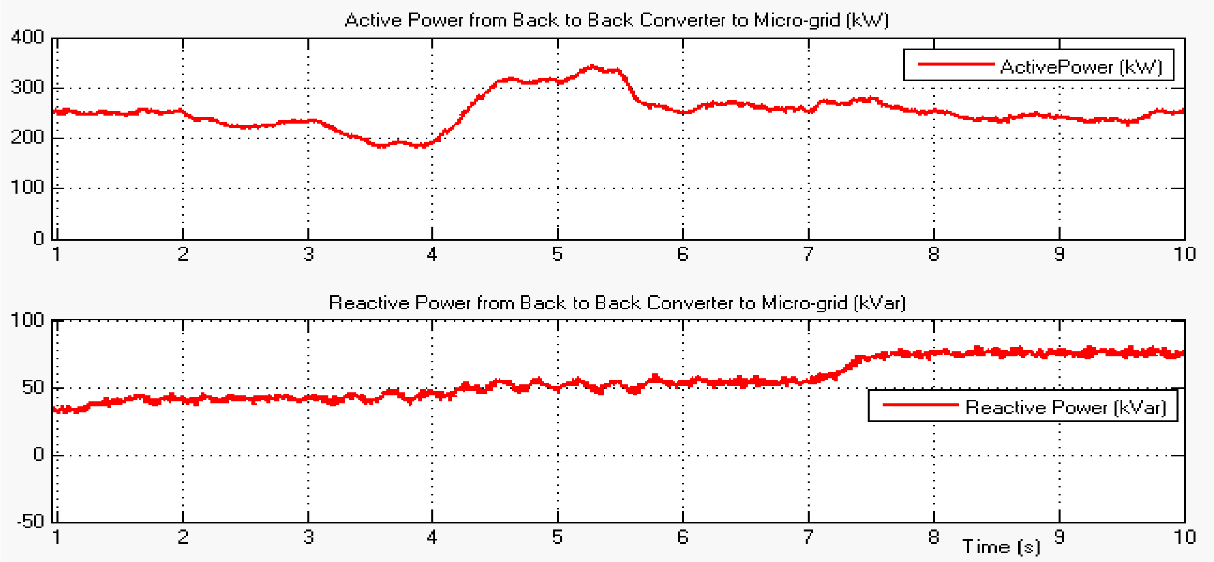


Figure 5.14: Power reference and measured values: Back-to-back converter to micro-grid

It is observed that until 4.3 s, there is power surplus in the micro-grid and the power from back-to-back converter become lower than 250 kW. However after that there is additional power requirement in the micro-grid and power delivery from back-to-back converter become higher than 250 kW. Furthermore, back-to-back converter can provide the reactive power demand of the micro-grid. Part of reactive power requirement is provided by SOFC unit.

5.5.7 Power from Main-grid to Back-to-back Converter

The power input variation of back-to-back converter is shown in Figure 5.15, where active power variation is same as in previous case. However in the proposed model, it expected to generate the reactive power requirement of the micro-grid locally. This gives favourable results to grid operators as they can see the total micro-grid as unity power factor load of average 250 kW with small power changes. This will help to reduce the transmission losses as reactive power is generated locally through back-to-back converter.

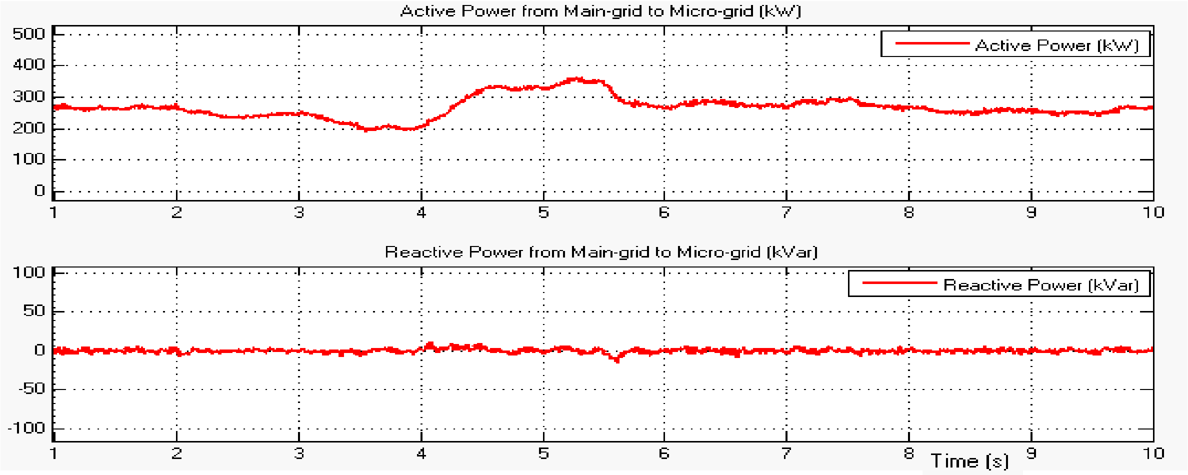
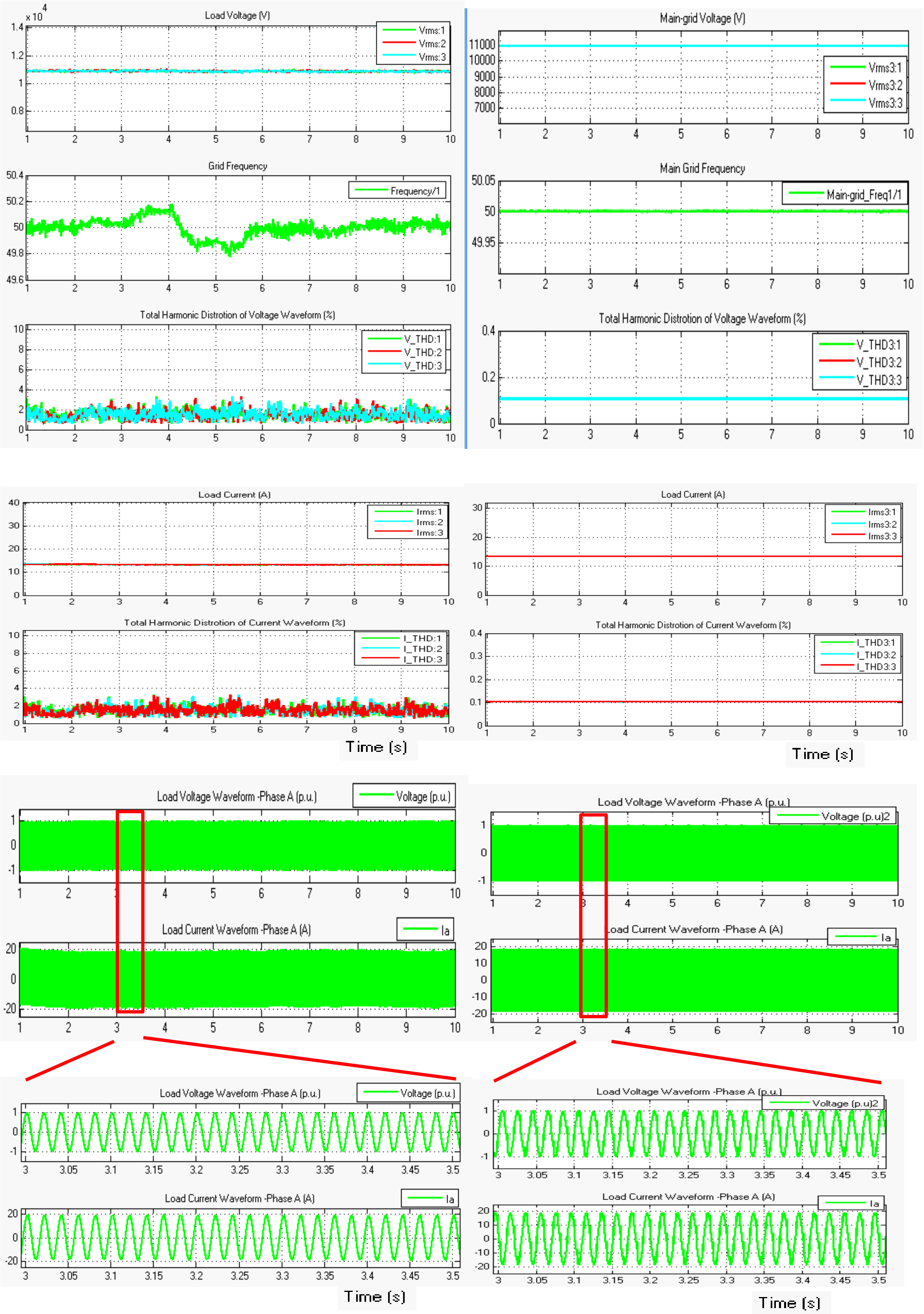


Figure 5.15: Power reference and measured values: main-grid to Back-to-back converter

5.5.8 Analysis of AC Network Operating parameters of Micro-grid and Main-grid

In the proposed micro-grid model, there are two areas of AC power systems. Micro-grid and main-grid operates in isolation on the areas. To analyse the operations, four test points have been selected.

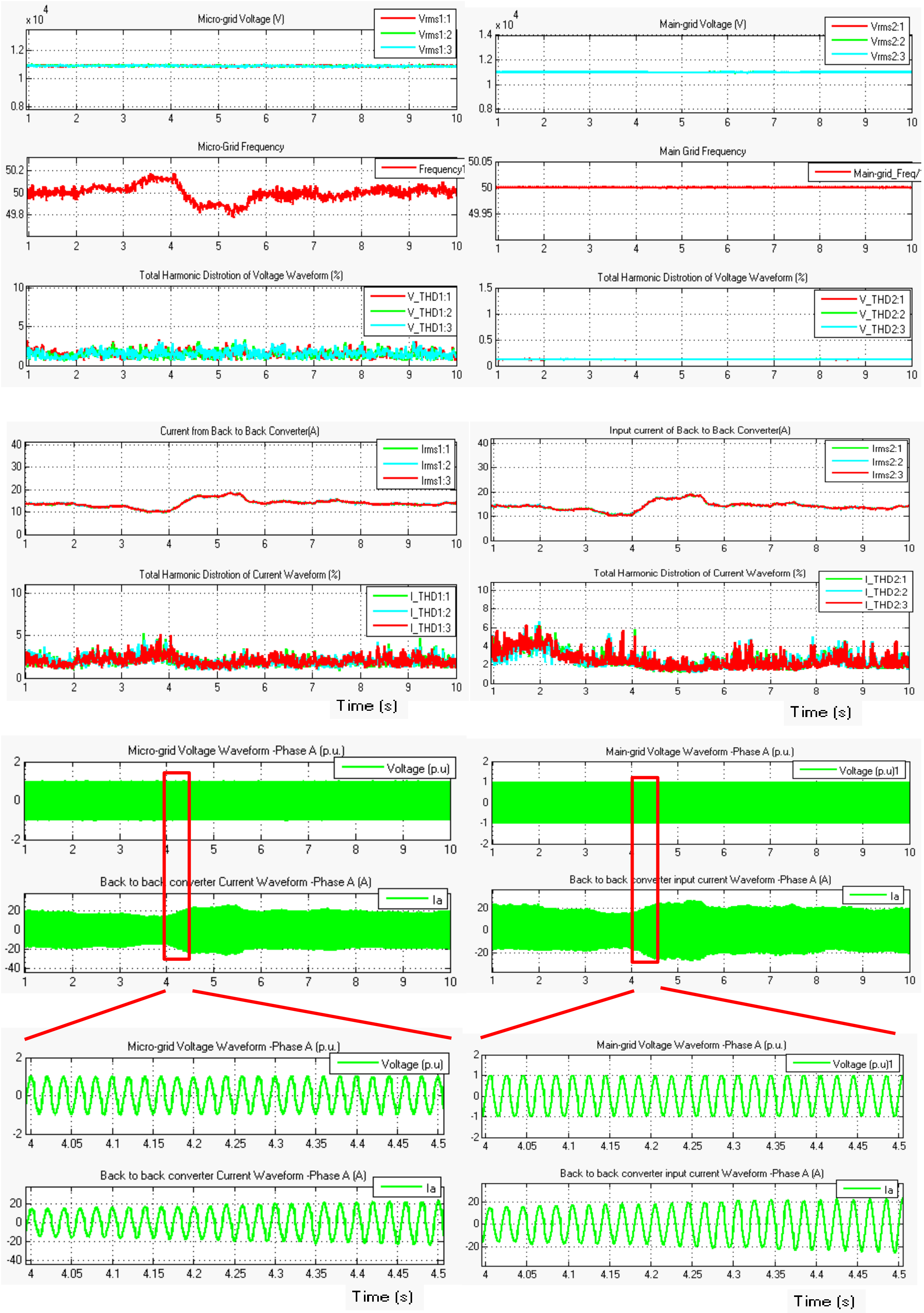
In Micro-grid and main-grid both areas have separate loads 250 kW, 50 kVar of each. The frequency, current, voltage and harmonics percentage measured in these two points and compared as shown in Figure 5.16. Further, the input and output terminals of back-to-back converter have been selected as measurement point and same comparison has been done which is shown in Figure 5.17.



(a) Micro-grid area operating parameters

(b) Main-grid area operating parameters

Figure 5.16: Comparison of Frequency, Current, voltage and THD at micro-grid and main-grid Loads



(a) Micro-grid area operating parameters (b) Main-grid area operating parameters

Figure 5.17: Frequency, current, voltage and THD at input and output terminals of Back-to-back Converter

When compare to the AC grid operating conditions (Figure 5.16) at loads of micro-grid and main-grid, it is clear that the main-grid conditions are more stable than micro-grid conditions. Micro-grid frequency varies in the 49.8-50.2 Hz range while main grid frequency remain 50 Hz. The RMS values of micro-grid shown small variations with less than 4 % THD in voltage. Main-grid voltage waveform is stable and the harmonics are negligible. The THD for current at micro-grid load is less than 4 % range while it is negligible at main-grid load. However the AC grid conditions in the micro-grid are well above the standard limits and system works well.

When consider the AC grid conditions at back-to-back converter terminals (Figure 5.18), it is clear that main-grid conditions are more stable as in previous case. However the THD in currents in both terminals are less than 6 %, which is an acceptable level.

5.6 Summary and Discussions

The simulation results shows that it is possible to achieve high penetration of renewable energy with the proposed micro-grid system. In the proposed system, the active power sharing with frequency droop method works well and each active generator can change their output power based on frequency droop to make the system power balance. SOFC can participate to share the reactive power based on the voltage drop present at its PCC. The simulation scenario has been selected carefully to test the different combination of power levels present in 300 to 500 kW load variation and 0 to 150 kW intermittent power variations. The model gives well acceptable results for the simulation scenario within standard AC network operating conditions with high quality power delivery.

As the grid operator's point of view, encapsulate several renewable generation and control strategies under micro-grid umbrella and treat it as one unit. This help to local utilization of DG energy within micro-grid. Furthermore, it will help to reduce the number of DG units in a virtual means and effort for power system control will be reduced. Also unity power factor operation will help to reduce the reactive power flow in the main-grid and the overall system loss. SOFC and Bio-energy based micro-turbines will be well suitable for operate as active generators for compensate the intermittent power. Combine heat and power operation can be used to get high efficiency in these systems.

From the results of this research study, it is proposed that, this kind of grid-architecture will be best suit for success in out green energy future.

Chapter 6

Conclusions

The main focus of this research study is to develop a grid connected micro-grid for increasing the penetration of renewable energy resources. Power dispatch strategies have been included in the active generators to achieve this task. The following research objectives are achieved.

1. Development and implementation of simulation model for a voltage source converter (VSC) for controlling active and reactive power dispatching based on frequency and voltage droop characteristics.
2. Development and implementation of simulation model for a back-to-back converter for grid connected micro-grid operation which operates as a separate AC power system through a DC interconnect.
3. Analysis of a grid connected micro-grid for achieving high penetration of renewable energy resources and proper load sharing among different renewable energy sources within the micro-grid.

Therefore in this research, three major problems of grid integration of renewable energy has been analysed and acceptable simulation results have been obtained. Specially, power dispatching of active generators based on droop control is implemented and successful results have been obtained. More details of the simulation study are discussed in next section.

6.1 Research Findings

Almost all renewable energy systems require the power electronic interfaces for grid integration. PV, Fuel cell and energy storage batteries are DC power sources and must be converted to AC for use in the electricity grid. Further, Wind and Micro-turbine power systems also cannot connect directly to the standard AC grids, which operate within strict frequency, voltage and THD regulations. VSCs are important in these conversion processes. Control system performances and stability of VSC systems become the main challenges.

In this research, grid integration of a SOFC and central battery storage system has been considered. Furthermore intermittent power unit has been modelled and which can represent the grid integration of PV or Wind power systems. The Power flow control, voltage, frequency control has been achieved with VSC systems. Frequency Droop control with PI control has been used to control active power flow, while voltage droop control is used to control the reactive power and fast control performances has been observed.

Most of renewable energy resources are distributed in nature. With DG power units, the grid integration become challenging as the existing grid architecture is based on centralized power generation concepts. To achieve large penetration of renewable resources, it might be necessary to use different grid architectures. Smart-grid concepts provide background for future distributed power generation and consumption based on the micro-grid concept.

In this research, a grid connected micro-grid power system topology is used. A Complete AC micro-grid model has been developed with DG power units and AC loads. The micro-grid has been connected to the main-grid via back-to-back converter and 50 % renewable power has been utilized within the AC micro-grid simulation model. Distributed micro-grid architecture is used with a back-to-back converter and transformer isolation. This system allows operation of the main grid and micro-grid as two different AC power system areas with different voltage, frequency and THD and power quality levels.

Most important renewable energy resources such as PV and Wind energy systems are delivering intermittent power. Their power cannot as reliable sources for real-time power demand for a load. Suitable dispatchable power generators with reserve power capacity is required to manage this intermittent power within the grid. Energy storage is another option and many storage technologies are available.

In this research, Intermittent power is managed with a dispatchable SOFC power sources and a centralize energy storage. SOFC system as the main dispatchable power source, changes its power output to provide power balance in the grid. In future, SOFC system will be a good choice as dispatchable power source. Other than pure hydrogen, many hydrocarbon gases can be used in SOFC and CHP operations of SOFC can ensure high efficiency in overall energy conversion process. The central Battery storage system also can participate for compensating the intermittent power within the micro-grid. Both systems work as active generators and provides power dispatching based on their defined frequency and voltage droop characteristics within micro-grid. This System can handle 50 % of intermittent power within the micro-grid with rapid power dispatching.

This research study suggest that grid connected micro-grid based distributed power systems can be used to achieve high penetration of renewable energy, where aim is to utilise the locally available renewable energy within the micro-grid. PV and Wind are the available major intermittence power sources. SOFC and bio-energy based micro-turbines can be used as the main dispatchable power source to ensure power balance and stable operations. If the SOFC and bio-energy based micro-turbines are used as combined heat and power applications, the overall system efficiency will be in high value.

6.2 Implication and Future Works

There are observed areas which can be improved in the micro-grid architecture. Future improvement of this model can be made in following directions.

1. In this study, stability analysis for each active generators are not considered. However, to get more reliable simulation results, it is necessary to perform a stability analysis with accurate mathematical models of the system. In the active generator model, PI controllers are used, but there are more advance control systems, such as robust control techniques which might be used for better performances. Further the control systems of active generators have to be improved with stabilization, disturbance handling and tracking capabilities of power system.
2. There can be found many studies related to traditional synchronous generators behaviours for droop control and power system operations. However the research studies for SOFC and battery system performances for droop control and power system operations seems limited. This simulation model might be extended to study the dynamic capabilities of SOFC and battery systems for real-time operational control of the AC grid. In this kind of research, it is important to develop detailed models for SOFC and battery systems and study the dynamic performance of them.
3. System harmonics level and power quality has to be reduced further. This can be achieved with proper tuning of LC filters and using the more sophisticated control systems in each active generators.

4. In this model, only primary control of the micro-grid is considered and secondary or supervisory control is not included. However in a complete development, secondary control for energy management with economical optimization is necessary.

DC power system or AC power system can be used in micro-grids. If an AC micro-grid is used, all DC power sources are required to have VSCs and control systems, where traditional power loads can be used. On the other hand, If DC micro-grid is used, power transmission within the micro-grid have to be in DC mains and traditional AC loads cannot be directly connected in micro-grid and additional power processing units are required. In this research AC micro-grid has been considered. The power quality levels and power conversion efficiency become a key factor which has to be carefully manage in AC micro-grid with DGs. The choice for AC or DC micro-grid should be based on complete techno-economic analysis. This has to be answered in future research.

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Appendix A: System Parameters

A.1 Active Generator Simulation model Parameters

Main Unit	Sub Unit	Parameter Name	Value
Active generator	Transformer	primary voltage	11000 V rms
		Secondary Voltage	260 V rms
	VSC	Input capacitor	12 mF
		Bridge	IGBT devices
	LC Filter	Inductor	0.5 mH
		Capacitor reactive power	5 kVar
	Current Controller	Proportional gain	0.3
		Integral gain	30
	PQ Controller	Proportional gain	0.1
		Integral gain	20
	V, F Controller	Frequency droop1	50 kW/Hz
		Frequency droop2	100 kW/Hz
		Proportional gain	1
		Integral gain	20
		Voltage droop	0.05 kVar/V
Grid		Voltage	11 kV
		Frequency	50 Hz
Transmission Lines		Inductance	0.3 Ω/km
		Resistance	1 mH/km
		Length	1 km each
Fixed Load		Active Power	250 kW
		Reactive power (Inductive)	50 kVar

A.2 Back-to-back Converter Simulation model Parameters

Main Unit	Sub Unit	**Parameter Name**	**Value**
Back-to-back Converter	Grid side LC Filter	Inductor	1mH
		Capacitor	8 uF (1 kVar)
	Grid side Transformer	Voltage ratings	11kV/400V
	Grid side Converter	PWM frequency	4000 Hz
		Voltage Regulator gains [Kp Ki]	[7 800]
		Current Regulator gains [Kp Ki]	[0.45 30]
	DC link	DC link capacitor	15 mF
		DC link Voltage	1000V
	Micro-grid side Transformer	Voltage ratings	400V/11kV
	Micro-grid side LC Filter	Inductor	1mH
		Capacitor	800 uF(100 kVar)
	Micro-grid side Converter	PWM frequency	2000
		Voltage Regulator gains [Kp Ki]	[0.3 300]
		Frequency Droop	0.002 Hz/kW
Main-grid		Voltage	11 kV
		Frequency	50 Hz
Micro-grid		Voltage	11 kV
		Frequency	50 Hz
Transmission Lines		Inductance	0.3 Ω/km
		Resistance	1 mH/km
		Length	1 km
Fixed Load		Active Power	250 kW
		Reactive power (Inductive)	50 kVar
Variable Power Unit		Active Power variation	-125 to +125 kW

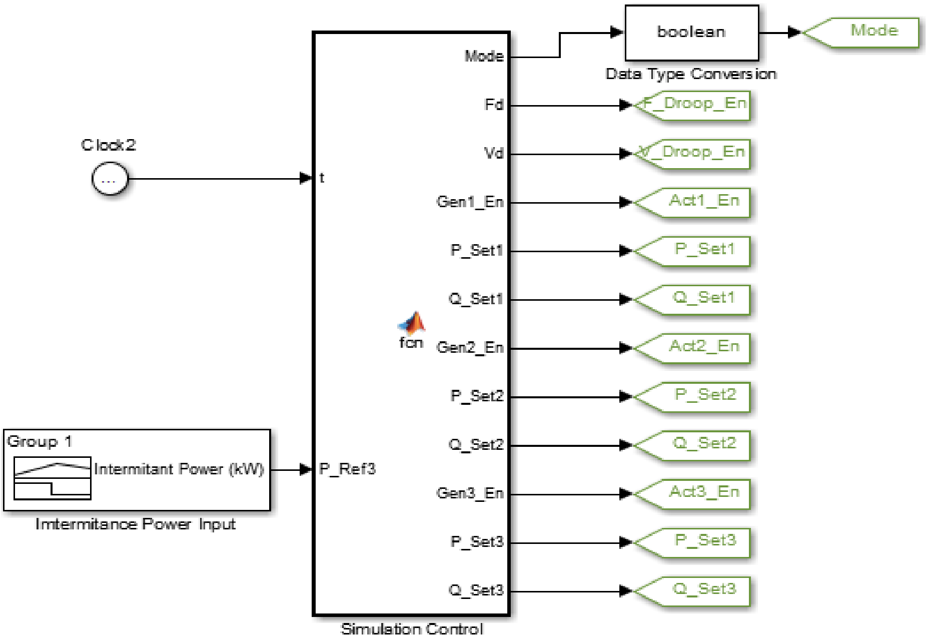
Appendix B: Micro-grid Simulation Model Details

B.1 System Parameters

Main Unit	Sub Unit	Parameter Name	Value
Back-to-back Converter	Grid side LC Filter	Inductor	1mH
		Capacitor	8 uF (1 kVar)
	Grid side Transformer	Voltage ratings	11kV/400V
	Grid side Converter	PWM frequency	4000 Hz
		Voltage Regulator gains [Kp Ki]	[7 800]
		Current Regulator gains [Kp Ki]	[0.45 30]
	DC link	DC link capacitor	15 mF
		DC link Voltage	1000V
	Micro-grid side Transformer	Voltage ratings	400V/11kV
	Micro-grid side LC Filter	Inductor	1mH
		Capacitor	800 uF(100 kVar)
	Micro-grid side Converter	PWM frequency	2000
		Voltage Regulator gains [Kp Ki]	[0.3 300]
		Frequency Droop	0.002 Hz/kW
Main-grid		Voltage	11 kV
		Frequency	50 Hz
Micro-grid		Voltage	11 kV
		Frequency	50 Hz
Transmission Lines		Inductance	0.3 Ω/km
		Resistance	1 mH/km
		Length	1 km
Fixed Load		Active Power	250 kW
		Reactive power (Inductive)	50 kVar
Variable Load		Active Power variation	50 – 250 kW
		Reactive Power variation	10 – 50 kVar
Battery System	Battery	Voltage	400 V
		Capacity	200 Ah (80 kWh)
		Type	Lead Acid
		State of charge when test begin	80 %
	DC-to-DC Converter	Output voltage	800 V
		Indicator	50 uH
		Capacitor before boost converter	1e-3 uF
		Capacitors before boost converter	2* 12 mF
		Switching Transistors	MOSFET
		PI values	0.01, 1
		PWM Frequency	5000 Hz
	Droop settings	Frequency droop1	50 kW/Hz
		Frequency droop2	25 kW/Hz
		PI gains[Kp Ki]	[1 20]
		Voltage droop	0.05 kVar/V
	Transformer	primary voltage	11000 V rms

		Secondary Voltage	260 V rms
	VSC	Input capacitor	12 mF
		Bridge	IGBT devices
	LC Filter	Inductor	0.5 mH
		Capacitor reactive power	5 kVar
	Current Controller	Current Controller gains [Kp Ki]	[0.3 30]
	PQ Controller	PQ Controller gains [Kp Ki]	[0.1 20]
Fuel Cell System	Fuel cell	Operating temperature	1273 C
		Initial Current	100 A
		Voltage	1.18*400 V
		Type	SOFC
		No of Units	2
		Capacity of one unit	100 kW
		Operating range	10- 100 kW
	DC-to-DC Converter	Output voltage	800 V
		Indicator	50 uH
		Capacitor before boost converter	1e-3 uF
		Capacitors before boost converter	2* 12 mF
		Switching Transistors	MOSFET
		PI values	0.01, 1
		PWM Frequency	5000 Hz
	Droop settings	Frequency droop1	50 kW/Hz
		Frequency droop2	100 kW/Hz
		PI gains[Kp Ki]	[1 20]
		Voltage droop	0.2 kVar/V
	Transformer	primary voltage	11000 V rms
		Secondary Voltage	260 V rms
	VSC	Input capacitor	12 mF
		Bridge	IGBT devices
	LC Filter	Inductor	0.5 mH
		Capacitor reactive power	5 kVar
	Current Controller	Current Controller gains [Kp Ki]	[0.3 30]
	PQ Controller	PQ Controller gains [Kp Ki]	[0.1 20]
Intermittent Power unit	Transformer	Primary voltage	11000 V rms
		Secondary Voltage	260 V rms
	VSC	Input capacitor	12 mF
		Bridge	IGBT devices
	LC Filter	Inductor	0.5 mH
		Capacitor reactive power	5 kVar
	Current Controller	Current Controller gains [Kp Ki]	[0.3 30]
	PQ Controller	PQ Controller gains [Kp Ki]	[0.1 20]

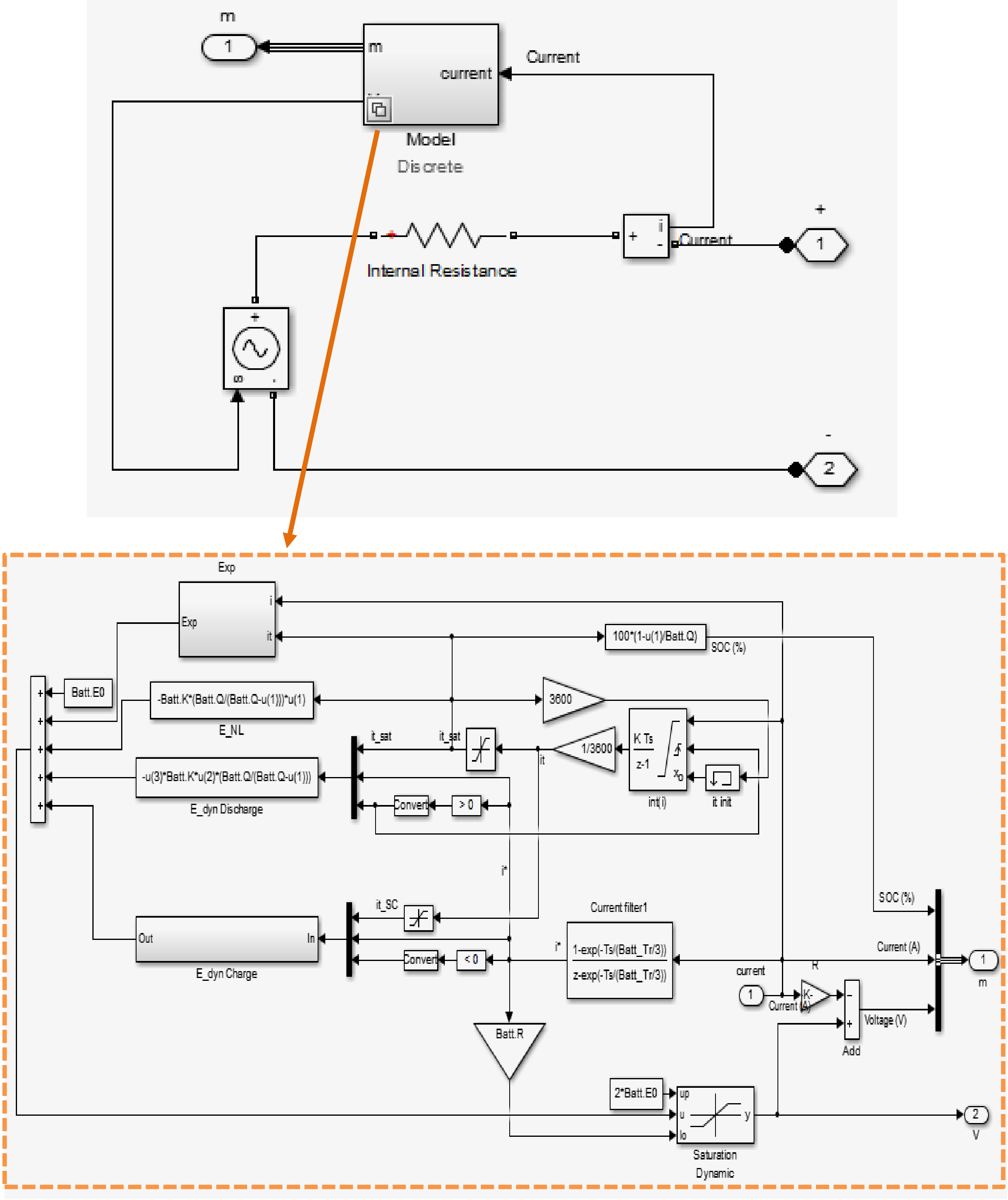
B.2 Simulation Control Logic



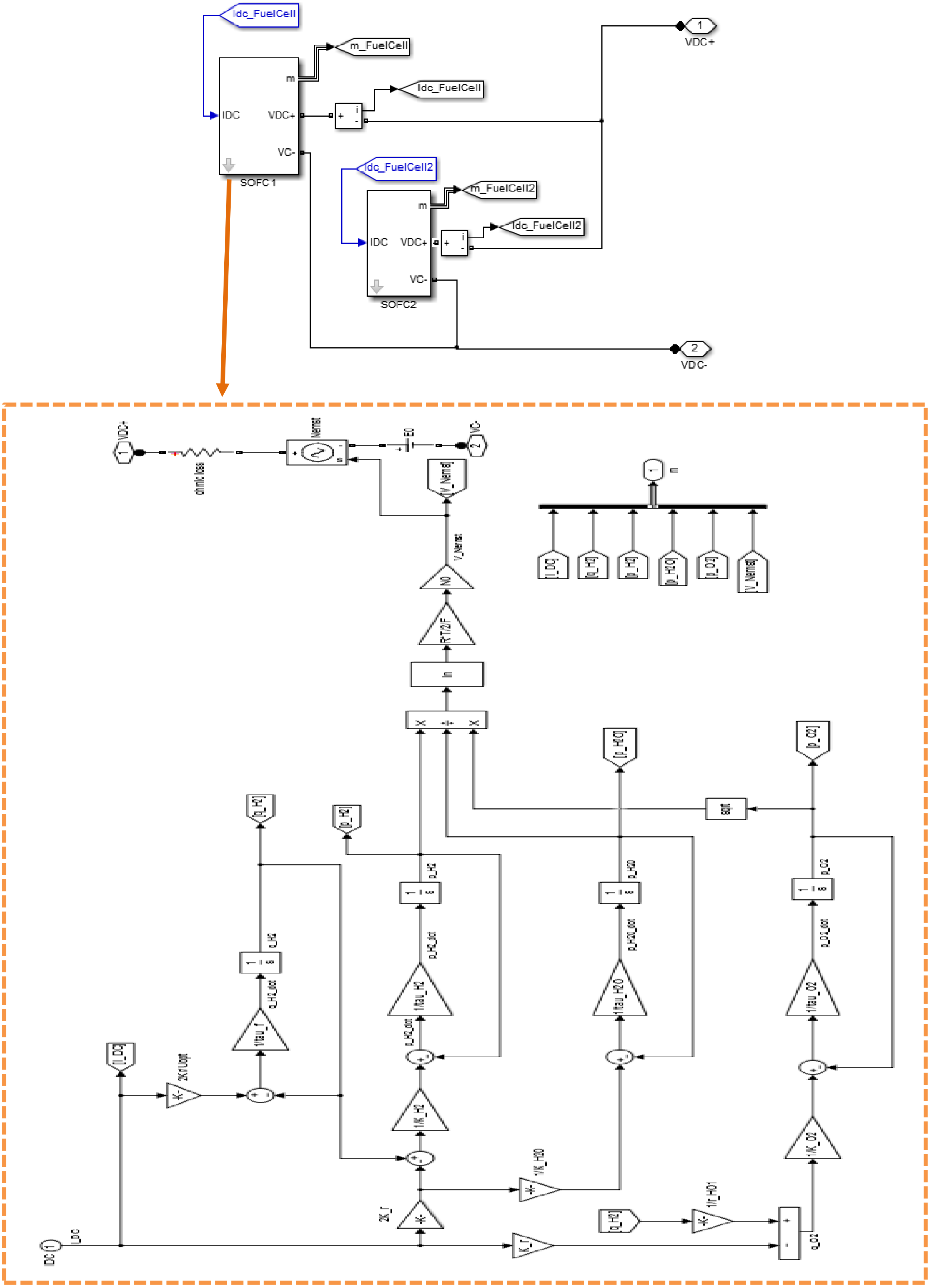
```
function[Mode,Fd,Vd,Gen1_En,P_Set1,Q_Set1,Gen2_En,P_Set2,Q_Set2,Gen3_En,P_Set3,Q_Set3]= fcn(t,P_Ref3)

%# micro-grid simulation model

Mode=1; %#select micro-grid mode

%#power settings of each active generetor
Gen1_En=1;
P_Set1=0;
Q_Set1=0;

Gen2_En=1;
P_Set2=50;
Q_Set2=0;

Gen3_En=1;
P_Set3=P_Ref3;
Q_Set3=0;

% Frequency and voltage droop enable at 0.25 s
if t<0.25
    Fd=0;
    Vd=0;
else
    Fd=1;
    Vd=1;
end;
```

B.3 Simulink Power Source Model Details

Lead-acid Battery Model

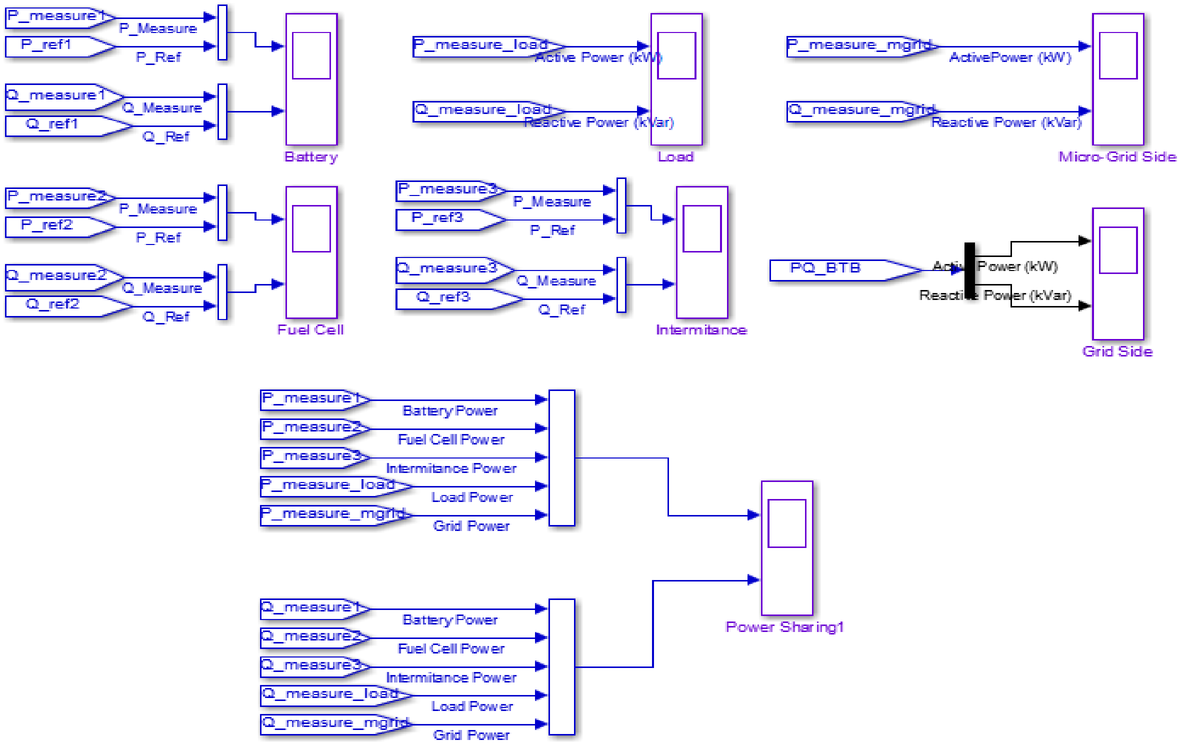


SOFC Model Details



B.4 Measurement Subsystem

Power Measurement



Grid Operating Parameter Measurements