New Paths Towards Building-to-Building Decentralized Energy Management

Submitted to the Department of Electrical Engineering, Electronics,
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by

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Abstract

Distributed generations (DGs) and Renewable energy sources (RES) have become most important and common these days. These DGs and RES have small or no rotating mass and damping behavior, which results a very low inertia and damping effect compared to conventional power plants. Studies showed this affects the grid dynamic stability, frequency and voltage regulation of energy exchange between buildings in a distributed network. So implementing a systems that emulates the behavior of synchronous generator for integration of DG's to grid is a must, to improve the inertia for dynamic stability of the power system.

This thesis presents design and simulation of a virtual synchronous generator (VSG) based control of building level interlinking converters for building to building energy exchange in islanded and grid connected operation. Details of the mathematical modeling for selecting the relevant parameters for the virtual synchronous generator, and state space modeling and analysis to enhance the dynamic response of the system is presented. The simulation of the islanded, grid connected and parallel operation is carried out in Matlab/SIMULINK with dynamic load. The transient behavior of the system at a time of connecting, disconnecting and reconnecting to the grid is minimized with an improved method for grid pre-synchronization. Finally the results and comparisons of the simulation results are presented in detail.

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Acronyms

AC Alternating current.

AVR Automatic voltage regulator.

BESS Battery energy storage system.

CAES Compressed air energy storage.

CHP Combined heat and power.

DC Direct current.

DG Distributed generator.

DNO Distribution network operator.

ESS Energy storage system.

GW Gigawatt.

ICT Information and Communication Technologies.

IEA International Energy Agency.

IEEE Institute of electrical and electronics engineers.

LC Load control.

LV Low voltage.

MC Microsource control.

MG Microgrid.

MGCC Microgrid central controller.

MV Medium voltage.

NERC North American Reliability Corporation.

PCC Point of common coupling.

PEC Power electronic converter.

PI Proportional integral (controller).

PLL Phase lock loop.

PV Photovoltaic.

RES Renewable energy sources.

ROCOF Rate of change of frequency.

SG Synchronous generator.

TES Thermal energy storage.

VSG Virtual synchronous generator.

Chapter 1

Introduction

1.1 Background

Starting from the last two decades carbon emission, power system stability and transmission losses have become the main concern as the consumption of energy is increasing. Studies from International Energy Agency (IEA) states that the global electricity demand is growing at a rate of 2.1% per year to 2040, stating this will make an increase in share of the total energy consumption from 19% in 2018 to 24% in 2040 [1]. This makes the government policies to conclude that, the electricity supply have to increase share of low carbon renewable sources from 36% to 52% in 2040 in their stated policies taking into account the climate effect[1]. It also predicts a sustainable recovery plan indicating the shift to the low-carbon energy sources, an average of 130 gigawatts (GW) additional from wind and solar photovoltaic (PV), and over 30 GW from hydro and nuclear would be installed every year from 2021 to 2023. This shows more concern is given to distributed renewable generations (DRG's) to be the main sources of supply. Energy storage systems (ESS) are used along with this distributed generations (DG's) to balance the supply and demand of distributed networks. Having DG's is allowing companies and individuals to have their own generation to supply their loads‘ and trade energy to each other. This have given advantage with a reduced transport costs, allowed buyers to choose the source of energy and use transparent transactions using new technologies like blockchain.

Integrating and energy trading of this DG's to the grid and to each other requires different layers of control which deals with, the electrical analysis, economic analysis, security and stability of the system. Transformers or power electronic interfaces are used to integrate DG's with the grid depending on the type of the generation. This power electronic interfaces requires appropriate control techniques to maintain the stability of a distributed network.

The integration of the DG's in a distribution network to a conventional network have many challenges in the electrical power stability of the system, voltage regulation and frequency stability, balancing the demand and supply, and transients during connecting and disconnecting of the generations from the grid. The decentralized group of loads and DG's which operate in connection to a synchronous source is called microgrid (MG). The connection of the DG's, ESS and loads is done through power electronic devices like converter and inverter. Based on the connection to the grid MG are classified as AC, DC and hybrid AC/DC MG's. In AC MG, the DG's are connected to the grid directly through a transformer or DC/AC or AC/AC power electronic converters. And DC MG's are connected to the grid through AC/DC or DC/DC power electronic converters. The structure of the three type of MG is shown in figure 2-1 . Hybrid AC/DC MG composes the behaviour of both AC and DC MG's. Even though most of the MG's in use at this time are AC, the move towards the DC generations like PV, DC loads, and the idea of taking advantage of the maturity of AC and DC MG's tends to have hybrid AC/DC MG's. Having DC photovoltaic sources and energy storage batteries, it is efficient to supply the DC loads from the DC source through a DC-DC converter and the AC loads with the grid side DC-AC inverter. The building side sources and loads are connected to the grid through DC-AC inverters.

MG have a hierarchical control strategy, which starts from the building level local converters, secondary, central and emergency, to the global or tertiary control. where the global deals with power flow analysis and the communication with neighbor generations and the main grid [4, 23]. The MG control takes in to account the type of generations and loads like direct current (DC) and alternating current (AC) loads, like elevators, ventilation and security systems as well as the future high-demanding systems related with electric vehicle charging infrastructure while connecting to the main grid.

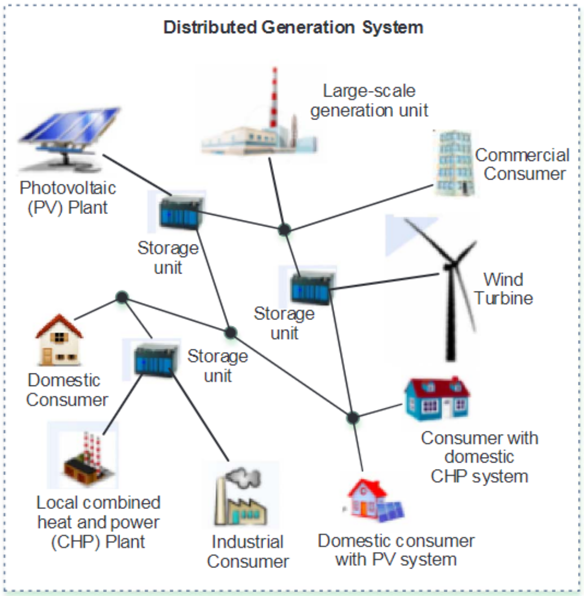


Figure 1-1: Distributed generation system [9]

The management of MG's are either in grid forming, where the DG's operate as a voltage source setting their own voltage and frequency and supplying the load or as a grid supporting as current sources following the grid voltage and frequency. They also compose the two behaviours and work as grid supporting forming or grid supporting feeding. This MG managements control the voltage and current of MG's and the frequencies have to follow the grid. With only voltage and current control approach energy exchange between building and integration to the grid affects the dynamics of the distributed network because of very low inertia in the renewable sources.

MG's are weak electrical networks, because of the nature of the generations, loads, integration of the networks, power sharing between the generations and connection to the conventional grid. Having the advantage on environmental issue and reduction of power transmission losses, the weakness of electrical network and complex control strategy needs a significant research. Even though studies and research's on on MG have been carried out they still require an improvement after looking on the behaviour of the distributed generations and the power electronic devices. Specially in a hybrid AC/DC MG the integration becomes more complex.

Building to building energy exchange and management have layers of control which takes control of electrical power control, communication control and business control. The electrical power control consists of the power flow analysis, integration of the DG's and control of power electronics interfaces between the buildings. The power electronic interlinking and their control strategy have to maintain the system power dynamic stability, and frequency and voltage regulation of the distributed network. This thesis focuses on control of the interlinking power electronic converters for the building to building energy management to have an improved system dynamics and frequency and voltage regulation.

The distributed generators and renewable energy sources (RES) used in MG have no rotating mass (inertia) and damping property. Connecting these DG's and RES which have no rotating mass (inertia) and damping property with very large synchronous generators of main grid power plant affects the power dynamics, frequency stability and voltage regulation of the grid. As a solution to this, a virtual inertia can be provided using an energy storage and a power inverter with a proper control mechanism that emulates the dynamics of synchronous generator. This mechanism which provides virtual inertia to improve the dynamics of the power system is called virtual synchronous generator (VSG) control mechanism. VSG mainly consist of energy storage, inverter and control mechanism[4].

In this thesis a VSG control is designed to emulate all the dynamics of the synchronous generator like the swing equation, which have a great impact on maintaining the frequency stability of the power system by providing the required inertia. The model of VSG control includes the virtual impedance of the generator, automatic voltage regulator (AVR), governor model and the current control of the inverter.

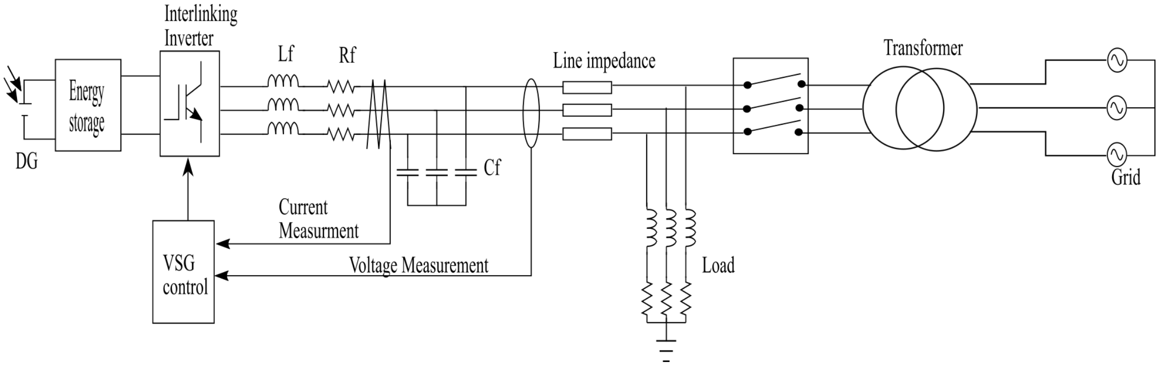


Figure 1-2: General VSG Structure

1.2 Motivation

The concerns about environmental effect from carbon emission from power generations is moving the power generation to be renewable generations such as wind and PV. These renewable generations are being used for distributed generation systems allowing consumers to be prosumers. The prosumers can either exchange power with their neighbors or the utility grid. This exchange of power requires an appropriate integration control of the distributed generations to keep the distributed network stable. The renewable generations like PV used in distributed system have no rotating mass (inertia) and damping property. Integrating this small generations with large synchronous generator based power plants affects the power system dynamic stability, frequency and voltage regulation of the distribution system. This also affects the power exchange and proper power sharing between buildings. As power systems have frequency and voltage deviation standards, the integration of this distributed generators have to be integrated with out deviating the standards and without affecting the loads.

To have a dynamic power stability, and frequency and voltage regulation for integration of parallel DG's to the grid, we need to improve the inertia of the system. Virtual synchronous generator based control of interlinking inverters improve inertia of the system by emulating the operation of synchronous generator. This allows parallel operation of distributed systems and seamless integration to the grid with an improved dynamic stability of the system.

1.3 Thesis Objective

This thesis proposes a control strategy for a parallel operation of DG's and seamless integration to the utility grid, to have decentralized building to building energy management. It mainly focuses on providing a virtual inertia by emulating the operation of synchronous generator to control the interfacing power electronics, for having power dynamic stability, frequency stability, voltage regulation and improved active power dynamics of the microgrids. This combines the following specific objectives:

- Design of a virtual synchronous generator control for islanded, grid connected, parallel islanded and parallel grid connected operations to have a proper energy exchange between buildings and the grid.
- Design of an improved pre-synchronization method that eliminates the transients and oscillations in power and frequency, when the system moves from islanaded to grid connected.
- Power transient stability analysis of grid connection, disconnection and reconnection to the distributed network.
- Design of DC link voltage controller and DC-DC converter controller for the integration of battery and PV system in the DC MG's system.

1.4 Thesis Structure

Chapter 2: Presents about distributed generation, review of studies on hybrid AC/DC micgrogrids and an existing virtual synchronous machine and droop control operation strategies. It investigates the advantages and problems of an existing control strategies. And the improvement and contribution of this thesis work to the future building to building energy management and dynamic stability of MG's.

Chapter 3: Establishes the working strategy and development of virtual synchronous generator (VSG) control from the idea and mathematical modeling of an actual synchronous generator operational working principle for the control of the interfacing power electronic devices. It presents the design of VSG control and selection of control parameters. The state space modeling of the active power is designed and dynamic analysis of the system is simulated with different inertia and damping value to study the stability behaviour of the system with an increase in the inertia and damping factor. It also presents the building to building energy exchange.

Chapter 4: Presents the design and simulation of the VSG control for islanded, grid connected, islanded parallel with power sharing and grid connected parallel operations. In this chapter an improved pre-synchronization method for grid connected operation is designed. A grid connected DC microgrid is also designed, and presented here including the DC voltage control and the PV and ESS connecting DC-DC boost converter control.

Chapter 5 and 6 presents the simulation results, summarization and conclusions from the development of the thesis and future work and extension in this research work.

Chapter 2

State of the art

2.1 Distributed Generation and Energy Storage System

Distributed generation which is also known as decentralized generation is a term to describe an “on-site” generation of electricity, rather than centrally generating in large level power plants and transmitting it for a long distance until it reaches the consumers[25]. The first power plants were small electricity generations which were able to supply close neighborhood customers. These power grids were DC and had battery storage to balance the generation and consumption. This shows that the idea of DG’s, small scale electricity generation near to the customers is not a new idea [25]. DG’s give an advantage on reducing long line transmission losses and cost of transmission. They have been most popularly used in rural areas where the distance between each houses is long that makes the transmission and distribution costs high as an off-grid generations.

DG’s includes renewable distributed generations and non-renewable distributed generations. The non-renewable generations are based on the combustion of fossil fuels like combined heat and power (CHP) or combined cooling, heating and power (CCHP), which have an additional advantage of a profitable thermal energy recovery[32]. [32], presents development of a CHP distributed generation with Compressed Air Energy

Storage (CAES) and Thermal Energy Storage (TES) for a school. They have made the study and analysis of the use of the energy storage, fuel consumption and the reduction of carbon emission. But still the carbon emissions and cost of generation are high compared to other generations as stated in their conclusion. The renewable distributed generations are photovoltaic, wind, biomass, small hydro power, geothermal, ocean energy and solar thermal. Except the hydro power which might have a hydro storage the other renewable generations are fluctuating depending on the climatic conditions. In this thesis only renewable distributed generations are considered. This thesis deals with PV DG and an ESS.

To avoid the effect of the generation fluctuations in renewable sources, energy storage systems (ESS) are used to balance the supply and demand and supply at the time of peak loads depending on the control and optimization of the system. This helps to avoid dependability on non-renewable sources and improve the power dynamics response, power quality, reliability and stability. A review from [7, 32] describes the ESS used in distributed system like mechanical storage systems (Pumped Hydro Storage, flywheel, Compressed Air Energy Storage (CAES)), electrical storage systems (Ultra-capacitor Energy Storage, Superconducting Magnetic Energy Storage (SMES)), chemical energy storage system (Hydrogen-based Energy Storage Systems) and electrochemical (Battery Energy Storage System (BESS)), and shows the comparison of these ESS's. Those days Li-ion battery are mostly used in of their high power density and improving power quality.

The integration of DGs can be done either by direct machine coupling or through power electronics interfaces. The ones that can be directly coupled are those that originally generate mechanical power such as hydro power, wind and CHP. The distributed power electronics interfaces include the DC/AC, AC/AC and AC/DC/AC, which are used to integrate renewable sources like PV and wind to a common point of local grid [6].

DGs can operate in a grid connected mode generating current to help the grid, by supplying a specified active and reactive power references using a local control method known as "PQ inverter control" or grid feeding. In this case the distributed generators follow the voltage and frequency of the medium voltage (MV) distribution grid and generate a specified current proportional to the power references. DG's can also operate in islanded mode, as the main objective of the generations is to supply the load keep the "lights ON". In this case the generators have to specify their own reference voltage and frequency as they have to operate as small scale grids, this operation is known as "VF mode" or grid forming. In islanded mode all the generators connected to the distributed network share the load depending on their droop constants, and respond to current faults and overloads happening on that MG network [4]. A grid supporting converter operator mode which can operate in islanded and grid connected mode by combining the features of grid forming and grid feeding.

In MG control the main variables to be controlled are frequency, voltage, active and reactive power. These controls are to regulate voltage and frequency of the system, have a proper power sharing between the DG's, optimize cost and generation and improve dynamic transients during connecting and disconnecting of the DG's from the grid. Based on the power type connection of the DG's to the grid, MGs are group as AC, DC and hybrid AC/DC MG's. Figure 2-1, shows the structure of the MG's. [16, 28] makes a review of AC, DC and hybrid AC/DC MG's stating the advantage and drawbacks of each type and the control strategies. As hybrid AC/DC MG that will be briefly discussed in the next section combines the advantage of both AC and DC MG's, this thesis work deals more on hybrid AC/DC MG.

2.2 Hybrid AC/DC Microgrid

These days hybrid AC/DC MG's are used for integration of DG's as they combine the advantages of the both AC and DC MG's, allowing direct integration of the AC and DC based DG's, ESS and loads to the main grid. 2-1 shows the general topology of hybrid AC/DC microgrid. Eneko Unamuno [28], revises hybrid AC/DC microgrid topologies and stating the advantages and drawbacks over AC and DC MG's. The advantages of hybrid topology includes the following:

- Allows direct integration of AC or DC devices and ESS with minimum inter-

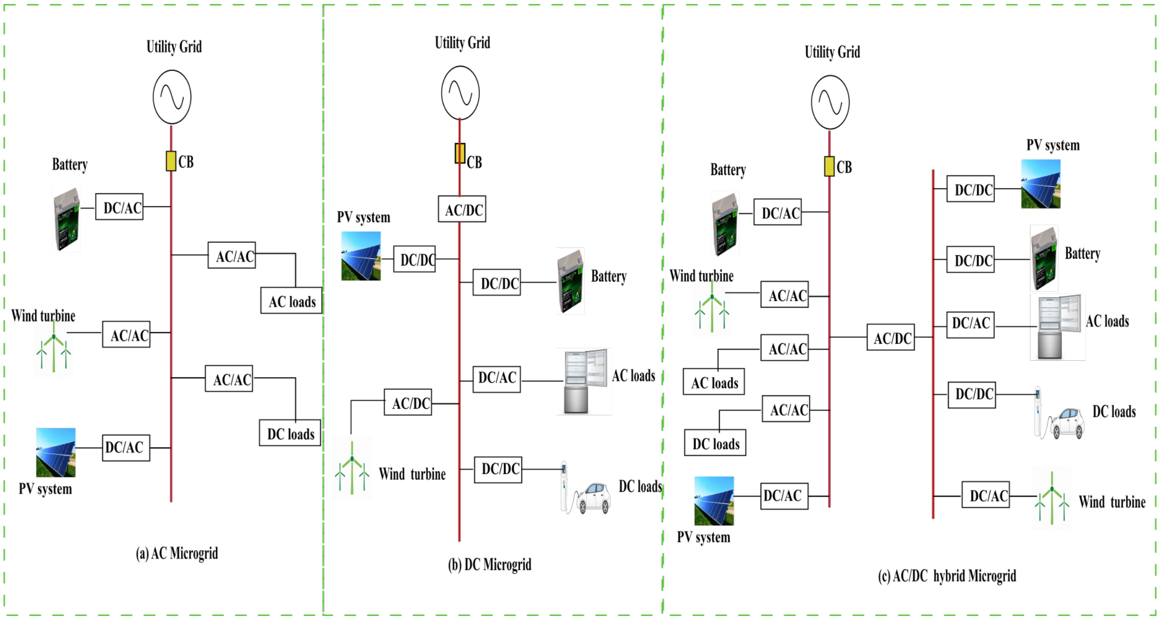


Figure 2-1: Structure of MG

facing elements. This reduces energy losses due to conversion steps.

- Energy storage devices need not to be synchronized.
- Voltage transformation can be done through transformers for the AC side and using DC-DC converter for the DC side.

Having the above stated advantages hybrid AC/DC MG requires a complex control strategy, because of the control of the AC, DC connected devices and interfacing PEC's. And have lower reliability compared to AC MG because of the interface PEC's, but the reliability increases with an increase in the size of the MG and can be improved by reducing the conversion stages. In the review and classification of hybrid AC/DC MG's [28, 29], two main topology groups are presented:

- Coupled AC MG's, the AC network is directly connected the main grid through a transformer. This is less expensive than decoupled MG's as it have a reduced conversion PEC's. In this topology the DC network can be connected after the AC network (fully isolated) allowing the isolation of the entire MG network, or directly to the main grid (partially isolated) through AC-DC converter instead of connecting it after the AC network. [14, 13] uses this topologies for the optimal power management of generators, battery management and power flow analysis.

- Decoupled AC MG's, the AC network of the MG is decoupled by a DC stage with an AC/DC/AC conversion. This topology have three different configurations depending on the connection of the isolating transformer and the DC network as, two-stage completely isolated configuration, two-stage partially isolated configuration and three-stage partially isolated configuration.

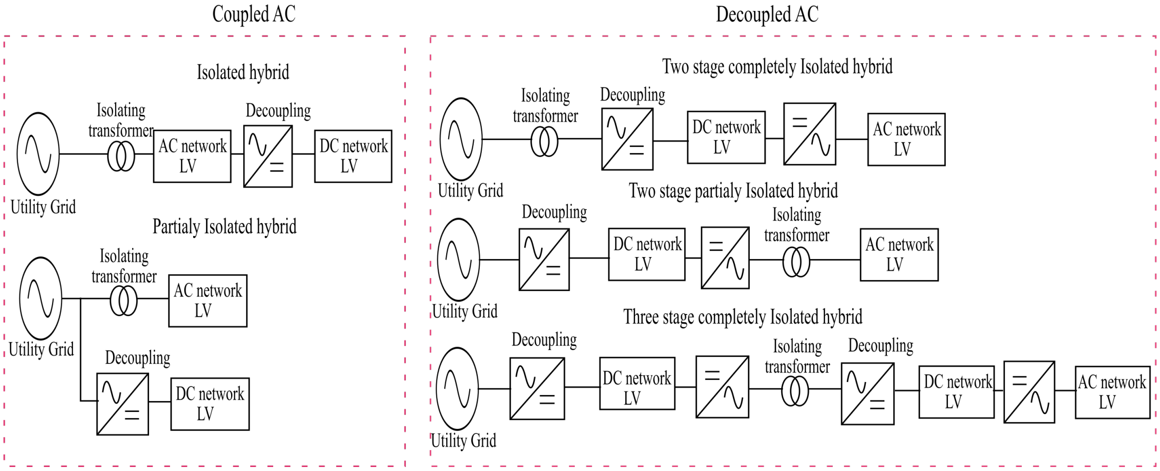


Figure 2-2: Hybrid MG architecture classification

As shown in figure 2-2 the two-stage completely isolated configuration is fully isolated from the main grid through transformer and AC/DC converter, two-stage partially isolated configuration: only the AC network is isolated through the isolating transformer and in three-stage partially isolated configuration, the networks are connected though a non-isolated AC/DC converter and isolated DC-DC converter that connects the DC and AC network. [20, 21, 26] uses the two stage topologies to study the integration of DG's to avoid the stability and synchronization issues. They show the feasibility and easy integration of DG's using two stage topology. Three stage topologies are most preferred and studied as they provide the feature for connecting MV and LV DC networks including the LV AC network. Studies from [17, 18, 15] show the advantages and uses of the three stage topology.

To have stability, protection, power transmission, optimization, synchronization and stable transition MG's need to have a proper control strategy. MG's have a hierarchical control architecture; primary (local), secondary and tertiary. In which the primary deals with the control of local interfacing devices, power sharing voltage and frequency stability of islanded and grid connected mode and the tertiary deals with market participation, optimization, power management and communication network. [28] shows the review and classification of control strategies of Hybrid AC/DC MG's concluding that droop based primary controls are more suitable for power sharing and stability in islanded and grid connected mode . Even though having all the stated advantages and studies on the topologies of hybrid AC/DC MG's, the control of the interfacing PEC's is the challenge and the most hot issue of researchers at this time to improve the performance and dynamic stability of the power system. Integrating DC energy sources that doesn't have any rotating mass, inertia to the distribution network with the large power plants with synchronous generator is part of the problem. This thesis deals with improving the dynamic power stability, frequency and voltage regulation using a virtual synchronous generator based control of the interfacing PEC's.

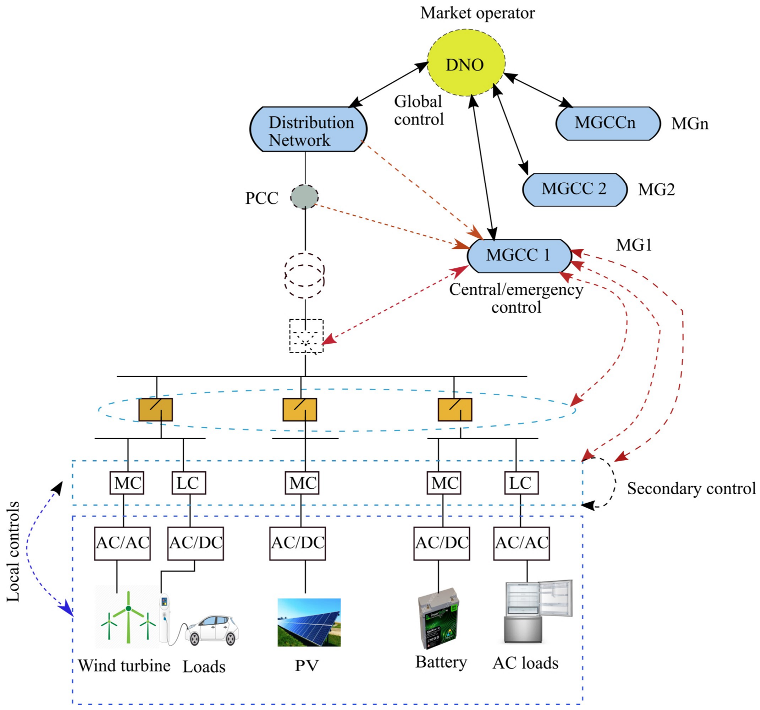


Figure 2-3: General scheme of MG hierarchical control [4]

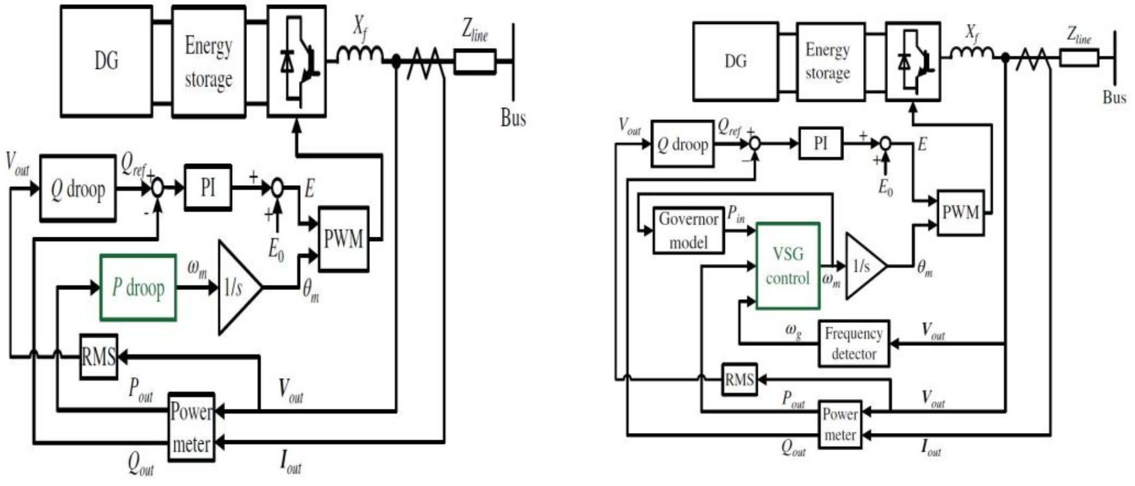
2.3 Virtual Synchronous Machine and Droop control operation

Distributed power systems consists of generating machines from the grid that have a rotating rotor which has an inertia, that affects the rise and fall of the rotor frequency, voltage regulation and dynamics of the power system [3]. In the other side this distributed networks also include the RES which doesn't have a rotating mass and damping behavior which results in low inertia affects the dynamic stability, frequency and voltage regulation of the distributed network. This makes reduced overall inertia and damping of the power system resulting in frequency fluctuation and dynamic instability. This leads researchers to propose the idea of virtual synchronous machine, to add a virtual inertia improving the dynamic response of the distributed network. The virtual synchronous machine emulates the working operation of synchronous generator to improve the inertia and damping of the power system. From [5] revised topologies of VSG and [27] the general block diagram for the droop and VSG based control of interfacing inverters is shown in figure 2-4 from [4]. Hassan bevrani [4] and [24] makes the comparison of droop control and VSG control with simulation and experimental tests looking onto the frequency stability, power transients and delay. This research's show that the frequency deviation can slower in VSG control than that of droop control, and the frequency variation depends on the inertia constant and time delay of the control.

Many researches have been carried out using different topologies of VSG control. [12] proposed the algebraic type model of VSG control in which it consists, the current control loop, simple droop based governor and automatic voltage regulator (AVR) models, a phase lock loop (PLL) for synchronization, and a virtual impedance model of synchronous generator. Except the virtual impedance model, this works similar way with the droop control and is doesn't make high improvement in the frequency regulation and power transients. [8, 30, 10]worked with a VSG control that includes the swing equation of synchronous generator. They have made the power transient and stability analysis for different DG sizes and varying the values of the inertia constant and damping constant using the Eigen values and root locus of the small signal modeling.

An enhanced model of VSG is proposed in [19], in which it emulates the operation of synchronous generator including the governor model, AVR, and the damper mode. And it also proposes a method to have reduce the power transient which is bus voltage estimation which acts as a voltage magnitude synchronizer, it uses the line impedance's to adjust the voltage of the VSG to the voltage of PCC [19]. This VSG topology have an improved power transients and frequency and voltage regulations. In practical in which we don't exactly know the impedance of the interconnecting lines, the bus voltage estimator may not adjust the voltage to the grid connecting point. In the above stated research studies the power transients and frequency variation during the disconnection and re-connection of the generations is not studied.

This thesis work proposes a VSG control that emulates the working of a synchronous generator and the droop control for islanded and grid connected mode with an improved pre-synchronization method to improve the transients during connecting, disconnecting and reconnecting of the DG's from the grid. It also investigates the stability of the system with the variation of the control variables like the inertia constant, damping constant, frequency and voltage droop coefficients by making state space modeling of the control system. And a DC-DC converter control is developed to control the voltage and currents from the ESS and the PV source.



a

b

Figure 2-4: General converter control block diagram (a) Droop control (b) VSG control [5]

Chapter 3

Virtual Synchronous Generator Operation and Control Design

3.1 Synchronous Generator Operation

Synchronous generator is an electrical machine made from two cylindrical ferromagnetic materials called stator and rotor. Based on the geometric shape of the rotor they are classified as round and salient pole [11]. A synchronous machine can be represented as a voltage source with an internal impedance as shown in figure 3-1. Where P_g and Q_g are the electrical powers defined as:

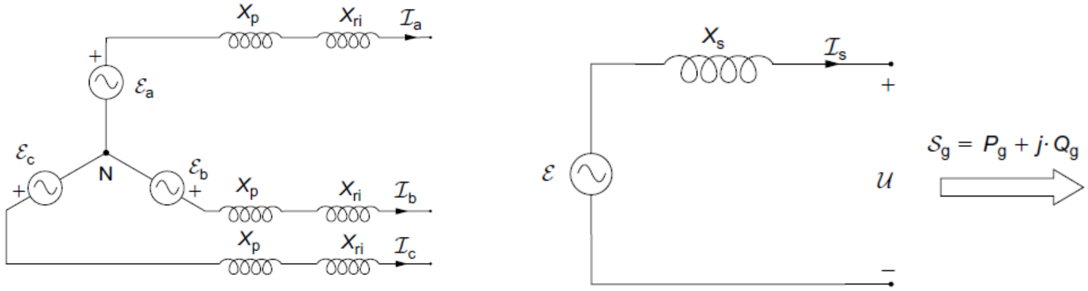


Figure 3-1: Three phase circuit of synchronous generator [11]

$$P_g = \frac{EU_g}{X_s} sin\delta \tag{3.1}$$

$$Q_g = \frac{EU_g}{X_s} cos\delta - \frac{U_g^2}{X_s} \tag{3.2}$$

δ is the angle between the E and U. The reactive power is related to the electrical parts. The prime mover power is the sum of the mechanical power losses plus the output active power. The output active power and the prime mover mechanical power are related based on the mechanics of the rotating mass. where the summation of the torques in the rotating mass of the machine is the moment of inertia times the angular acceleration of the rotating mass[11].

$$P_m - P_g + P_{loss} = M\frac{d\omega_r}{dt} + D(\omega_r - \omega_{rs}) \tag{3.3}$$

Where M is moment of inertia constant, D is the mechanical damping constant, ω_r is the rotor angular speed and ω_{rs} rotor angular synchronous speed. This equation is the main equation that relates the speed of the machine with the power.

In electrical power systems the power generation have to be balanced with the consumption of the loads. Sudden change of the load results in variation and fall of the frequency of the power system. It is the inertia of the generator that stabilizes the system on this conditions by supplying the loads as it is the stored rotating energy that contributes to the system on variation of load for a specified time depending on the inertia time constant. For large synchronous generator ratings the inertia time constant varies in the range between 2 to 9 s.

Synchronous generators are the main devices that maintain the frequency of the power system network. They have a frequency control P-f and voltage magnitude control Q-V. The output terminal voltage and frequency are specified based on the P-f and Q-V regulator. This are namely known as the governor model and AVR model of the synchronous generator. This machine is reversible can operate as a generator or motor. This is important in DC and AC/DC hybrid MG Building to building (B2B) exchange of power between DG's and grid either receive or send power to neighbourhood.

In this thesis work the electrical operation of an actual synchronous generator is taken

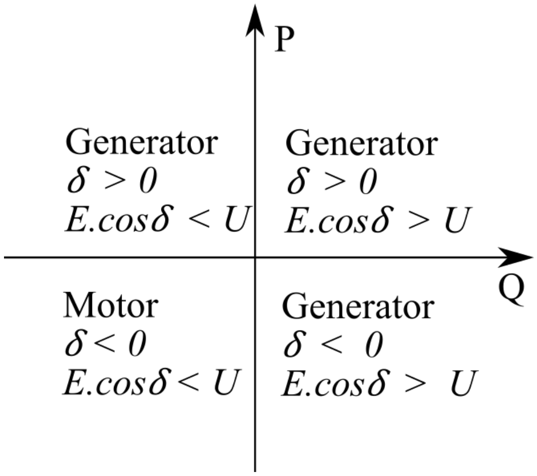


Figure 3-2: Operation of synchronous machine [11]

in to consideration while designing the VSG control. This includes the impedance model, governor model, AVR, turbine and the swing equation of the synchronous generator. In the impedance model the transient and sub-transient impedances are not considered as the interfacing inverter can not respond fast to simulate them.

3.2 Modeling of Virtual Synchronous Generator Control and Parameter Selection

For proper power sharing and dynamic stability of a MG, the control of the interfacing inverter plays a vital role. In this section the design of VSG control is presented. The designed VSG is current controlled based. It includes the impedance model, AVR model, governor model, damper model and rotor model. Based on the mathematical modeling of SG, stability analysis and power system standards, control variables are determined. The VSG is designed to operate in islanded and grid connected with a pre-synchronized method. figure 2-4 b shows the general block diagram of VSG control. To start with the emulation, the main part that provides the inertia to the system to stabilize the frequency is the swing equation. The swing equation is expressed as:

$$P_{in}(t) - P_{out}(t) = J\omega_m(t)\frac{d\omega_m(t)}{dt} + D_f P_{baseDG}\frac{\omega_m(t) - \omega_g(t)}{\omega_0} \tag{3.4}$$

Where J is the virtual inertia constant which can be expressed as $2HS_0/\omega_0^2$. H is the inertia time constant, S_0 the nominal apparent power of the DG and ω_0 the nominal system frequency. This shows the inertia depends on the rating of the DG. Theoretically the higher the value of the inertia, the improved frequency regulation and system stability.

$P_{in}(t)$ is the input power from the virtual shaft which is calculated using the governor model, $P_{out}(t)$ is the measured output power, D_f is the virtual damping factor of the VSG, $\omega_m(t)$ is the rotor virtual angular frequency and $\omega_g(t)$ is the angular frequency of the measured output voltage.

The governor model represents the ω-P droop controller, and the Q-droop is V-Q droop controller. The governor and AVR model are designed using the droop control characteristic shown in figure 3-3

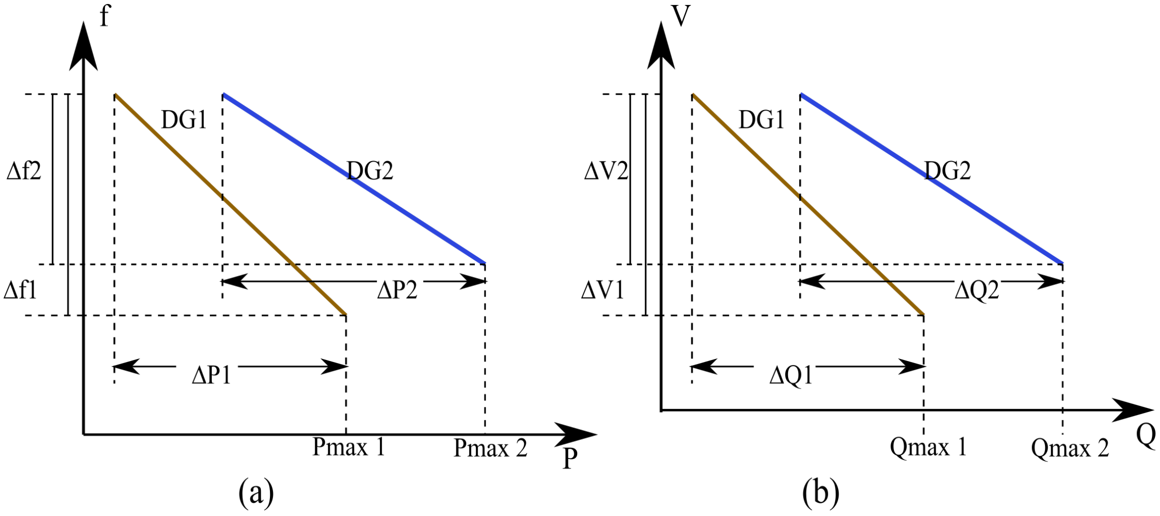


Figure 3-3: Droop characteristics (a) P - f droop characteristic (b) Q - V droop characteristic

$$P_{in} = P_0 - k_p(\omega_m - \omega 0) \tag{3.5}$$

Where k_p is the active power droop coefficient expressed as $\Delta\omega\ /\Delta P$

$$Q_{ref} = Q_0 - k_q(V_{out} - E) \tag{3.6}$$

Where $k_q$is the reactive power droop coefficient expressed as $\Delta V/\Delta Q$ and E is the reference nominal voltage.The droop characteristics is included in the VSG control to have an appropriate power sharing between the distributed generators based on the droop coefficients.

$$T_{dq0} = \frac{2}{3}\begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta - \frac{2\pi}{3}) \\ sin(\theta) & sin(\theta - \frac{2\pi}{3}) & sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} \tag{3.7}$$

The power meter is for calculating the output active and reactive power supplied by the DG to the load, this is calculated using the following formulas.

$$P_{out} = \frac{3}{2}(V_{gd}I_{gd} + V_{gq}I_{gq}) \tag{3.8}$$

$$Q_{out} = \frac{3}{2}(V_{gd}I_{gq} - V_{gq}I_{gd}) \tag{3.9}$$

Assuming $D_{dg} = (D_{dg}P_{baseDG})/\omega_0$ and substituting $P_{in}(t)$ of equation (3.4) by (3.5), the swing equation can be rewrite as:

$$P_0 - k_p(\omega_m(t) - \omega_0) - P_{out}(t) = J\omega_m(t)\frac{d\omega_m(t)}{dt} + D_{dg}(\omega_m(t) - \omega_g(t)) \tag{3.10}$$

$$-k_{p_{dg}}\Delta\omega_{m_{dg}} - \Delta P_{out_{dg}} = J(\omega_{m_{dg}}s\Delta\omega_{m_{dg}} + s\Delta\omega_{m_{dg}}^2) + D_{dg}(\Delta\omega_{m_{dg}} - \Delta\omega_{g_{dg}}) \tag{3.11}$$

Where the subscript dg is to represent the distributed generator. The VSG control developed is current control based. The current control PI controllers are tuned considering the transfer function of the filter as a system.

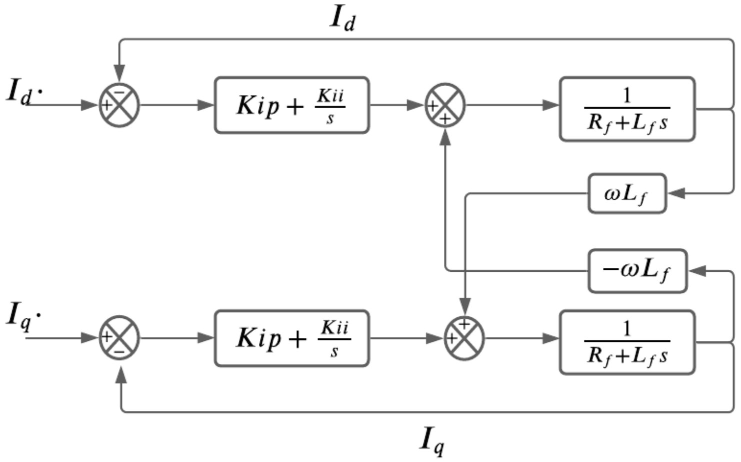


Figure 3-4: Current Controller model

3.2.1 Virtual Impedance Model

The current control of the inverter takes current references from the impedance model. The impedance model emulates the impedance characteristics of the synchronous generator. The impedance model considers impedance of synchronous generator without transient, as the transient and sub-transient components doesn't allow the controller to respond very fast. A cylindrical synchronous generator in the range of 50-100 kVA data sheet is considered to determine the values of the impedance and resistance. The impedance x can be approximately the transient impedance of a synchronous generator if the inverter is operating in parallel with a synchronous generator to have proper power sharing. The impedance model uses the Park's transformation from equation (3.7). The grid voltage is considered to be in parallel with the d axis in steady state as shown in the phasor diagram of figure 3-5 The reference current is determined using a transfer function of the impedance model. Where r and l are the virtual impedance and inductance of the VSG.

$$\begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} = \frac{1}{r+ls} \begin{bmatrix} E_d - V_{gd} \\ E_q - V_{gq} \end{bmatrix} \tag{3.12}$$

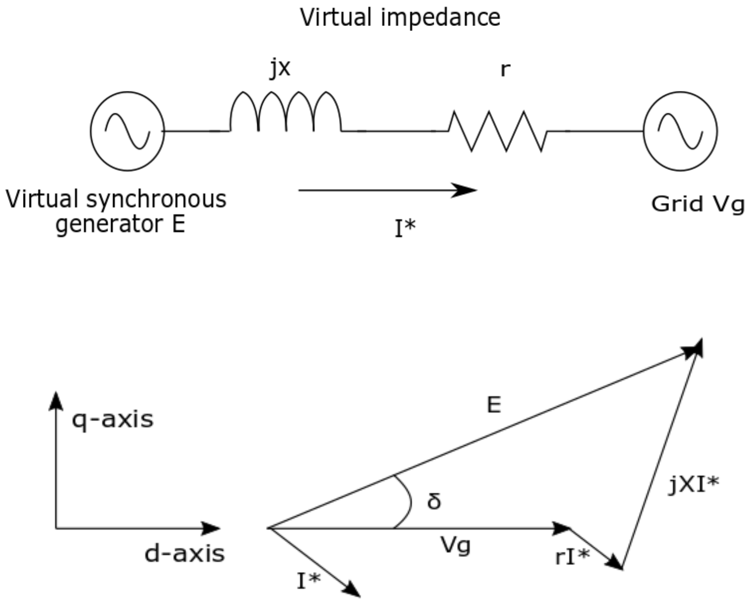


Figure 3-5: Virtual impedance model and phasor diagram

3.2.2 Virtual Inertia and Damping

For electrical power systems, the generated power have to be balanced with the consumption of the load. In case of sudden change of the load, the system frequency will fall and this will continue until the proportional mechanical power of the generator is equal to the electrical power consumption. The frequency fall depends on the variation of the power generation and consumption. The swing equation in (3.4) shows this relationship between power, frequency and inertia. Inertia is the stored rotating energy that will contribute in the variation of the loads to keep the system stable. The inertia of synchronous generator is expressed as $2HS_0/\omega_0^2$. This shows the inertia is dependent on the size of the generator. The inertia time constant H is the one that determines the time that the generator is able to supply the load using the stored rotating energy. For large synchronous generators ratings the inertia time constant varies in the range between 2 to 9 s. The larger the value of J means that the higher the time that the generators can supply the load and lower variation of

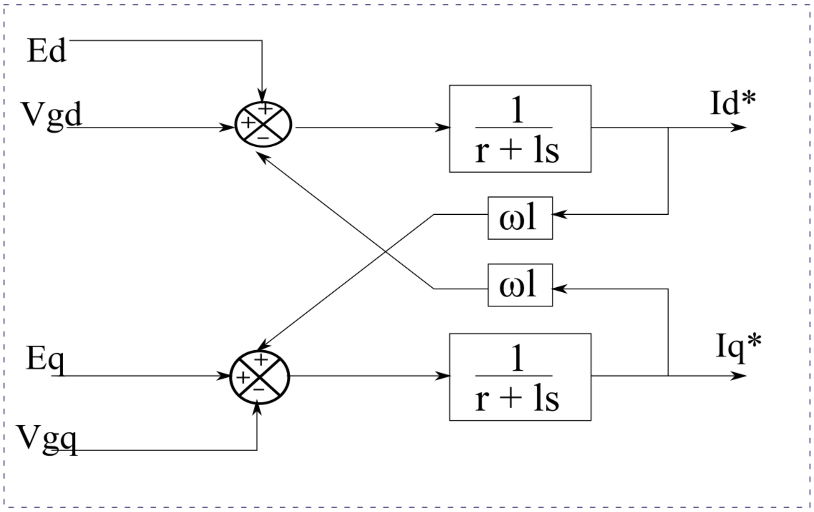


Figure 3-6: Current reference calculation block

frequency resulting in lower rate of change of frequency (ROCOF). But it should be optimal based on the capacity of the distributed generator as this results an overload, that can damage the interfacing inverters. The virtual inertia of the proposed VSG is chosen after looking data sheet of synchronous generators with a capacity range of 50-100kVA and the stability analysis.

It is the damper winding that plays a vital role in stability of the rotor swing in actual synchronous generators. The selection of inertia and damping factor must be so that the DG's can exchange the maximum power the can generate. The electrical torque of a generator is determined using:

$$T_e = E_d i_d / \omega \tag{3.13}$$

$$J \frac{d\omega_r}{dt} = T_p - T_e - T_d - D_{dg}\omega_r \tag{3.14}$$

Where ω_r is the angular speed of the rotor, T_d damping torque, T_p torque and D_{dg} the damping of the prime mover. The T_d damping torque is given by:

$$T_d = K\tau_d \frac{d}{dt} T_e \tag{3.15}$$

Where τ_d is the damping time constant, it have to be small enough to remove noises from the inverter. In steady state assuming $E_d = E$ and $V_{gd0} = V_g$ and taking into consideration the impedance model, the damping torque equation (3.15) can be re write as:

$$T_e = -\frac{x}{r^2 + x^2}(V_{gq0-\Delta\delta}) \tag{3.16}$$

$$T_d = K\tau_d \frac{x}{r^2 + x^2}\frac{d\Delta\delta}{dt} = D\frac{d\Delta\delta}{dt} \tag{3.17}$$

Taking into account the calculation of damping torque of actual synchronous generator which is $P_d \frac{d\Delta\delta}{dt}$, where P_d can be determined from the transient impedances of the synchronous generator as [4]:

$$P_d = V^2((\frac{1}{x''_d} - \frac{1}{X'_d})T''_d sin^2\delta_0 + (\frac{1}{x''_q} - \frac{1}{X'_q})T''_q cos^2\delta_0) \tag{3.18}$$

From this we have $P_d = D$. Using the same data sheet of synchronous generator the values for K and D are selected.

3.2.3 Emulation of Governor Model and Automatic Voltage Regulator

The VSG model emulates the governor model and the automatic voltage regulator (AVR), to have a proper power sharing between the distributed generators. When the VSG is operating in islanded model the DG's have to share the load proportional to the droop regulator coefficients.

An actual synchronous generator have a mechanical governor delay. The mechanical governor delay of the VSG is emulated in the governor model and AVR as a low pass filter with a specified time delay. A PI controller is included in the governor model to regulate the frequency of the system. With the inclusion of the mechanical delay the droop characteristics of the governor model and AVR can be rewritten:

$$P_{in} = P_0 - \frac{k_p}{1 + \tau_{dg}}(\omega_m - \omega 0) \tag{3.19}$$

$$Q_{ref} = Q_0 - \frac{k_q}{1 + \tau_{dg}}(V_{out} - E) \tag{3.20}$$

The turbine model is also emulated as a first order transfer function with a turbine time constant which is determined from the selected inertia and damping factor using the formula from [8]:

$$T_{tur} = \frac{J_g}{D_{dg}} \tag{3.21}$$

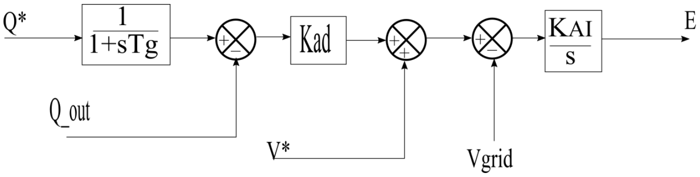


Figure 3-7: AVR model

Where the K_{ad} is the V-Q droop coefficient and K_{gd} is the $\omega - P$ droop coefficients of the AVR and governor models. the governor model is shown in the proposed VSG control diagram shown in figure 3-8 including the rotor and turbine models.

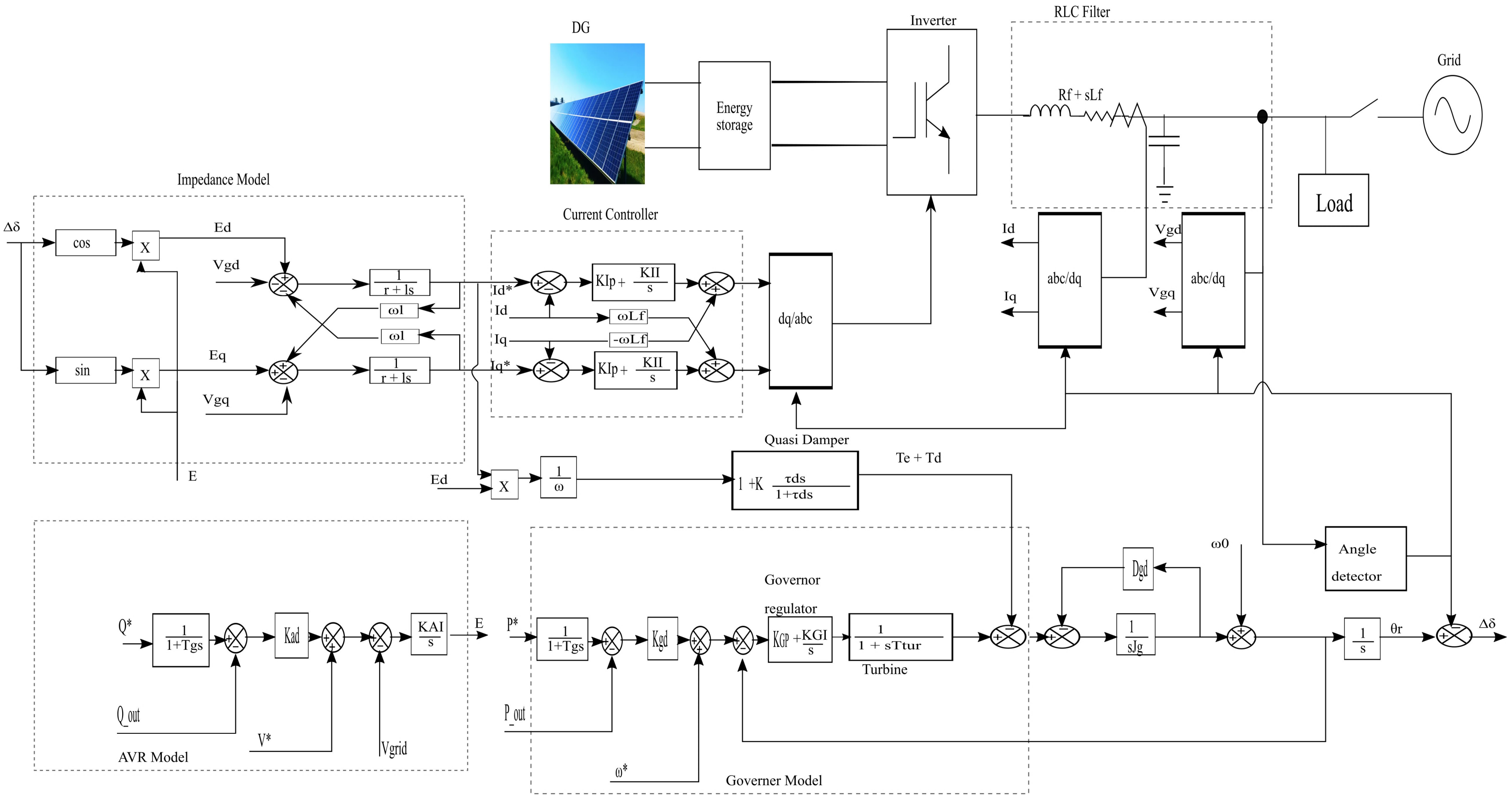


Figure 3-8: Proposed VSG model

3.3 State Space Modeling and Power Stability Analysis

In this section the state space model for the stability analysis of the the system is modeled. Increasing the virtual inertia and damping factor have an effect on the stability of the active power of the system. A simplified model of the system from the reference input power to the out put power is modeled as shown in figure 3-9, where the K_{pp} is:

$$K_{pp} = \frac{314x}{r^2 + x^2} \tag{3.22}$$

by considering at steady state $V_{gd} = V_g$ and the nominal system frequency 50Hz. Here the impedance linear formulas are considered for determining K_{pp}, $E - V_g = (r + jx)(I_d^* + jI_q^*)$.

From the simplified model the state space model is developed using figure 3-10

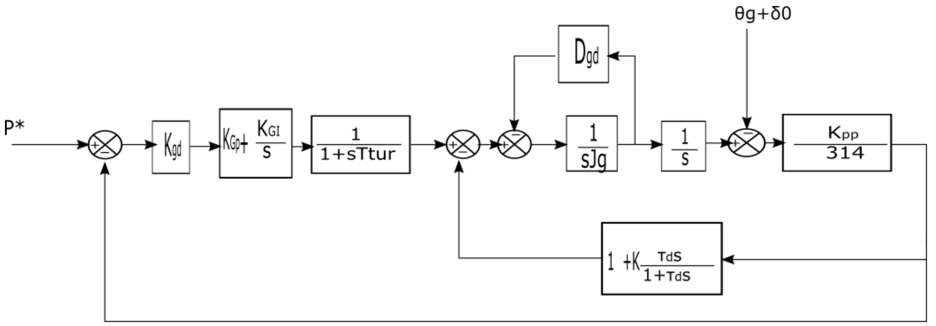


Figure 3-9: Simplified active power control loop [4]

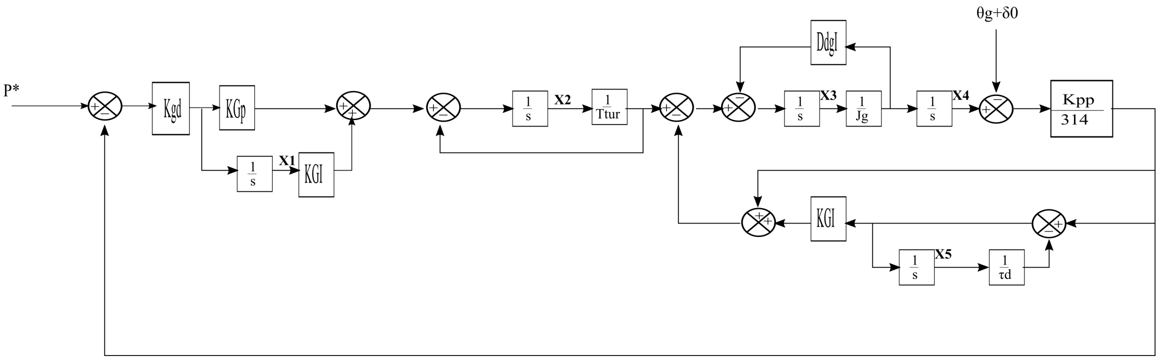


Figure 3-10: State space model block

$$\mathbf{x'} = \mathbf{Ax} + \mathbf{Bu} \tag{3.23}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \tag{3.24}$$

Where **A** , **B** , **C** and **D** are matrices, and **x** and **u** are the state variables and inputs. The inputs are the power reference and the grid angle. The output the system is the active power feedback and the state variables are taken as the inputs of the integrator and the output of the derivatives of this block.

The matrices are given as:

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & -K_{gd}K_{pp} & 0 \\ K_{GI} & \frac{-1}{T_{tur}} & 0 & -K_{gp}K_{gd}K_{pp} & 0 \\ 0 & \frac{1}{T_{tur}} & \frac{-D_{dg}}{J_g} & -(KK_{pp} + K_{pp}) & \frac{K}{\tau_d} \\ 0 & 0 & \frac{1}{J_g} & 0 & 0 \\ 0 & 0 & 0 & K_{pp} & \frac{-1}{\tau_d} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} K_{gd} & \frac{K_{gd}K_{pp}}{314} \\ K_{gp}K_{gd} & \frac{K_{gd}K_{gp}K_{pp}}{314} \\ 0 & \frac{KK_{pp}}{314} + \frac{K_{pp}}{314} \\ 0 & 0 \\ 0 & \frac{-K_{pp}}{314} \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & K_{pp} & 0 \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} 0 & \frac{-K_{pp}}{314} \end{bmatrix}$$

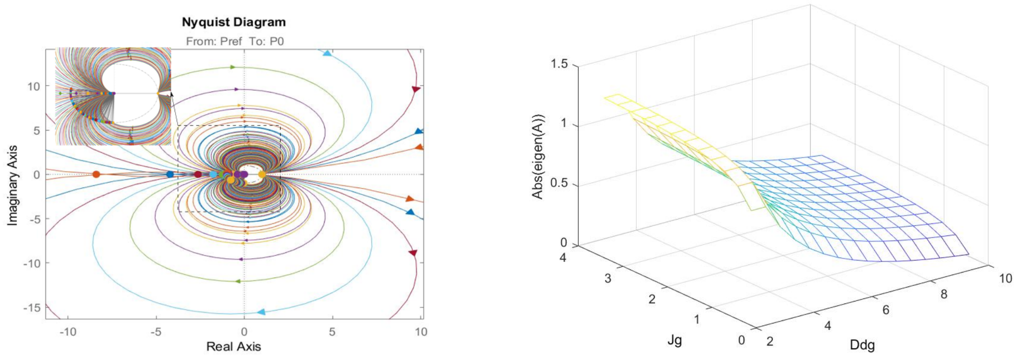
The transfer function from the reference power to output power is a fourth order, this might make the tuning of the governor regulator parameters difficult. so a Routh stability criteria in equations (3.25) and (3.26) is used for tuning the proportional and integral values of the governor regulator.

$$\frac{(D_{dg}T_{tur} + J_g)(D_{dg} + K_{GP})}{J_g T_{tur}} > K_{GI} \tag{3.25}$$

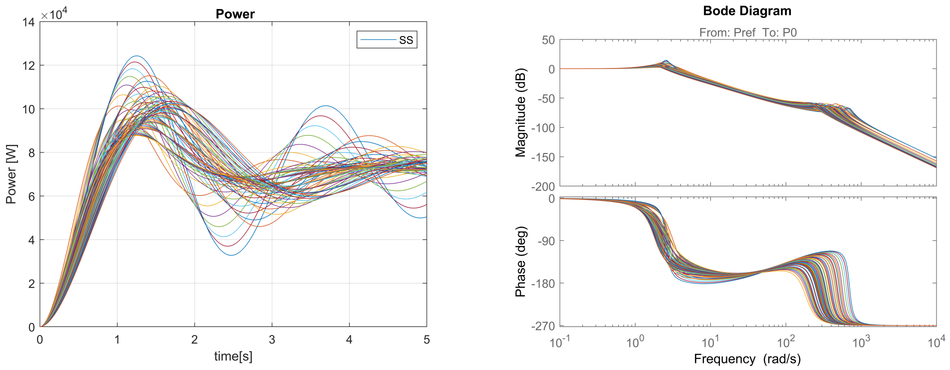
$$\tau_d K > \frac{-(T_{tur}K_{pp} + 2D_{dg} + J_g) + \sqrt{(T_{tur}K_{pp} - J_g)^2 + 4J_gK_{pp}(1 + K_{GP}K_{gd})}}{2K_{pp}} \quad (3.26)$$

Figure 3-11a shows the the behaviour of the active power control loop with variation of inertia and damping factor. As it is shown the stability of the system increases with an increase in the inertia, but we have to take into consideration that the selected inertia should be proportional to the capacity of the DG. Increasing the inertia value to have more stable system can result in an overload of the system which can damage the interfacing power electronics. The virtual synchronous machine parameters and control variables have an effect on the dynamic stability of the system. The effect of the inertia and damping are analyzed as the droop parameters are selected based on the electrical power standards and the regulators using the Routh stability criteria equations (3.25) and (3.26) after the selection of appropriate inertia and damping factor. While changing the values of the inertia and the governor regulator and time constant parameters are recalculated. So the effects shown in figure 3.25 and 3.26 are not only from the variation of the inertia and damping factor by keeping the other variables, but with variations of the other parameters in proportion to the inertia and damping factor of the DG taking into consideration the Routh stability criteria. The K_{gd} and K_{ad} are set equal to the frequency and voltage droop gain values. The proportional gain of the of the regulator K_{GP} of the governor is designed to one over the droop gain value $\frac{1}{K_{gd}}$. And the integral gain of the governor regulator is designed to satisfy the Routh stability criteria of equation (3.26).

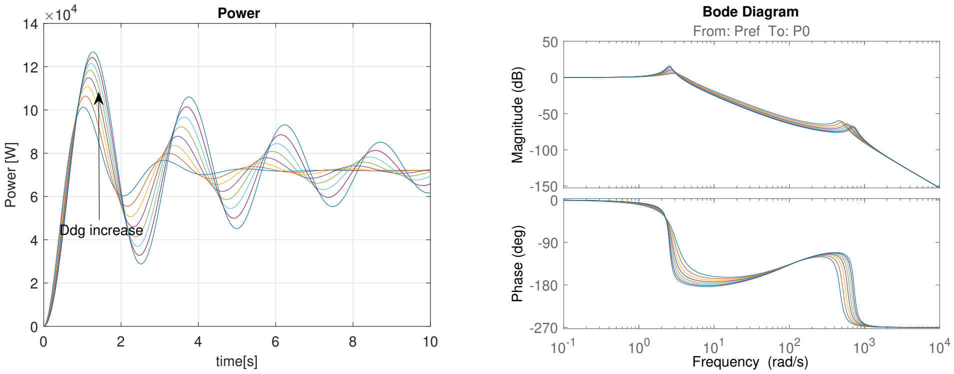
Figure 3-11b shows the time and frequency response of the active power control of the proposed system with variation of inertia and damping values. The inertia and damping values are give as coordinates, with all inertia values coordinated with all the damping values. As it is shown in figure 3-11a the stability of the system increases with in inertia.



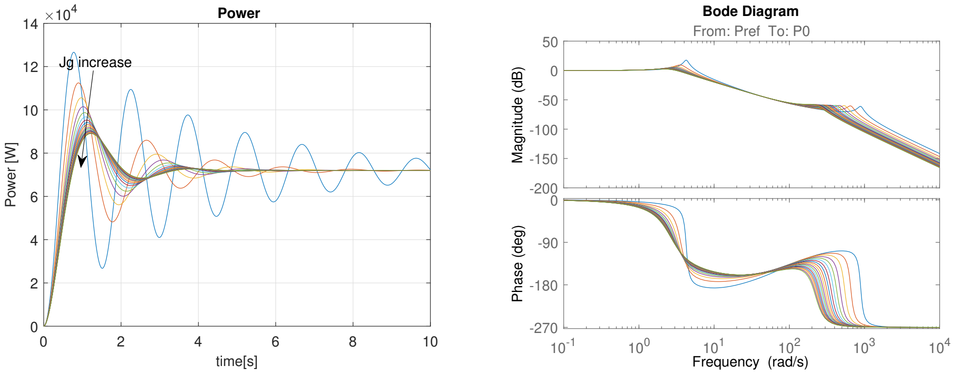
(a) Stability Nyquist results, J_g: 0.146 to 4 and D_{dg}: 2.4 to 10



(b) Time and frequency response of active power control, J_g: 0.146 to 3 and D_{dg}: 2.4 to 6



(c) Time and frequency response, D_{dg}: 2.4 to 6



(d) Time and frequency response, J_g: 0.12 to 2

Figure 3-11: Stability analysis with varying virtual inertia and damping

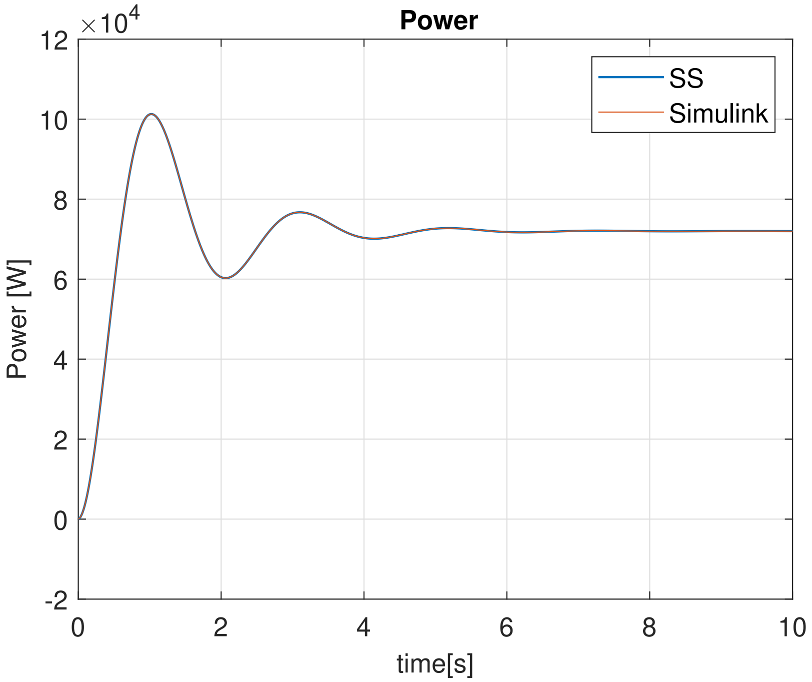


Figure 3-12: Simulink and state space matlab simulation comparisons, $J_g = 0.426$ and $D_{dg} = 2.48$

3.3.1 Frequency and Voltage Standards for Microgrid

A MG systems is a weak power systems network and the non rotating power generations has a severe effect on the frequency stability of the system. Changes in the generation can result in frequency variations in the power system that are outside standard limits and affects the stability of the power system network. Microgrids can operate in islanding or grid connected modes. For islanding operation the frequency variation depends on the droop characteristics of the MG and it is not a big deal about the standards of the frequency and voltage, even though they have to be with in a limit. In a grid connected operation the DG's have to follow the frequency of the grid. As the integration of DG's which doesn't have rotating mass or have no inertia like PV is increased, standards for frequency variation and voltage variations are set. Electrical energy is a product like any other products so it should be with in specified standards and quality range. This gives an emphasis to the stability of an electrical power system. The North American Reliability Corporation (NERC) a maximum frequency variation of 57 Hz to 61 Hz on a nominal frequency of 60 Hz. It recommends disconnection of the distributed generation if it goes below 57 Hz or above 61.8 Hz [2]. European Norm EN50160 states frequency and voltage variations for low voltage (LV) and medium voltage (MV) power system networks ±% (49.5 - 50.5 Hz) and voltage variation of LV, MV: ±10% for 95% of week[22]. The Institute of Electrical and Electronic Engineers (IEEE) recommends a frequency operating standard of ±0.036 Hz for grid-connected systems. There are no specific standards for frequency and voltage limits in isolated MG systems. This mainly depends on the load and generation. Some standards like ISO 8528-5 gives a general gideline for frequency limits that can also be used in islanded MG's.

- Grid connected standards
    - European Norm EN50160: LV, MV: ±1% (49.5 - 50.5 Hz) for 99.5% of week ±6%/+4% (47- 52 Hz) for 100% of week with a nominal frequency of the system 50 Hz and voltage variation of LV, MV: ±10% for 95% of week[22].
    - IEEE recommended standard: frequency variation range of ±0.036 Hz
    - NERC recommended standard: maximum frequency variation of 57 Hz to 62.8 Hz and automatic trigger for frequency <59.3 Hz of under frequency load shedding.[2]
- Islanded operation
    - ISO Standard8528-5 for Generators: Normal frequency range of ±1.5 Hz and critical frequency range of ±9 Hz with a recovery time of 10 s and maximum ROCOF 0.6 Hz/s. And voltage variation of ±5%.

In this thesis work to have a proper working for islanded model and grid connected a maximum voltage variation of 5% and frequency variation of 1% are set. The droop coefficients are determined based on this voltage and frequency variation for a maximum acive and reactive power variation with an apparent power of the distribution system 100 kVA and assuming a minimum power factor of 0.9.

$$K_p = \frac{\Delta\omega}{\Delta P} \tag{3.27}$$

$$K_q = \frac{\Delta V}{\Delta P} \tag{3.28}$$

3.4 Building to Building Energy Exchange

These days with the increase in size of DG's consumers are becoming prosumers, they generate energy and consume. They store the energy in ESS or sell it to other prosumers or directly feed to the grid when they have surplus electricity, depending on the generation prediction and cost of electricity. This have changed the traditional one way power transmission and trading which was from the main grid to consumers. This has allowed prosumers trade energy with out an intermediate aggregators and gave the opportunity to select the type of source from which they want to buy.

The energy exchange between buildings require different layers of control. The building to building energy exchange have power grid, Information and Communication Technologies (ICT), control and business layers [31]. The power grid layer is includes all the physical elements of the power system like transformers, loads, smart meters, distributed sources and interfacing power electronics devices.The ICT layer includes all the communication devices and protocols for transferring data of sensors and other commands. It can be a wired or wireless communication. The business layer governs issues related to the energy market exchange between the buildings.

The control layer contains all the control of power exchange in the distributed network between the buildings. It is all about the MG control, to control the reliability and quality of the of the power flow, control of frequency, voltage and active power of the building to building energy exchange.

The proposed model for the building to building energy exchange is shown in figure 3-13. Each building is considered to have PV system, AC and DC loads, and battery

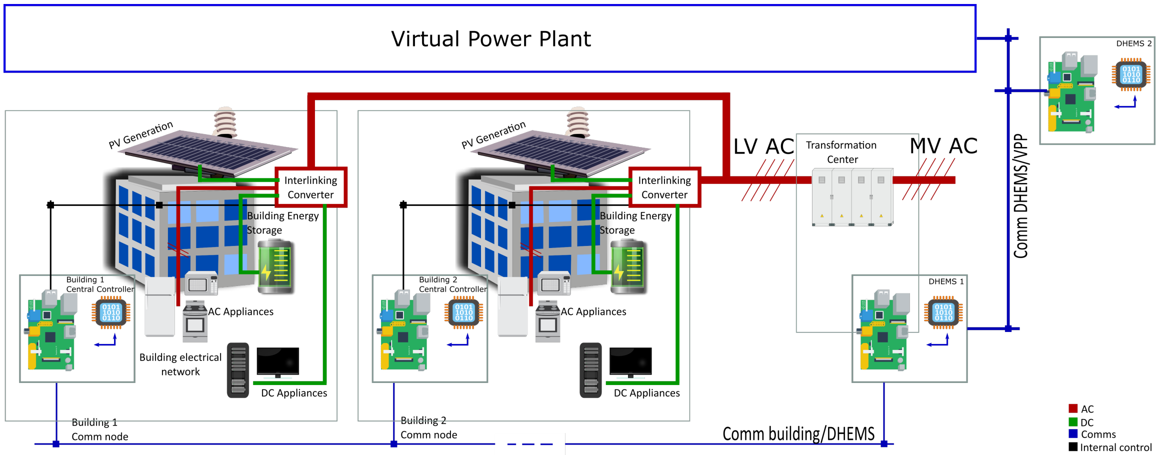


Figure 3-13: Building to building energy exchange system model

storage. In a building level we do have interlinking converters which connects the building with other buildings and the grid. And we have a building level central controller which takes all the measurement data in the building, and controls the interlinking converter by receiving control signal from the secondary. Control signals for energy exchange come from the global controller both to the secondary control and the building level central controls. The energy exchange is based on the generation of building level generators, load demand and the cost of energy. The global control decides the operation of the building either in grid connected or islanded, market participation and optimization of variables with power flow analysis. And the building level central controller, controls the voltage and frequency, power exchange and primary active and reactive control. The coordination of the control layers make building to building energy exchange with optimal power and cost.

3.5 Conclusion

With the working operation of a synchronous generator and studying the effect of the parameters on the stability of the system, it is concluded to control the interlinking inverters with VSG based control to have a proper integration of the DG's to the grid and exchange power between buildings. The proposed connection of the final

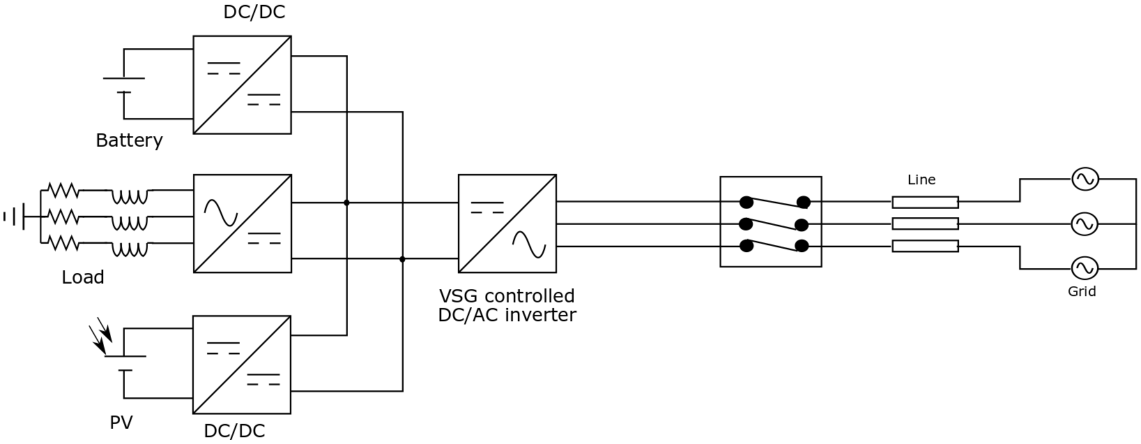


Figure 3-14: Proposed building level MG connection model

developed system id shown in figure 3-14. With this VSG model, we can integrate additional DG's to operate in parallel with grid connection, while improving the dynamic stability of the system.

Chapter 4

Simulation Design

In this thesis work the simulation of VSG control for islanded and grid tied mode of AC and DC MG is simulated in MATLAB/Simulink®. The simulations are first done using Simscape specialized power systems libray blocks and then using the Simscape electrical.

4.1 Islanded Operation

An islanded inverter with VSG control is designed with the control scheme shown in figure 3-8. The designed islanded MG have an RLC filter to filter the higher order harmonics, and a connecting line impedance as shown in figure 4-1. The values for filter and line parameters are selected based on the size of the proposed MG. The simulation system parameters used for this simulation are listed in table A.1. The control parameters are determined based on the operation and stability analysis presented in chapter three. To see the behaviour of the inverter control system for different load power characteristics in the distributed network, a dynamic four quadrant balance load system is designed and simulated. The time sequence for the load variation is listed in table 4.1

Table 4.1: Islanded operation simulation load power sequence

Time	P_{load}	Q_{load}
t<0.4 s	Positive	Positive
0.4 s <t<0.5 s	Negative	Positive
0.5 s <t<0.6 s	Negative	Negative
0.5 s <t<0.6 s	Positive	Negative
t>0.6 s	Positive	Postive

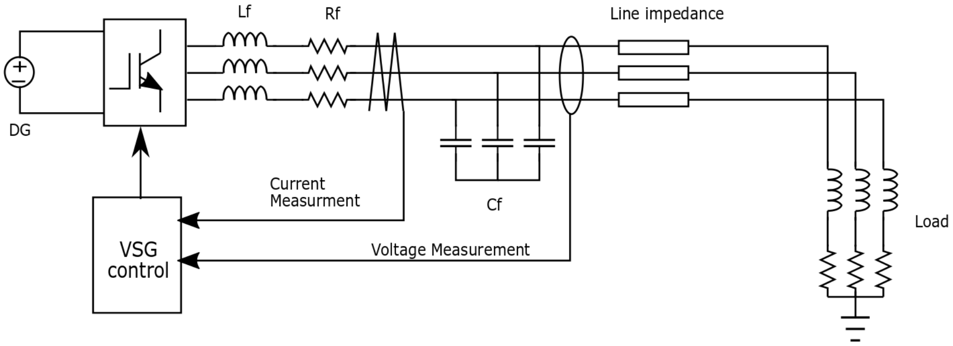


Figure 4-1: Islanded operation simulation circuit model

4.2 Grid Connected Operation

One DG in a grid connected mode is designed and simulated in MATLAB/Simulink®. The control system is designed to operate both in grid connected and islanded modes. When operating in grid connected mode, it supplies power based on the set reference power to maintain the system frequency and voltage. When it moves from the grid connected to islanded mode, it starts operating based on the droop characteristics to supply the required load demand. A pre-synchronization system is designed for the system to operate continuously with out stopping when the system is transition from islanded to grid connected. For the grid connected mode, two systems are developed, the first one is for AC MG, with a DC voltage source connected to the inverter and the load connected to the AC side of the system. The second one is for DC MG, where a PV and ESS are considered, and the load is connected to the DC side with another DC/AC inverter. For the DC MG other four additional controls are designed for controlling the power from the PV and battery, controlling the voltage of load

DC/AC inverter and controlling the DC link voltage using the power flow to the grid. The VSG control parameters used for the grid connected simulation are the same as the islanded model, except the additional parameters of the pre-synchronization. The switching of the grid connecting switch is done by a synchronization logic from the pre-synchronization model, that checks if the voltage and frequency of the DG are synchronized with the grid and is ready to connect with the grid.

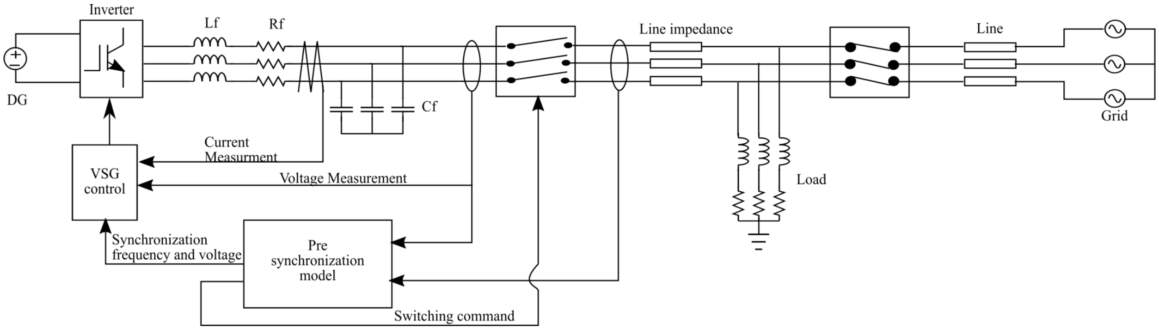


Figure 4-2: Grid connected simulation circuit model

4.2.1 Pre-Synchronization Control

To continuously run the DG system from islanded to grid connected and synchronizing the frequency, and voltage to have minimized transients, a pre-synchronization method is developed and simulated. This pre-synchronization works for moving from islanded to grid connected and to connect a DG to the distributed network.

The frequency synchronization works by accelerating or decelerating the speed of the VSG until it gets close to the frequency of the grid. Similarly the voltage is synchronized by increasing or decreasing the AVR voltage to the grid voltage at the point of common coupling (PCC). This works by taking the three phase voltage measurement before the switch V_{vsg} and after the switch V_{grid}. From the three phase voltages the magnitude and angle of the two voltages are determined. Error of the magnitude and angle of the voltages is determined taking the grid voltage magnitude and angle as a reference, and is feed to a PI controller. To avoid the use of unwrap for the angle difference, A polarity detector and a PI controller is designed that makes the angle variation continuous.

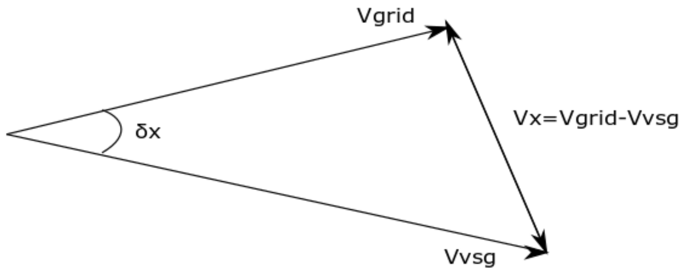


Figure 4-3: Grid and VSG voltage difference phasor diagram

$$\dot{V_{df}} = \dot{V_{grid}} - \dot{V_{vsg}} \tag{4.1}$$

Minimizing the vector difference between the grid and VSG voltages, minimizes the angle and the magnitude. This helps to know the synchronization of the of the DG with the grid. Based on this voltage, a synchronization logic is developed as shown in figure 4-4 to switch ON the connection to the grid when the system gets synchronized .

The switching of the grid connecting switch is done automatically when the system gets synchronized. For this purpose, a synchronization logic is designed based on minimizing the vector difference voltages V_x. Minimizing the vector V_x minimizes both the angle and magnitude. This is designed by comparing the voltage difference between the grid and DG with the maximum allowed voltage for connecting the system to the grid. Flip flops are used to keep the the value. A zero crossing detector of the grid voltage is used so that the DG connects to the grid on the next zero crossing. an AND gate is used to fulfil both the maximum voltage and the zero crossing criteria for the connection.

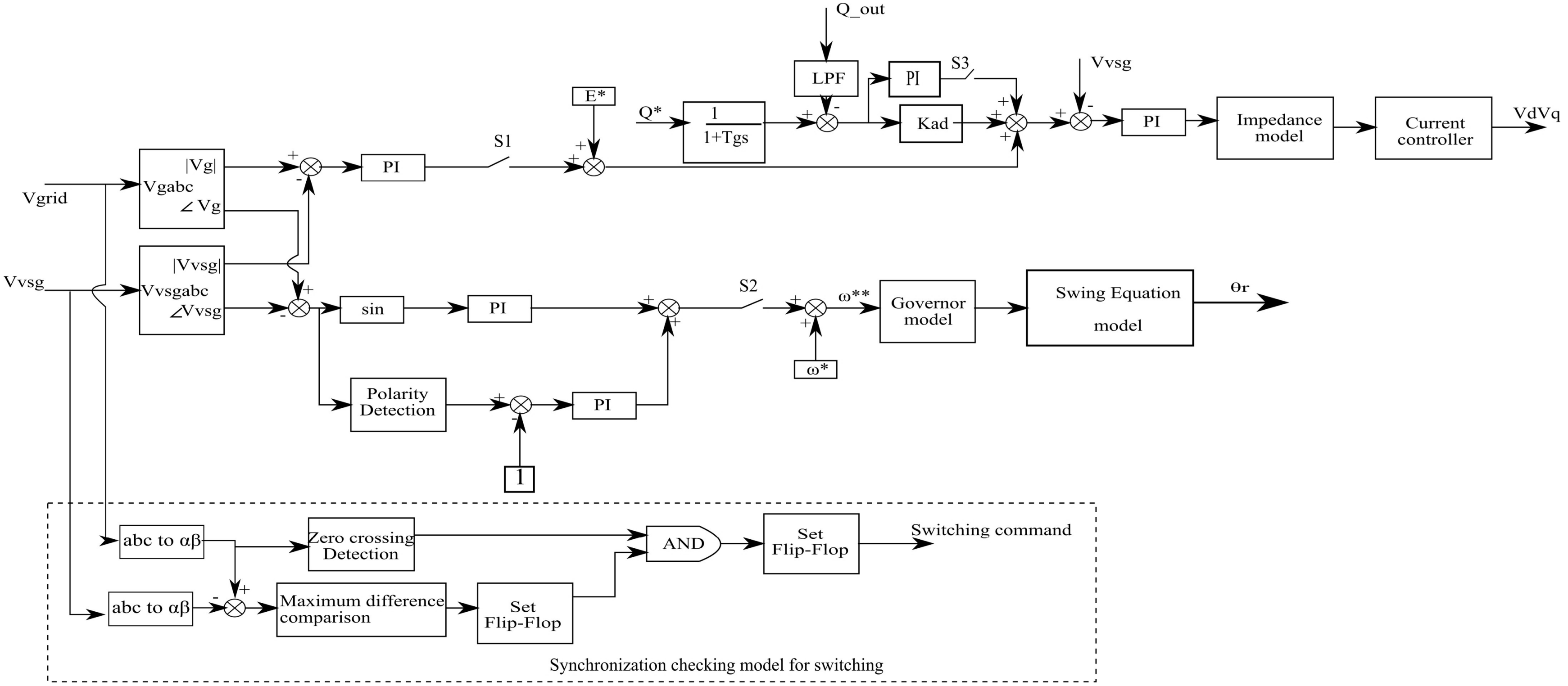


Figure 4-4: Pre-synchronization simulation model

The pre-synchronization designed model is shown in figure 4-4 . contains voltage synchronization, frequency synchronization and the synchronization checking model for switching. The switches S1, S2 and S3 turns ON when a command is sent to connect the DG to the grid. The switch S3 is kept ON when the system is operating in grid connected mode, to set the reactive output power of the DG to the set reference value. This is done because the distribution connecting line impedance's will make a voltage droop that affects the voltage magnitude synchronization. At this time the synchronization starts by minimizing the voltage and frequency difference using the PI controllers. The synchronization frequency and voltage are added to the reference frequency and voltage of the VSG control. The synchronization checking model, continuously checks if the system is synchronized or not. The zero crossing detection is used in the synchronization switch logic to make the connection to the grid in the next zero crossing, when the system is synchronized. When the system gets synchronized the connection to the grid is turned ON and the switches S1 and S2 are turned OFF, the system continues to follow the grid frequency and voltage. The synchronization checking model may also have additional advantages to isolate the DG from the power system in case of any fault happening on the grid. This pre-synchronization allows continuous running running of the system from islanded to grid connected with a minimized power transients and allowing the inverter to follow the specified active and reactive power references.

4.3 Parallel Operation

Two VSG controlled DG inverters are designed for simulating operation of parallel islanded inverters with a common load. The two DG's have an RLC filter, and are connected through a line impedance and a switch that connects the DG's to the distributed network to a common load in the AC bus. The designed VSG control have same parameters with the islanded one DG system defined in table A.1, except having different droop coefficients to see their power sharing behaviour. A pre synchronization method that is presented in section 4.2 is used to synchronize the DG's, excluding the switch S3 as they have to share the active and the reactive power and the switch S1 in 4-4 is used to set the output reactive power to the reference value. The simulation circuit is shown in figure 4-5. The two VSG's share the load depending on their voltage and frequency droop coefficients. The simulation sequence is, first supplying the load with the first DG, then synchronizing the second DG and connecting it in parallel to share the load power between the two DG's.

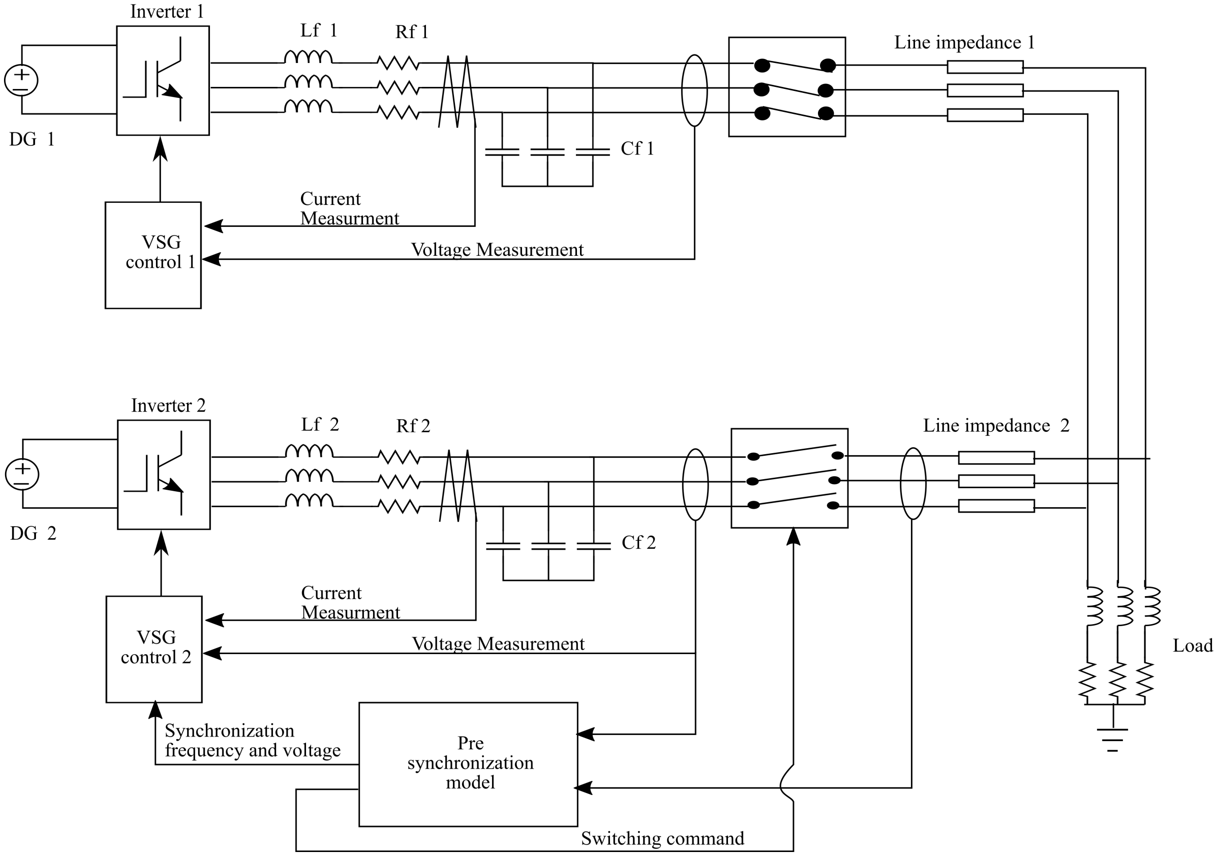


Figure 4-5: Islanded parallel simulation model

4.4 Grid Connected Parallel Operation

A grid connected two parallel VSG controlled inverters simulation is designed based on the operation of grid connected and islanded parallel design. The two VSG controlled inverters are connected to the grid, and a common load through a distribution line impedance and connecting switches. For this design model, a pre-synchronization is used for the two inveters. The connecting switches of each DG are controlled with two Pre-synchronization logic blocks controlling each of them. the load is initially supplied by the grid, and then the two DG's are connected to the grid at different time. Synchronization is used to connect the DG's to the grid and for reconnecting the distributed network to the grid after disconnection of the grid for some time. In this design the inverters are expected to support the grid with a specified active and reactive power, no matter how the load changes when they are operating in grid connected mode. The switch S3 in the synchronization model figure 4-4 makes the reactive power supplied to follow the reference. The two inverters work with a power sharing mode when the grid is disconnected from the system to supply all the demand load and they are responsible for any overload happening on that distributed network. The simulation circuit model of the two inverters with a grid connected is shown in figure 4-6. The control parameters for the two inverters are same for both as listed in table A.1. The power references for each inverter and synchronization PI controller gains are in given table 4.2.

Table 4.2: Parallel grid connected control parameters

Parameter	Value
P_{ref1}(kW)	50
Q_{ref1}(kVar)	30
P_{ref2}(kW)	60
Q_{ref2}(kVar)	20
Voltage frequency synchronization PI gains	
kP_V	$2\pi/5$
kI_V	20
kP_f	20
kI_f	377

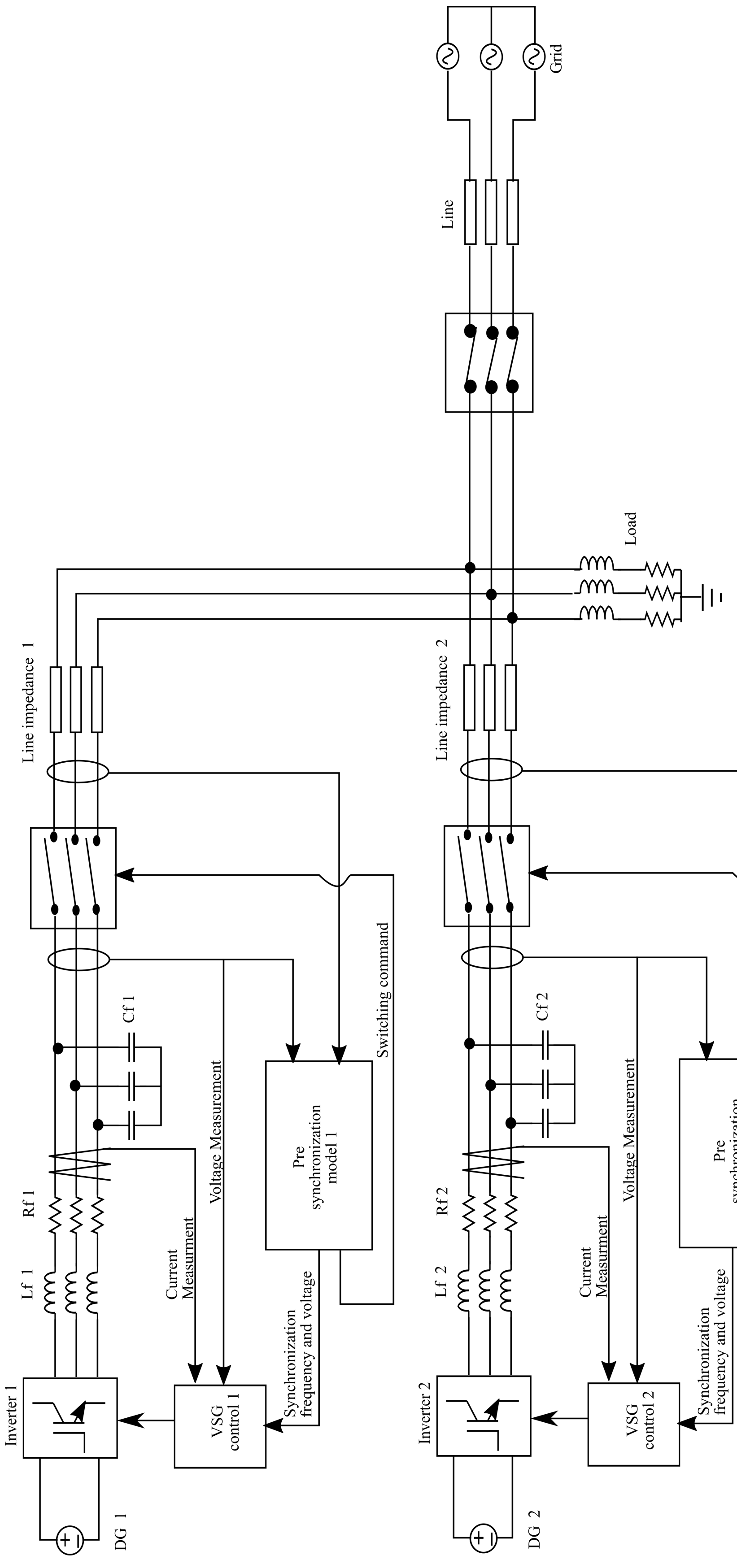


Figure 4-6: Grid connected parallel simulation model

4.5 DC Microgrid control

DC MG's have higher efficiency as they have reduced conversion losses of the inverters and there is no need for synchronization. And any blackout in the grid side doesn't affect the DC bus of the MG as it have a stored energy of the DC capacitor. In this section a DC MG system that have ESS, PV source, load and grid is designed and simulated in MATLAB/Simulink®. The system contains two DC/DC converters for the battery and PV system connection to the DC bus. A DC/DC control is designed to control the power from the PV and battery storage to the system using a current controller. A voltage controlled DC/AC inverter is designed to connect the load to the DC bus. The DC MG is connected to the grid through a transmission line. For islanded model operation the battery is used to regulate the DC bus voltage, and for grid connected operation the grid is used to regulate the DC bus voltage. The grid connecting inverter is controlled with a VSG control that presented in chapter three and using the control parameters from table A.1. Control simulation circuits for the DC/DC boost converters of the PV and the battery storage, and DC/AC inverter connecting the load are designed. The DC- link voltage is controlled using grid, and it also controls the active power flowing to the grid.

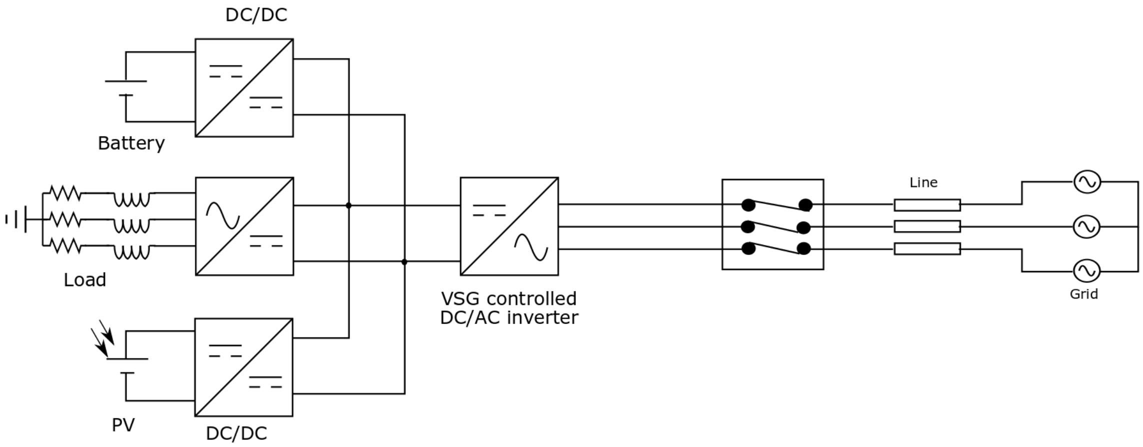


Figure 4-7: Proposed DC MG model

4.5.1 DC Voltage Control

The DC bus voltage of the system is regulated using the grid. this is done using a PI controller and computing the required active power to send or receive from the grid. This computed power is given as a reference power to the VSG controller of the DC/AC interlinking inverter.

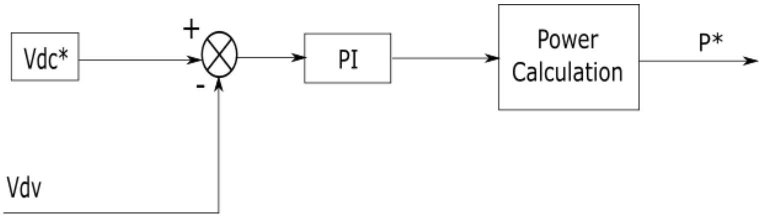


Figure 4-8: DC bus voltage controller

4.5.2 DC/DC Boost Converter Control

For controlling the power from the PV and battery storage two average model DC/DC converters are used. The DC/DC converter design used for the controller design is shown in figure 4-9. The control of the current is done with the duty cycle of the converter. The controller design is shown in figure 4-10 and the simulation circuit model for two DG's connected to grid is shown in figure 4-11

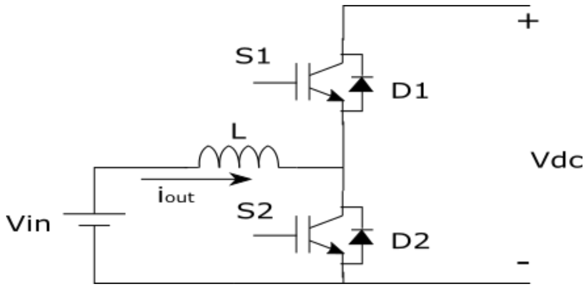


Figure 4-9: DC/DC converter circuit

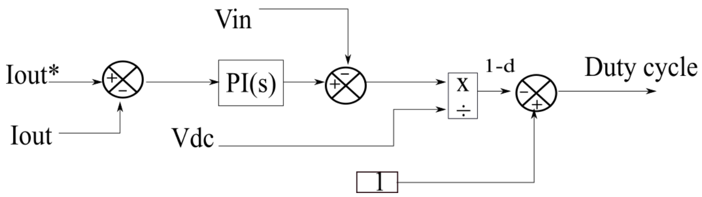


Figure 4-10: Battery current controller

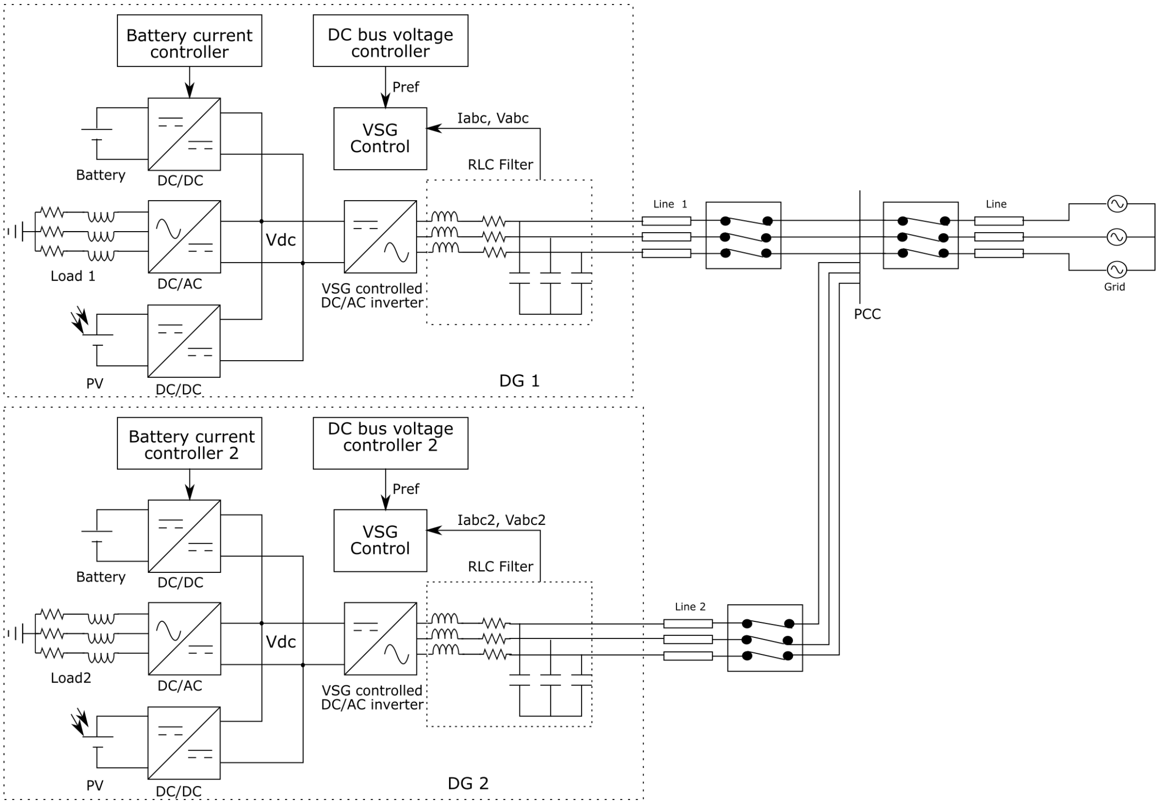


Figure 4-11: Grid connected parallel DC MG simulation circuit model

4.6 Conclusion

Energy exchange between buildings and the grid concluded to be done with a VSG control based interlinking converters. The models for the integration of DG's in islanding mode and grid tied mode are already discussed in this chapter, and to avoid transients when moving from islanded to grid connected a pre- synchronization method is modeled. And it is concluded to simulate all the islanded and grid connected modes with AC and DC MG. And the final simulation is done with two DC MG in grid connected mode as shown in figure 4-11.

Chapter 5

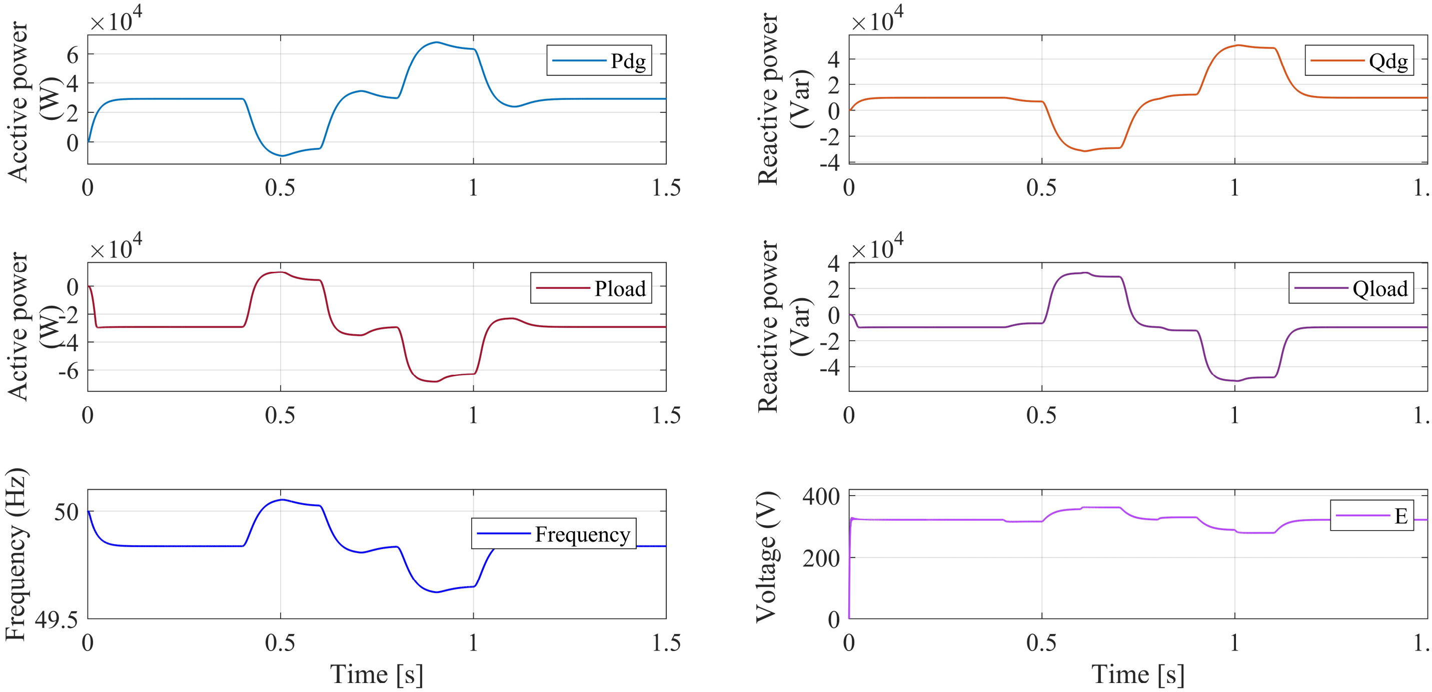
Result and Discussion

5.1 Islanded Mode Results

The VSG controlled islanded system is simulated in MATLAB/Simulink® to verify the effective working of the proposed system. A wye connected RL load and the designed dynamic load are used. The system parameters used for this simulation are listed in table A.1. And the load sequences used for the simulation are listed in table 5.1, where S_{base} is 100kVA. In this simulation the reference active and reactive powers are set to zero. The reference frequency and voltage are set to the nominal value.

Table 5.1: Simulation load values

Time	P_{load}	Q_{load}
t<0.4 s	$0.3S_{base}$	$0.1S_{base}$
0.4 s <t<0.5 s	$-0.1S_{base}$	$0.1S_{base}$
0.5 s <t<0.6 s	$-0.1S_{base}$	$-0.3S_{base}$
0.6 s <t<0.7 s	$0.3S_{base}$	$-0.3S_{base}$
0.7 s <t<0.8 s	$0.3S_{base}$	$0.1S_{base}$
0.8 s <t<0.9 s	$0.7S_{base}$	$0.1S_{base}$
0.9 s <t<1 s	$0.7S_{base}$	$0.5S_{base}$
t>1 s	$0.3S_{base}$	$0.1S_{base}$



(a)

(b)

Figure 5-1: Islanded system simulation results (a) Active power and frequency (b) Reactive power and EMF of VSG

As shown in figure 5-1, when the MG operates in islanded the DG is supplying the load and the line losses. The frequency of the MG decreases when the load increase and increase when the load decreases. The frequency goes less than 50 Hz when the load is positive and greater than the nominal frequency 50 Hz when the load is negative, as the reference active power is set to 0W. The system follows the governor droop characteristics shown in equation (5.1). It is also illustrated that the system doesn't have oscillations and overshoots in the frequency and active power. This shows the inertia and mechanical damping of the VSG control are helping in frequency stability of the system.

$$\omega_{ref} - \omega = -K_{gd}(P_{ref} - P) \tag{5.1}$$

Moreover, the reactive power is also supplied to the load with eliminated oscillations and overshoots. And the reactive power response is independent of the active power change. The VSG voltage E is responding according the voltage droop characteristics with the change in reactive power as shown in equation (5.2)

$$E_{ref} - E = -K_{ad}(Q_{ref} - Q) \tag{5.2}$$

5.1.1 Power Sharing

Two VSG controlled inverters connected in parallel are simulated to verify the power sharing on parallel operation. The load is initially supplied using VSG 2 and the connection of VSG 1 is done after 1 second. The two VSG controller's have the same control parameters except the active and reactive power references. The control and system parameters of the two VSG controller's are from table A.1. And a synchronization is used to connect DG 1 to the network. This is done to show sharing response of the two VSG's depending on the droop characteristic, to maintain the system frequency and voltage. The connection and reference powers are listed in table 5.2. It is simulated for 20 seconds. For this simulation a four quadrant sequence of load variation is used, the sequence is listed in table 5.3. As it can be seen in figure

Table 5.2: Parallel operation Power references

Time	VSG 1		VSG 2	
t <2 s	Disconnected		Connected	
	$P_{ref} = 0$	$Q_{ref} = 0$	$P_{ref} = 0$	$Q_{ref} = 0$
2 s <t<10 s	Connected		Connected	
	$P_{ref} = 0$	$Q_{ref} = 0$	$P_{ref} = 0$	$Q_{ref} = 0$
10 s <t<12 s	$P_{ref} = 0$	$Q_{ref} = 20$ kVar	$P_{ref} = 0$	$Q_{ref} = 0$
t >12 s	$P_{ref} = 30$ kW	$Q_{ref} = 20$ kVar	$P_{ref} = 0$	$Q_{ref} = 0$

Table 5.3: Load sequence for islanded parallel operation

Time	Active power P_l	Reactive power Q_l
t<8 s	$0.2S_{base}$	$0.01S_{base}$
8 s <t<9 s	$-0.2S_{base}$	$0.01S_{base}$
9 s <t<10 s	$-0.2S_{base}$	$-0.39S_{base}$
10 s <t<11 s	$0.2S_{base}$	$-0.39S_{base}$
11 s <t<13 s	$0.2S_{base}$	$0.01S_{base}$
12 s <t<13 s	$0.6S_{base}$	$0.01S_{base}$
13 s <t<14 s	$0.6S_{base}$	$0.41S_{base}$
14 s <t<15 s	$0.2S_{base}$	$0.41S_{base}$
t>15 s	$0.2S_{base}$	$0.01S_{base}$

5-2, DG 2 supplies the load before the connection of DG 2 to the system. After 2 second the two DG start working in parallel. As the droop coefficients and reference active and reactive powers of the two VSG controls is the same, both of them share the load power and line losses equally. This is verified even with the increase and decrease of the load with the sequence of load listed in table 5.3. At 10 second the reactive power reference of VSG 1 is set to 20 kvar, so DG 1 starts to share high power to maintain the system voltage. This is done with the increase in the EMF of VSG 1. This is also tested with a load variation, and as shown in the figure 5-2 (b) the two VSG's are sharing the reactive power proportionally to their set reference reactive power.

Further more, the active power sharing is working perfectly. After the connection of DG 1 to the system, the two VSG controlled inverters start sharing the active power equally as the frequency droop and reference power of both are the same. A very small transient in the frequency is seen at the time of the connection of DG 1, but is negligible value. Changing the load active power, the two DG's continue sharing equally the active power. At 12 second the reference active power for DG 1 is changed to 30 kW. DG 1 starts sharing higher power to maintain the system frequency. This is also tested with an increase and decrease of the load power, and the sharing proportion of the two DG's continue smoothly as shown in figure 5-2 (a). And as shown in figure 5-2 (a) the two DG's are able to maintain the system frequency the same with no oscillations and overshoots while running in parallel.

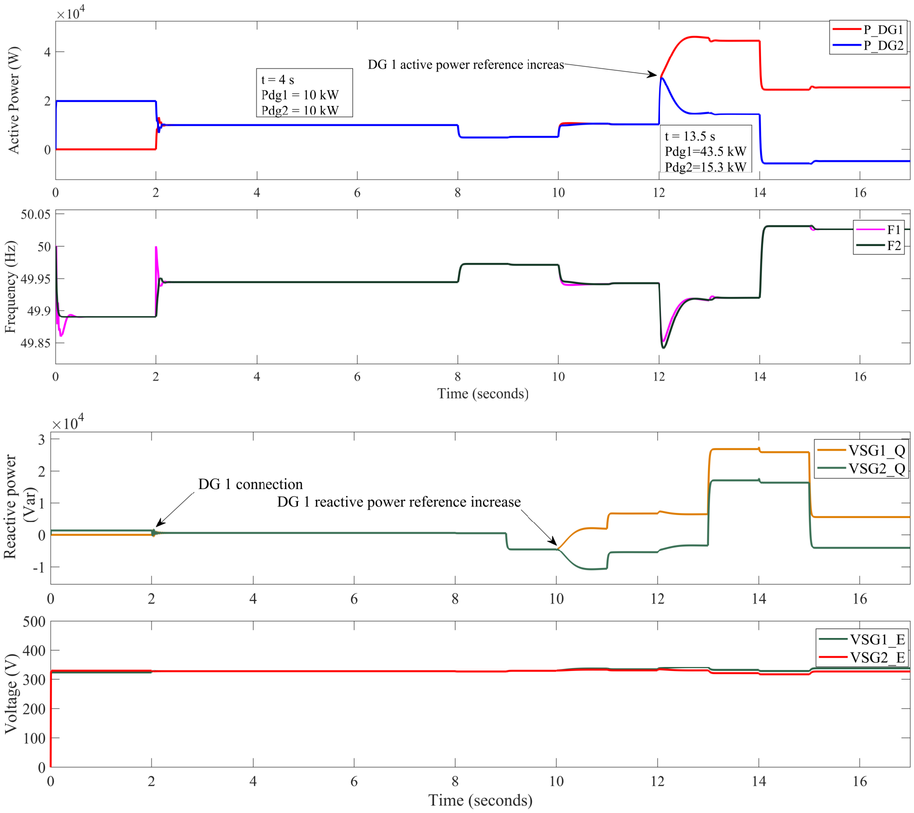


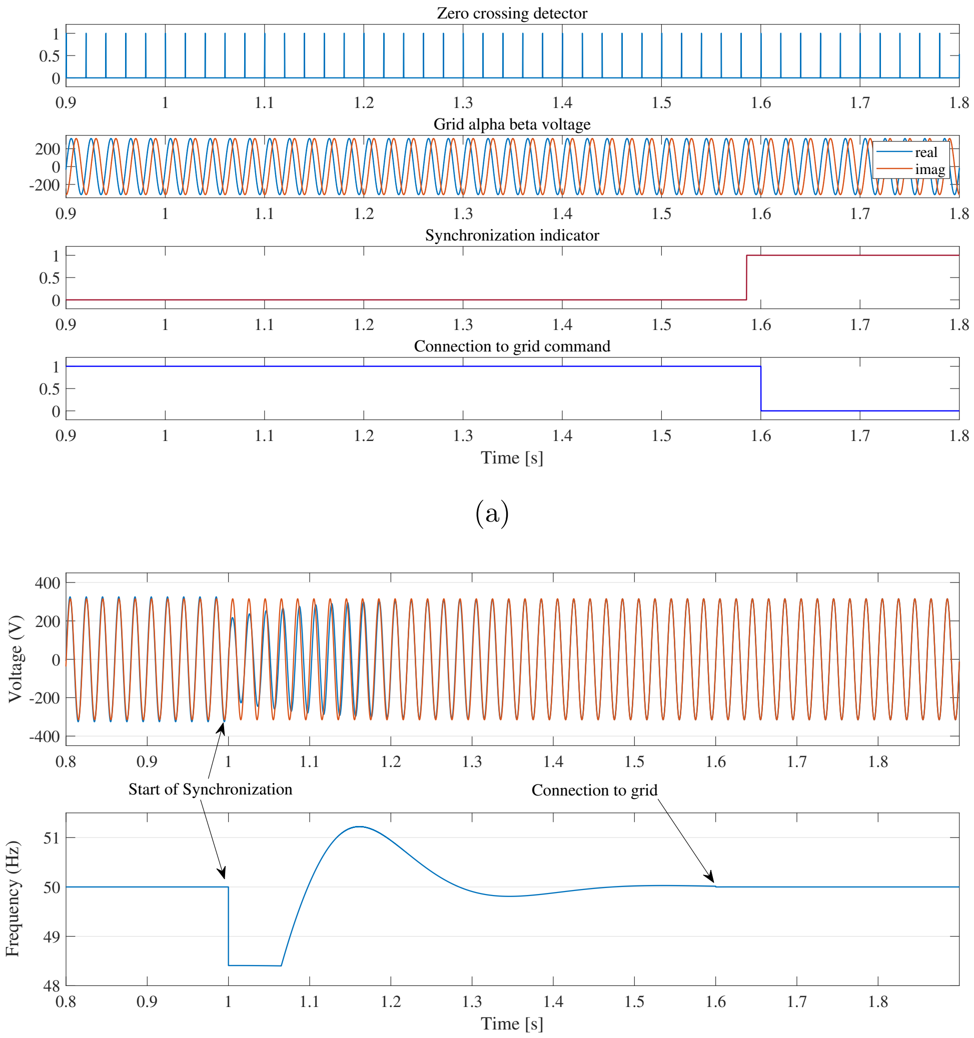
Figure 5-2: Parallel power sharing system simulation results, active power and frequency, and reactive power and EMF of VSG's

5.2 Grid Connected mode

A grid connected operation of MG with VSG controlled interlinking inverters is simulated in MATLAB/Simulink® for both AC and DC MG. Both the AC and DC MG are simulated using one DG and parallel two DG's.

The simulation of one DG connected to grid is done using the simulation circuit shown in figure 4-2. The connection to the grid is commanded to start at 1 s. The pre-synchronization starts at 1 s and continues to work until the DG gets synchronized with the grid. The pre-synchronization switching simulation result is shown in figure 5-3. When the DG system frequency and voltage gets synchronized with the grid, it waits for the next zero crossing of the grid voltage and turn ON the connection to the grid.

The pre-synchronization results are shown in figure 5-3.



(a)

(b)

Figure 5-3: Synchronization results (a)Pre-synchronization model switching outputs (b) voltage and frequency results

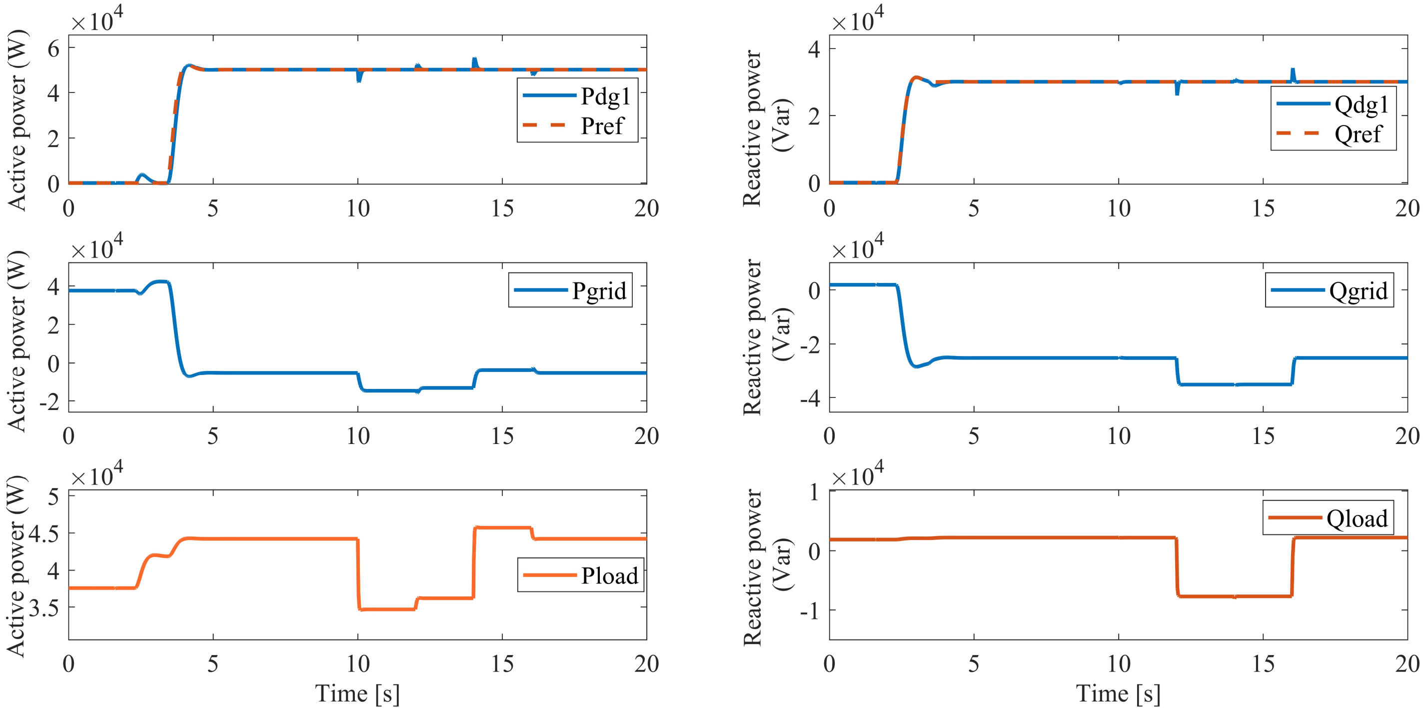


Figure 5-4: Active and reactive power results of one DG grid connected simulation

As it is shown in figure 5-4, with the help of the pre-synchronization the DG is able to connect to the grid with a negligible transient. And it is shown that the DG follows the reference set active power while working in grid connected mode and the governor delay result on the active power is also seen in the transition of the DG power from zero to 50 kW. The variation in the load doesn't have any effect on the DG. The DG continues to support the grid with the specified active reference power. It is also verified that the frequency follows the grid frequency with out any deviation starting from the connection of the DG to the grid. The overshoots shown in frequency of figure 5-3 are from the Pre-synchronization PI gains, and this is before the connection to the grid. This doesn't have any effect on the distributed network as it is happening before the connection to the grid.

The reactive power simulation result is also shown in figure 5-4. As it seen grid connection doesn't have any effect on the transient of the reactive power. The DG is following the reference reactive power. Unlike the active power the reactive power doesn't have delay to follow the reference, as the governor delay only works for the active power and frequency response. The load variation doesn't have an effect on the reactive power of the DG, it continues to support the grid with the specified reactive power reference.

As shown in figures 5-4, the DG supports to the grid with specified power and the grid either send or receive power depending on the load power. If the power provided by DG is greater than the load demand, power is supplied to the grid otherwise power will be supplied from the grid to the load. in this operation the grid is responsible to line loss's.

A 2^{nd} simulation is run with two DG connected to the grid. The two DG are synchronized to the grid at different times. The connection on the two DG to the grid is done with the pre-synchronization automatic switching shown in figure 5-5. The pre-synchronization starts at 1 s for DG 1 and at 4 s for DG 2, and then they connect to the grid after they got synchronized. The frequency overshoots are before the connection to the grid at the start of the synchronization. This doesn't have any effect in the system. The connection of the two DG's to the grid doesn't affect the frequency

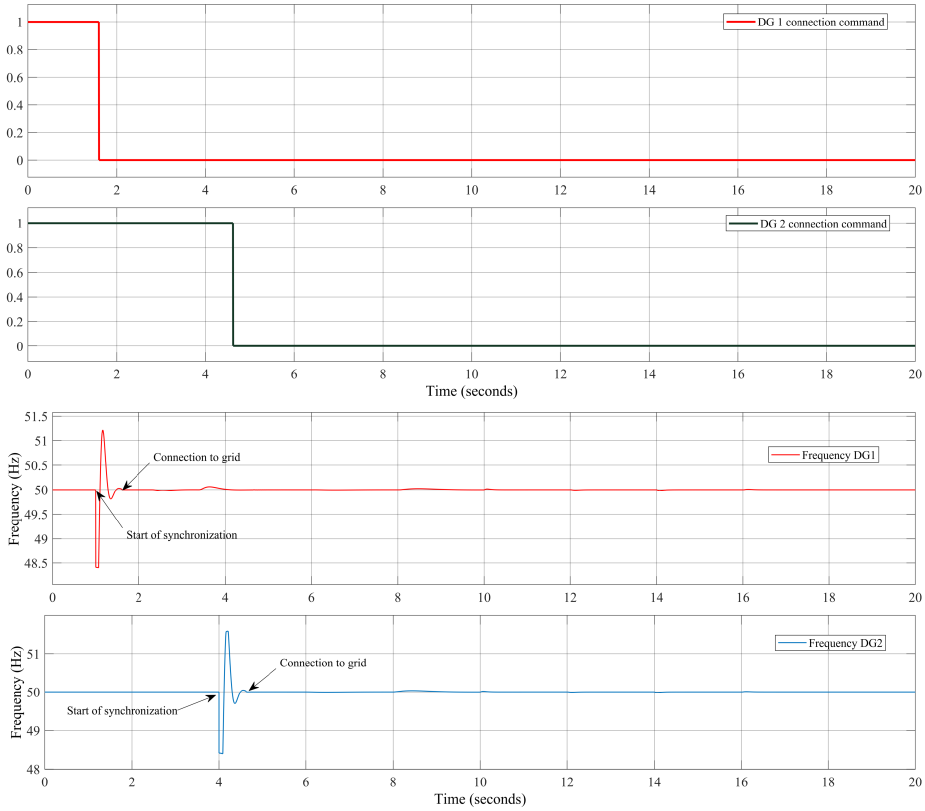


Figure 5-5: Two DG's connection logic and frequency result's

and power. And two DG's are supporting the grid with the specified active power reference. The change in the load have almost negligible transient on the DG's power response. They continue to follow the set reference active power, no matter how the load is varied. The load variation makes only make a change in the power supplied or received by the grid. When the sum of the two DG's power is greater than the load demand is send to the grid and if it is less than the load demand power comes from the grid.

The reactive power of the two DG follows the reference values as shon in figure 5-6 (a), and the load variation doesn't affect the reactive power send from the two DG's. Similar to the one DG connected to grid the simulation results of active and reactive power of the DG shows the working of the governor delay on the active power waveform.

The simulation results show the use of VSG controlled interlinking inverters in stabilizing the frequency, and remove oscillations maintaining the system stability.

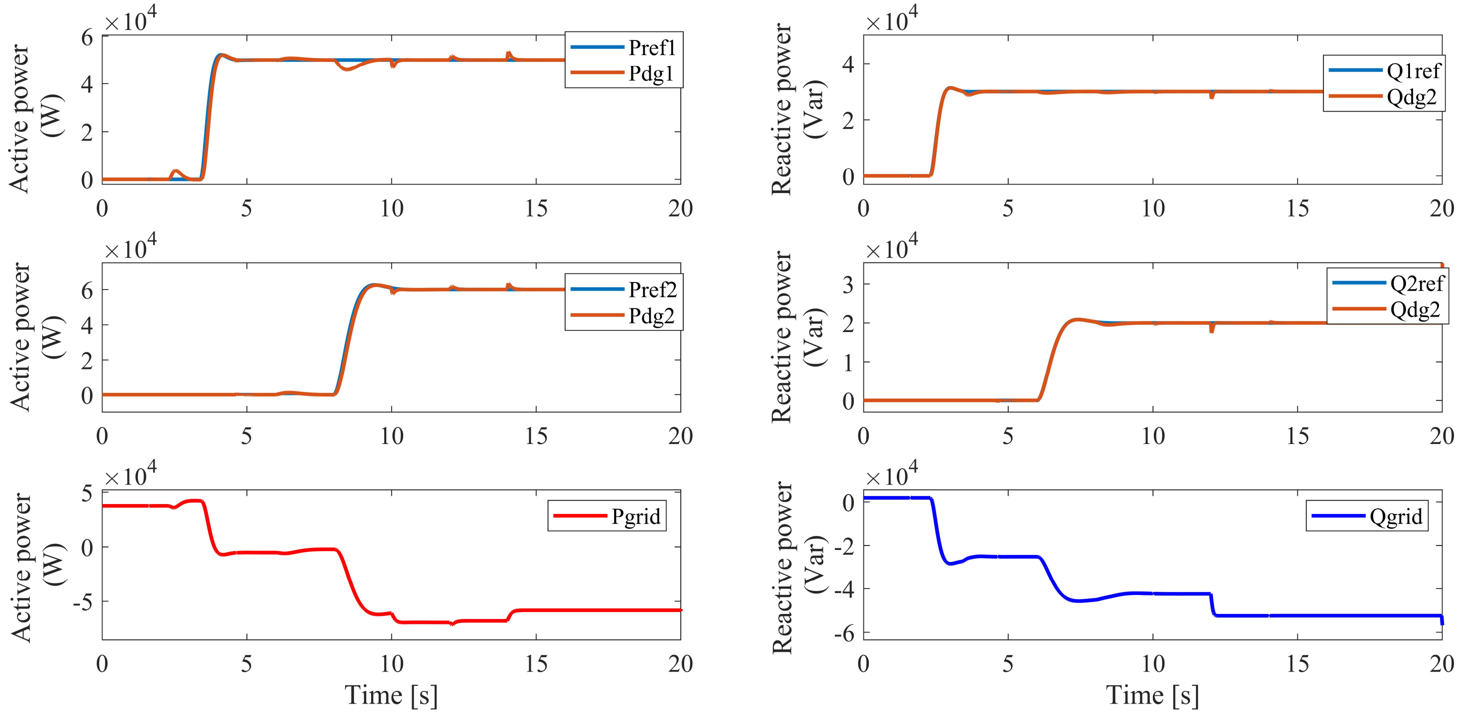


Figure 5-6: Grid connected parallel DG's simulation results (a) Reactive power results (b) Active power results

5.2.1 Transient Analysis of Connecting, Disconnecting and Re-connecting to The Grid

To confirm the performance of the proposed VSG control and pre- synchronization method, a grid connected with one DG and with parallel connection of two DG with grid are simulated using the proposed pre-synchronization. The simulation is done first by connecting the DG's to the grid, and then disconnecting the grid from the distributed network and reconnecting back the grid to the distributed network.
For the two DG's operating in parallel with the grid, the load is initially supplied by the grid. Then the two DG's are commanded to connect with the grid at 1 s and 4 s. The synchronizations start at the time command, after 0.6 s seconds from the command time the two DG's get synchronized and connected to the grid. After they work in a grid tied mode until 11 s, the grid disconnected from the distributed network and reconnected back at 17 s. As shown in figure 5-8, The two DG's supply a specified power to the network when they are operating in grid connected mode and starts to share the power when the grid is disconnected. As it can be seen the connection of the DG's to the grid have no transients. And the disconnection of the grid is making a very small transient in the DG's power, this is because the disconnection is like a sudden disconnection. But it is almost negligible and doesn't affect the system as the two DG's are in islanded mode and the frequency is with in the limit. The re connection of the grid to the distributed network is command at 17 s. At 17 s the pre-synchronization starts working and the re connection is done around 19 s, when the distributed network gets synchronized with the grid. As it can be seen the re-connecting of the grid to the distributed network have no transient in the active power and have a very small transient in the reactive power.

Figure 5-7 shows the frequency response of DG 1 for the transition from islanded to grid connected and vise versa. It is shown that the DG works in governor droop based in the islanded part. And the system has eliminated transients and oscillations in frequency.

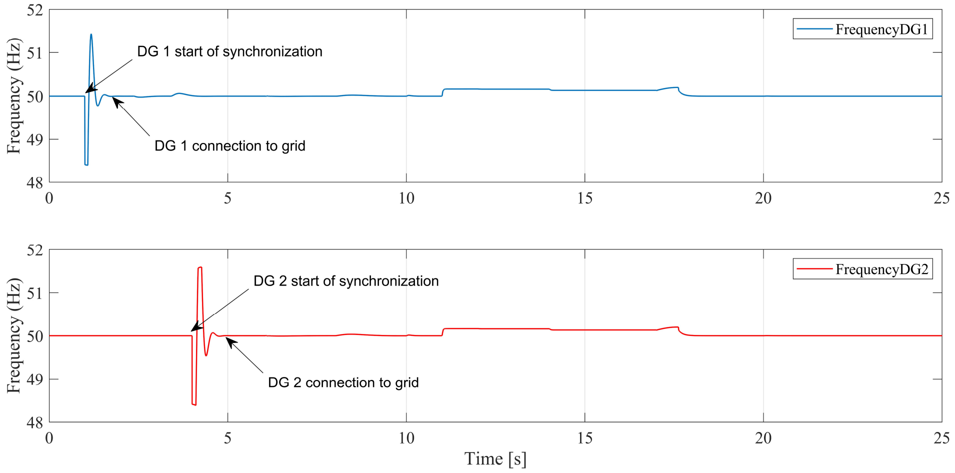


Figure 5-7: Transient frequency response (DG 1 connection at 1 s, DG 2 connection at 4 s, grid disconnection at 11 s and re-connection at 17 s)

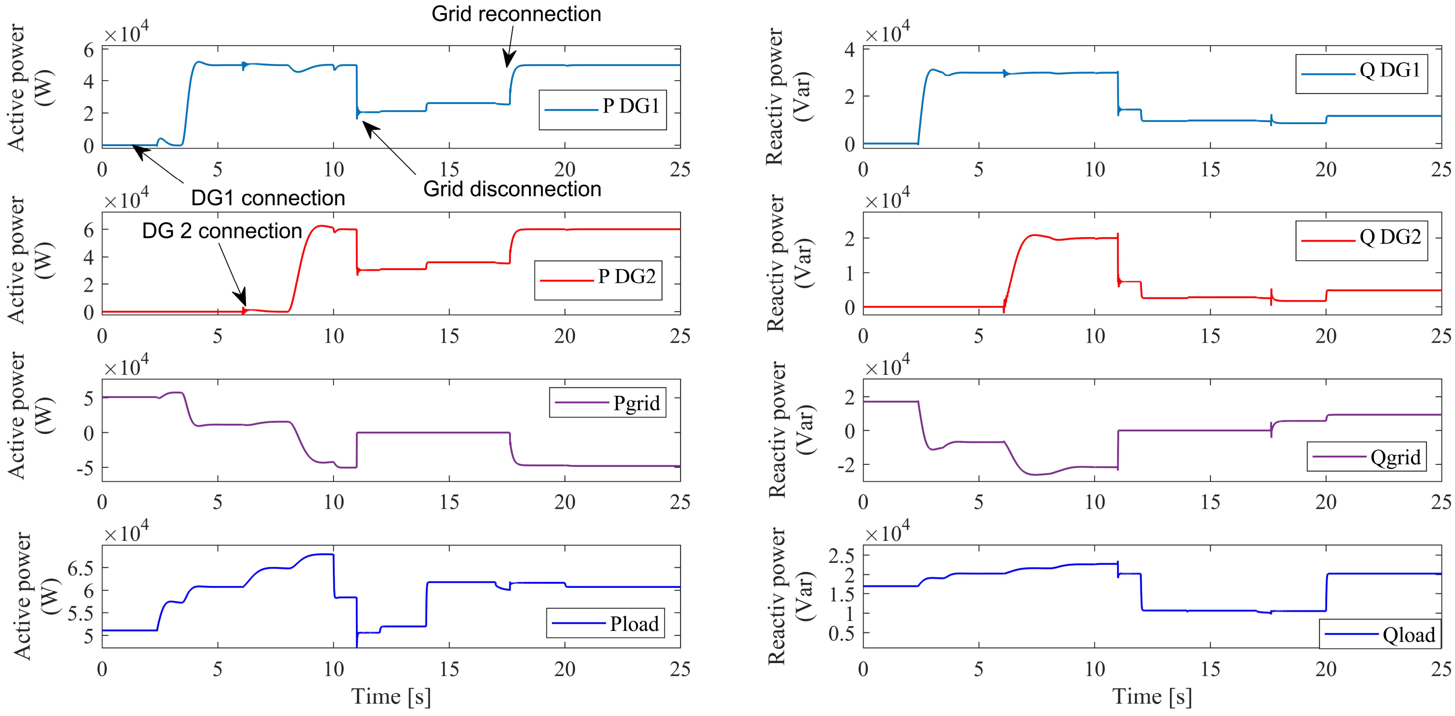


Figure 5-8: Transient response for grid connected parallel DG's with connecting and disconnecting the grid

5.2.2 DC Microgrid

A grid connected DC MG model shown in figure 4-11 is simulated with one DG . The DC side load power and battery currents are varied. this is done to increase and decrease the power supply from the DC side to show how the power send or received from the grid is controlled. When the power supply from the DC side is greater than the load demand power is send to the grid while keeping the DC bus voltage constant . And power is received from the grid when the generation of the building generations and battery supply is lower than the load demand.

As it is shown in figure 5-9 The system is able to send and receive active power depending on the power supply from the DC side and load demand while keeping the DC bus voltage at 750V. The power from the DC side is initially supplied to the grid, and at 2 s a load of 70kW is connected to the DC side of the building and the building starts receiving power from the grid as as the generation of the building is not enough to supply the load. Again at 15 s the power supply from the battery is increased, the building starts sending power to the grid. The reactive power send to the grid doesn't depend on the DC side load, it was commanded with a specified reference value 30kVar at 8 s, and the system is able to maintain the reactive power support to the grid too. The power delivered to the grid are able to change smoothly with out any oscillations. And no synchronization is used for this simulation, as it can be seen it is able to maintain the system frequency and voltage without any synchronization.

A DC MG with two DG's in parallel with grid is simulated using the model shown in figure 4-11. Figure 5-10 shows the power and frequency simulation results of the two DG's. The parallel operation of the DG's working similar way with the one DG, and is able to maintain the frequency and power. The two VSG controlled inverters are able to send and receive power. The summation of the two inverter powers is sent to the grid. Here when DG1 is asking power, and DG2 is generating more power than its load demand power, some of the power is sent from DG2 to DG1 and the rest to the grid. And when both are generating higher than their load or asking for power, Power is received from the grid. This is done for this simulation, but for an

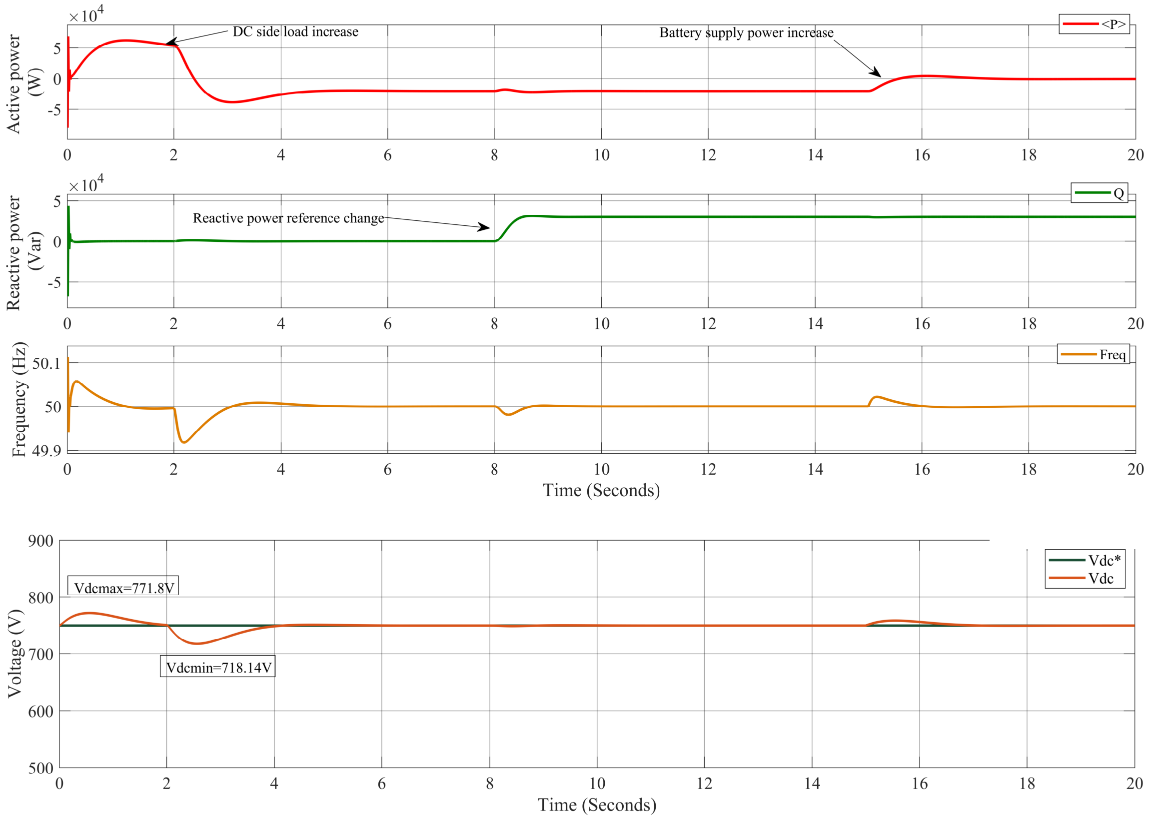


Figure 5-9: Power, frequency and DC voltage simulation results of grid connected one DC MG, Qref=30kVar at 8 s.

experimental validation, the other layers of control will be included and the buildings will decide from where to buy the power.

Figure 5-10: Power and frequency simulation results parallel grid connected DC MG($P_{loadDG1}$ set to 70 kW at 4 s and $P_{loadDG2}$ at 8 s, Q_{refDG1}= 30 kVar at 11 s, Q_{refDG2}= 30 kVar at 12 s and battery supply increase at 15 s)

5.3 Conclusion

Power dynamic stability and , frequency and voltage regulations of a distributed power system are very critical for exchanging power between buildings and the utility grid. From the simulation results, it can be concluded that VSG based inverter control for integration of DG's to a distributed network improves power and frequency stability. This has allowed power exchange between building and seamless integration of the DG's to the grid with the proposed pre-synchronization method.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This masters thesis have addressed the control of decentralized energy management for islanded and grid tied AC and DC MG's for dynamic stability of the distributed system. It was mainly focused on the frequency and voltage dynamic regulation, power sharing and DG's synchronization to the grid for having smooth transition from islanded to grid connected and the reverse. The main control scheme is done using a VSG control approach, a control that emulates the working of synchronous generator and improves the system inertia and damping. As briefly shown in chapter 5 with the simulation results, the control approach have worked as expected and is able to improve the system dynamics of the distributed system. Islandined DG's are able to supply the load with out any frequency deviations and oscillations. And power sharing is working perfectly with the connected DG's. It can be concluded that, the virtual inertia of the VSG have improved the power dynamics, frequency and voltage regulation of the islanded MG. And having the VSG have helped to chose and change suitable parameters depending on the stability of the system unlike the synchronous generator where everything is set at the time of manufacturing.

Further more for grid connected operations, having the VSG control with a novel method of pre-synchronization have allowed the distributed network to move from islanded to grid connected with minimized transients, allowed to maintain the system frequency and improve the dynamics of the distributed network.

It can be concluded that the building to building energy management is able to be improved by using this VSG controlled building level interconnecting DC/AC inverters with a the novel pre-synchronization method. This improves the power grid dynamics, frequency, and voltage regulation and other operations.

6.2 Contribution

This thesis work have contributions to islanded and grid connected MG's with battery and PV system. This contribution are:

- Improve the power dynamics, frequency and voltage regulation of building to building decentralized energy management in AC and DC MG's with the emulation of synchronous generator operation.
- Allowed smooth transition of distributed networks from islanded to grid connected with a minimized transients and eliminating oscillations using the proposed pre-synchronization method. And it allowed the connecting, disconnecting, and reconnecting of the grid to the distributed network with a minimized transient.
- Studied the response of a VSG generator for different values of inertia and mechanical damping. This allows VSG controls to have suitable parameters that can give higher system stability unlike the actual synchronous generator in which its parameters are set at the time of manufacturing.

6.3 Future Work

Starting from the contributions stated in section 6.2, this thesis opens opportunities to continue working on the building to building energy management. This includes:

- Experimental validation of the islanded and grid connected AC/DC MG simulation results.

- Improvements on the DC bus voltage control of grid connected DC MG's. And working with grid tied AC/DC hybrid MG's.
- Integrating intelligent upper layer controls for the building to building energy management in connection with the grid.

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Appendix A

Design Parameters

Table A.1: VSG parameters

Parameter	Value	Impedance model	
Rated powe(kVA)	100	xd (%)	220
Rated voltage E (V)	230	xq (%)	120
Nominal Frequency (Hz)	50	x'd (%)	17.6
Voltage droop (%)	5	x"d (%)	8.7
Frequency droop (%)	1	x"q (%)	10.4
Inertia (kgm^2)	0.426	Phase resistance (Ω)	0.1
Filter resistance R_f (Ω)	0.0106	T'do (s)	0.76
Filter inductance L_f (H)	5.05×10^{-4}	T"d (s)	0.01
Filter capacitance C_f (F)	20×10^{-6}	T'd (s)	0.062
τ_d (ms)	120	Ta (s)	0.012

Table A.2: DC MG control parameters

Parameter	Value
Kpdc (DC bus voltage controller proportional gain)	1.123
Kidc (DC bus voltage controller integral gain)	2.842
Kpic (Battery current controller proportional gain)	0.7109
Kiic (Battery current controller integral gain)	888.57
V_{dc} (V)	750