Modeling and Control of Directly Connected and Inverter Interfaced Sources in a
Microgrid

by

Manohar Chamana, B. E

A Thesis

In

ELECTRICAL AND COMPUTER ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTERS OF SCIENCE

IN

ELECTRICAL ENGINEERING

Approved

Dr. Stephen Bayne

Chair of Committee

Dr. Hamed Mohsenian-Rad

Peggy Gordon Miller
Dean of the Graduate School

August, 2011

Copyright 2011, Manohar Chamana

ACKNOWLEDGMENTS

The credit for the completion of my thesis has to go to several people. Firstly, I would like to thank my thesis advisor and committee chair, Dr. Stephen Bayne for his guidance, motivation and valuable inputs. I would also like to thank Dr. Hamed Mohsenian-Rad for serving as a committee member on my thesis panel.

I would also like to show my gratitude towards my group members in the lab for their valuable suggestion and discussions, which had immensely helped me in the completion of my thesis.

Last but not the least, I wish to acknowledge support from my family and friends throughout my graduate studies.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	ii
ABSTRACT	v
LIST OF TABLES	vi
LIST OF FIGURES	v ii
I. INTRODUCTION	1
1.1 Microgrid Concept	2
1.2 Control of Microsources	3
1.3 Background	4
1.4 Thesis Outline	5
II. DISTRIBUTED ENERGY RESOURCES	6
2.1 Wind Turbine	6
2.2 PV Array	8
2.3 Fuel Cell	13
2.4 Storage Device	19
III. GRID CONNECTED MODE	20
3.1 PQ Control	20
3.2 Theory behind the P-Q Control	20
3.3 Current-Mode Control	22
3.3.1 Space-Phasor Representation in d-q frame	22
3.3.2 Dynamic Model for Active-/Reactive-Power Controller	22
3.3.3 Phase-Locked Loop (PLL)	24
3.3.4 Current Mode Control of Active-/Reactive-Power Control	26
IV. ISLANDED MODE	30
4.1 V/f Control	30
4.2 Master-Slave Operation	32
4.3 Droop Control	33
4.3 Novel Modified Method for Generation Control	33
V. TIME DOMAIN SIMULATION RESULTS	37
5.1 Overview of Simulation Case Studies	37
5.2 Case Studies	37
5.2.1 Case 1	37
5.2.2 Case 2	49
5.2.3 Case 3	54

VI. CONCLUSION AND FUTURE WORK	60
6.1 Conclusion	60
6.2 Future Work	60
 REFERENCES.....	 62
 APPENDIX.....	 64

ABSTRACT

Distributed Generation is becoming popular these days due its superior feature of satisfying the local loads and improving reliability of the overall system. Microgrids (MGs) are connected to the main grid through a Point of Common Coupling which separates the former from the latter. At the time of an intentional islanding or fault at the grid level, a microgrid is able to disconnect itself from the rest of the grid and operate by itself. A microgrid may contain both directly connected and inverter interfaced sources with different control configurations. When disconnected or islanded from the main grid there are various approaches to share the load, one of them being master-slave control where a storage device may become the reference DG to set the nominal voltage and frequency. When the main grid is brought back to normal operation, the microgrid is able to resynchronize itself to the main grid only when it meets certain conditions so as to avoid transients. All the microsources, power electronics and their control with power management were developed in Matlab/Simulink.

LIST OF TABLES

1.1	Classification of Control Strategies for Inverter Interfaced Microsources. ...	3
5.1	Power Generated within the Microgrid.....	49
5.2	Power Demand within the Microgrid.....	49
A.1	DG Model Parameters.....	64
A.2	Load Parameters.....	65

LIST OF FIGURES

1.1	An Example of a Microgrid	2
2.1	Wind Turbine Characteristics	7
2.2	Two Diode Model for a Single Solar Cell	9
2.3	Series Parallel Combination in a PV array.....	10
2.4	An Example for PV Array I v/s V Characteristics.....	12
2.5	Incremental Conductance Algorithm Flowchart.....	13
2.6	SOFC Model	14
2.7	SOFC System Dynamic Model.....	19
3.1	Control Block Diagram of a PLL.....	25
3.2	Schematic for abc to dq -frame Transformation along with PLL	26
3.3	Control Block Diagram of a Current-Controlled VSC System.....	29
3.4	Current-Controlled Power Controller in dq -frame.....	29
4.1	General V/f Control Scheme in a Distribution Network.....	31
4.2	V/f Control Scheme in Matlab/Simulink Environment	32
4.3	Algorithm for Main Storage Device Protection	35
4.4	Reference Active Power Setter for Reserve Storage.....	36
5.1	Main Grid Output Power.....	38
5.2	Main Storage Device Output Power	39
5.3	Wind Turbine Output Power	40
5.4	PV array Output Power	41
5.5	Fuel Cell Output Power.....	42
5.6	Lumped Load Power Absorbed	43
5.7	Motor Load Power Absorbed.....	44
5.8	Voltage at the PCC.....	45
5.9	Frequency at the PCC.....	46
5.10	Total Active Power	47
5.11	Total Reactive Power	48
5.12	Main Grid Output Power.....	50
5.13	Main Storage Device Output Power	51

5.14	Wind Turbine Output Power	52
5.15	Reserve storage Output Power	53
5.16	PV Output Power	54
5.17	Main Grid Power	55
5.18	PV Output Power	56
5.19	Main storage device Output Power	57
5.20	Reserve storage Output Power	58
5.21	Wind Turbine Output Power	59

CHAPTER I

INTRODUCTION

Power demand has been increasing significantly over the past few years. Till this date the major share of power is supplied from conventional sources like nuclear, thermal, hydro etc., which are centralized. Most of the power coordination is also centralized through a SCADA system. The Northeastern blackout in 2003 is an example which exposes the sensitive nature of a centralized grid. An objective way for the conventional grid to move towards a smarter one is by decentralizing the grid, both in terms of supply as well as its control. The concept of microgrid (MG), where all the Distributed Generators (DGs) including the renewable energy sources can be operated and controlled at the distribution level itself, reduces the pressure on the main grid and hence the chance of a blackout is minimized. Some of the microsources are inverter interfaced, which makes the power control more flexible while others are directly connected. DC sources like PV's, SOFC's, storage etc are directly connected to the inverter while AC sources like Microturbine, flywheel etc are first rectified and then inverted to three-phase for grid connection. There are also some micro-sources like small hydro-power plants, fixed-speed wind turbine generators, diesel generators which are connected directly to the grid [1]. MG's are interfaced to the main grid through a Point of Common Coupling (PCC) which consists of a Circuit-Breaker (CB). The CB is able to connect or disconnect the MG from the main grid by receiving trip signals from a local control unit.

After islanding, reconnection of the Microgrid with the main grid at the PCC is possible only when the voltage error is below 3%, frequency error is below 0.1Hz and phase angle error is below 10^0 [2]. If these conditions are satisfied the resynchronization is possible with minimal transients. Figure 1.1 shows an example of a microgrid with various DGs along with loads connected within it.

Figure 1.1 An Example of a Microgrid [1].

1.1 Microgrid Concept

The Department of Energy defines a microgrid as “A combined energy system consisting of organized loads as an integrated system with distributed energy resources which can operate in parallel as well as in islanded mode”. When power is generated at huge power plants, the voltage is stepped up and transmitted through long distances to reach the distribution systems where the voltage is stepped down to meet the power demand at the load sites. The distribution system is a complex network hence its control becomes very difficult. This gave the idea of breaking down the distributed system into separate individual entities where management of these entities becomes much simpler. These separate entities or Microgrids that are dedicated to a particular area are able to separate themselves from the main grid and continue normal operation. The reason for disconnection could be due to a voltage collapse, faults or by purpose for maintenance [3]. This increases the local reliability due to sustained power supply [4].

1.2 Control of Microsources

The control of the microsources within the microgrid depends upon the required functions and general setup of the AC system. The main control functions of a microgrid control are voltage and frequency control and/or Active Power/Reactive Power control. The categorization of the different control functions with their division into grid forming and grid following controls are shown in Table 1.1

Table 1.1 Classification of Control Strategies for Inverter Interfaced Microsources.

Control Method	Grid-Following	Grid-Forming
Non-interactive	Power export (with/without MPPT)	Voltage and frequency control
Interactive	Power dispatch Real and reactive power support	Load sharing (droop control)

The controls are further divided into interactive and non-interactive strategies. The grid following control technique is utilized only when there is no reference voltage and frequency available at the PCC. Within the grid following control strategy the grid non-interactive strategy is utilized to control the microsources that are independently controlled without the consideration of the other microsources or load. An example of this could be a PV array based on Maximum Power Point Tracking (MPPT) control where the MPPT dispatches the reference power settings based on the Maximum Power Point. Another kind is the grid interactive strategy where the set-points are dispatched by a local control units based on the load demands and ratings of the microsource.

The grid-forming strategy is applied during the islanded mode. In the non-interactive strategy there is a single microsource which covers up the power imbalance while simultaneously stabilizing the voltage and frequency, while in the interactive strategy there are several microsources that share the load as well as its changes based on droop control by changing the voltage and frequency of the microsources.

1.3 Background

Around the world there are many experimental test beds setup for studying the microgrid. Each microgrid is different from one another both in structure and in application. In the US one of the most prominent test bed facilities is the CERTS microgrid facility [5], its main objective being to improve the overall reliability of the customer's electrical supply based on plug-and-play operation of the waste heat and intermittent sources. When islanded the microgrid sources provides power to the local loads within the microgrid by using active power-frequency droop and reactive power-Voltage droop characteristics. As all the sources within the microgrid share power in peer-to-peer manner the failure of one microsource does not affect the remaining microgrid system as the performance of the microsources are not dependent on each other, hence improving the reliability of the whole system. There are three major microgrid projects going on in Japan. The Aichi project in Japan used a PV system, a fuel cell stack and a battery storage system, where the battery storage system helps to regulate the voltage and balance the load by using converter controls. Even the Kyotango project in Japan uses a master control system to regulate voltage and frequency when islanded. The European Union has two major research projects: the Microgrids and More Microgrids projects. In Greece there is a laboratory setup to test a microgrid by using wind, PV and a battery storage. When islanded the battery acts as the main regulating system in the test facility by using active power-frequency and reactive power-voltage droops. As seen from above each microgrid test facility has its own combination of microsources with different control configurations mainly dependent on the customer needs. The motivation for this thesis comes from these above project to show the complete operation of a microgrid with a different set of microsources and show the transition during grid connected to islanded and then back to grid connected mode. A novel control scheme would be discussed in the master-slave control during the islanded mode.

1.4 Thesis Outline

The thesis has been divided into 5 chapters. In the first chapter the modeling of various Distributed Generators would be discussed in detail. In the second chapter the grid connected mode control strategy would be discussed. In the third chapter the islanded mode control strategy would be discussed. The fourth chapter will cover all the simulation results for different case studies. Finally the fifth chapter would include the conclusion and future work that could be implemented.

CHAPTER II

DISTRIBUTED ENERGY RESOURCES

2.1 Wind Turbine

The wind generation model used in this paper is a fixed speed wind turbine, which means that the wind turbines rotor speed is constant and depends upon the grid frequency, the gear ratio and generator design [6]. The fixed speed wind turbine in this paper uses a squirrel cage induction generator and is connected directly to the main grid. Due to its intermittent nature it is considered as a negative load but is a major power source when the wind blows within proper limits. As the model uses a squirrel cage induction generator it absorbs reactive power for establishing magnetic flux, so instead of taking reactive power from the main grid there is a capacitor bank provided for power factor correction which becomes more important during islanded mode. With higher wind speeds the active power delivered increases but at the same time the reactive power absorbed also increases. The rotational speed of the generator is determined by the grid frequency and the pole pairs of the machine. There is minimum deviation (1-2%) in the operating speed of the turbine [7].

$$P_m = 0.5\rho AC_p(\lambda, \beta)V^3 \quad (2.1)$$

where,

P_m Mechanical output power of the turbine (W)

C_p Performance coefficient of the turbine

ρ Air density (kg/m^3)

A Turbine swept area (m^2)

V Wind speed (m/s)

λ Tip speed ratio of the rotor blade tip speed to wind speed

β Blade pitch angle (deg)

The performance coefficient C_p can be expressed as,

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-21/\lambda_i} + 0.0068\lambda \quad (2.2)$$

Where λ_i can be expressed as a function of the equation,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} + \frac{0.035}{\beta^3 + 1} \quad (2.3)$$

The mechanical power P_m as a function of generator speed, for different wind speeds and for blade pitch angle $\beta = 0$ degree, is given below in Figure 2.1.

Figure 2.1 Wind Turbine Characteristics.

As seen from the figure the fixed speed wind turbines have a limited range of operation just above the synchronous speed for varying wind speeds.

2.2 PV Array

A photovoltaic array is an intermittent DC power source. Since a PV array needs to be grid connected it has to be interfaced through an inverter. The PV array is a combination of series and parallel connected solar panels. Each solar panel is a combination of several interconnected solar cells. In this paper a two diode mathematic model is used to represent the I-V characteristics of an individual solar cell. Figure 2.2 shows the two diode model for a single solar cell.

The reverse saturation current due to diode 1:

$$i_s = C_s T^3 e^{-E_g/kT} (e^{qV - I_{r_s}/kT} - 1) \quad 2.4$$

Where C_s is the Shockley saturation diode parameter, E_g is the band gap of the semiconductor material, k is the Boltzmann constant, T is the temperature, q is the elementary charge and V is the voltage across the panel. The current due to charge carrier recombination is given by:

$$i_r = C_r T^{5/2} e^{-E_g/2kT} (e^{qV - I_{r_s}/2kT} - 1) \quad 2.5$$

Where C_r is the photocurrent losses due to carrier recombination. The current due to recombination losses is represented by using the second diode which is neglected in the single diode model representation of a solar cell.

The overall current of a two diode model including the irradiance dependent photo-current, $i_{ph} = (C_{ph} + C_t T) G$, where C_{ph} is the photocurrent coefficient and C_t is the temperature coefficient, is given by:

$$I = -i_s - i_r - \frac{V - I_{r_s}}{r_p} \quad (2.6)$$

Figure 2.2 Two Diode Model for a Single Solar Cell

The last term on the right hand side of equation (3) characterizes the current due to the voltage drop across the parallel and series resistances, R_{SH} and R_S respectively. The overall current can only be calculated using an iterative process. For a given solar cell I-V characteristics depicted in the datasheets of a solar panel the different parameters of the $I = f(V)$ equation. The six unknown parameters of the equation are C_{ph} , C_t , C_r , C_s , R_S and R_{SH} . The known terms that can be obtained from a given datasheet are Short Circuit Current (I_{SC}), Maximum Power Point Current at STC (I_{mp}), Open Circuit Voltage (V_{OC}), Maximum Power Point Voltage @ STC (V_{mp}), Thermal coefficient of Short Circuit Current (αI_{SC}) and Thermal coefficient of Open Circuit Voltage (βV_{OC}). These terms lie on the I-V curve of a solar cell and can be used to solve for the constant parameters. After obtaining these constants the equation can be modified to simulate a large PV array. Each solar cell is connected in series to form a solar panel and these panels are connected in a series parallel structure (i.e. $N_{ss} * N_{pp}$) to form a large PV array to obtain the required voltage and current ratings [8]. Figure 2.3 shows the $N_{ss} * N_{pp}$ series parallel combination in a PV array.

$$I = I_{PV}N_{pp} - I_{01}N_{pp} \left[e^{\frac{V + IR_s \left(\frac{N_{ss}}{N_{pp}} \right)}{V_T N_{ss}}} - 1 \right] - I_{02}N_{pp} \left[e^{\frac{V + IR_s \left(\frac{N_{ss}}{N_{pp}} \right)}{2V_T N_{ss}}} - 1 \right] - \frac{V + IR_s \left(\frac{N_{ss}}{N_{pp}} \right)}{R_{SH} \left(\frac{N_{ss}}{N_{pp}} \right)} \quad 2.7$$

Figure 2.3 Series Parallel Combination in a PV Array [9].

An MPPT algorithm can be used to operate the PV panel at its maximum power point. The inverter in this case is operated at a constant active and reactive power based on set-points dictated by the MPPT algorithm [9]. In this paper an incremental conductance MPPT algorithm was used to operate the PV panel, where the power generated from the array was differentiated with respect to voltage and then equated to zero [10,11].

$$\frac{dP}{dV} = I + V \frac{dI}{dV} = 0 \quad 2.8$$

Rearranging the equation gives,

$$\frac{I}{V} = -\frac{dI}{dV} \quad 2.9$$

In equation (2.9) the left hand side represents the opposite of the PV array's instantaneous conductance, while the right-hand side represents its incremental conductance. Thus, at the MPP, these two quantities must be equal in magnitude, but opposite in sign. A set of inequalities can be derived from Equation (2.9) that indicates whether the operating voltage is above or below the MPP voltage.

$$\frac{dI}{dV} = -\frac{I}{V} \quad \left(\frac{dP}{dV} = 0 \right) \quad 2.10$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad \left(\frac{dP}{dV} > 0 \right) \quad 2.11$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad \left(\frac{dP}{dV} < 0 \right) \quad 2.12$$

Equation (2.10) represents the goal operating point to be reached while the inequalities (2.11) and (2.12) represent the direction in which the perturbation must move in order to reach the maximum operating point. Once the MPP is reached it remains unchanged until a current change occurs due to change in irradiance.

As shown in the figure 2.4, as the irradiance increases the operating point moves to the right to reach the maximum power point, which is achieved by the MPPT algorithm by increasing the voltage further. The same is true with the decrease of the irradiance where the voltage is decrease to move the MPP to left.

Figure 2.4 An Example for PV Array I v/s V Characteristics [9].

Figure 2.5 shows a flowchart for the incremental conductance algorithm. When $dI = 0$ and $dV = 0$ there is no change in atmospheric conditions and the solar array operates at its MPP, but when $dI > 0$ or $dI < 0$ there is a change in irradiance detected which moves the operating point accordingly to reach the MPP.

Figure 2.5 Incremental Conductance Algorithm Flowchart [11].

2.3 Fuel Cell

In this paper a Solid-Oxide Fuel Cell was considered, which acts as a controllable power source. A fuel cell used for Power Systems consists of three main parts, i.e. the Fuel Processor: where the fuels like natural gas are converted into Hydrogen and byproducts, Power Section: which consists of many combined fuel cells and used for producing electrochemical electricity and the Power Conditioner or the inverter section: where dc power is converted into ac power. A typical SOFC model is shown in figure 2.6.

Figure 2.6 SOFC Model.

The dynamic model was taken from [12]. The core idea of power flow from the SOFC is the chemical reaction given by:

The above reaction takes place in two halves i.e. at the anode and cathode of a cell given by

The electrons released from the anode pass through an external circuit towards the cathode and react with oxygen molecules, hence producing current while the produced oxygen ions at the cathode pass through the electrolyte and react with the Hydrogen molecules for a chemical balance. Numerically the voltage produced from these reactions for one fuel cell is low; hence these fuel cells need to be stacked in order to produce high voltages for grid connection purpose.

The model used in this research uses CO that contains water as a fuel for the production of Hydrogen and oxygen, given by the chemical reaction:

The characteristics of the exhaust of the channels define the dynamic model of a fuel cell. For a mixture of gases with average molar masses, M (kg/kmol) and equal specific heat at same temperature, is defined by the equation [13].

$$\frac{W}{P_u} = K\sqrt{M} \quad 2.17$$

Where W is the mass flow [kg/s]; K is the valve constant [$\sqrt{\text{kmol kg}} / (\text{atm s})$]; P_u is the pressure upstream [atm].

The fuel utilization, U_f is given by the ratio of the reacting fuel flow to the input fuel flow.

$$U_f = \frac{q_{\text{H}_2}^r}{q_{\text{H}_2}^{\text{in}}} \quad 2.18$$

According to (2.18) the equation (2.17) can be modified as

$$\frac{W_{\text{an}}}{P_{\text{an}}} = K_{\text{an}} \sqrt{(1 - U_f)M_{\text{H}_2} - U_f M_{\text{H}_2\text{O}}} \quad 2.19$$

Where W_{an} is the mass flow through the anode valve [kg/s]; K_{an} is the anode valve constant [$\sqrt{\text{kmol kg}} / (\text{atm s})$]; M_{H_2} , $M_{\text{H}_2\text{O}}$ are the molecular masses of hydrogen and water, respectively [kg/kmol]; P_{an} is the pressure inside the anode channel [atm].

Assuming that the molar flow of a gas is proportional to the partial pressure inside the channel, the equation can be written as

$$\frac{q_{\text{H}_2}}{p_{\text{H}_2}} = \frac{K_{\text{an}}}{\sqrt{M_{\text{H}_2}}} = K_{\text{H}_2} \quad 2.20$$

and

$$\frac{q_{H_2O}}{p_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O} \quad 2.21$$

where, q_{H_2}, q_{H_2O} are the molar flows of hydrogen and water, respectively, through the anode valve [kmol/s]; p_{H_2}, p_{H_2O} are the partial pressures of hydrogen and water respectively [atm] ; K_{H_2}, K_{H_2O} are the valve molar constants for hydrogen and water, respectively [kmol/(s atm)], the equation (2.19) can be deduced as

$$\frac{W}{P_{an}} = K_{an} \left[1 - U_f \sqrt{M_{H_2}} + U_f \sqrt{M_{H_2O}} \right] \quad 2.22$$

From equations (2.19) and (2.22), for the fuel utilization value of 70 % the error is around 7%. If the equations (2.20) and (2.21) are slightly modified, the error can be further reduced.

Considering each gas separately and applying the perfect gas equation to them, the perfect gas equation for H_2 for example would be given by

$$p_{H_2} V_{an} = n_{H_2} RT \quad 2.23$$

Where V_{an} is the volume of the anode [l from the paper] ; n_{H_2} is the number of hydrogen moles in the anode channel; R is the universal gas constant [(l atm)/(kmol K)] ; T is the absolute temperature [K].

By applying time derivative to the above equation, the equation can be modified as

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} q_{H_2} \quad 2.24$$

where q_{H_2} is the time derivative of n_{H_2} representing the hydrogen molar flow [kmol/s]; The hydrogen molar flow can be represented by the terms input flow, q_{H_2}

[kmol/s]; the flow that takes part in the reaction, $q_{H_2}^r$ [kmol/s] and the output flow $q_{H_2}^{out}$ [kmol/s]. Thus the above equation can be modified as:

$$\frac{d}{dt}p_{H_2} = \frac{RT}{V_{an}}(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^r) \quad 2.25$$

The reacting fuel flow is given by,

$$q_{H_2}^r = \frac{N_0 I_{fc}^r}{2F} = 2K_r I_{fc}^r \quad (2.26)$$

Where N_0 is the number of cells associated in series in the stack; F is the Faraday's constant [C/kmol]; I_{fc}^r is the stack current [A]; K_r is a constant defined for modeling purposes [kmol/(s A)]. Thus the equation (2.25) can be modified as

$$\frac{d}{dt}p_{H_2} = \frac{RT}{V_{an}}(q_{H_2}^{in} - q_{H_2}^{out} - 2K_r I_{fc}^r) \quad (2.27)$$

If in the above equation the output flow is replaced by the equation (2.20) and taking the Laplace transform on both sides, the hydrogen partial pressure can be written as

$$p_{H_2} = \frac{1/K_{H_2}}{1 - \frac{1}{H_2 s}}(q_{H_2}^{in} - 2K_r I_i) \quad 2.28$$

where,

$$H_2 = \frac{V_{an}}{K_{H_2} RT} \quad 2.29$$

All other reactants and products can be derived in the same manner.

The stack voltage V_{fc}^r can be derived from the Nernst's equation and ohm's law, given by:

$$V_{fc}^r = N_0 \left(E_0 - \frac{RT}{2F} \left[\ln \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}} \right] \right) - r I_{fc}^r \quad 2.30$$

The demand current can be controlled within a range given by,

$$\frac{0.8q_{H_2}^{in}}{2K_r} \leq I_{fc}^{in} \leq \frac{0.9q_{H_2}^{in}}{2K_r} \quad 2.31$$

For optimal fuel utilization, U_f is set at 85%, therefore

$$q_{H_2}^{in} = \frac{2K_r I_{fc}^{in}}{0.85} \quad 2.32$$

The peak power capacity, p_k is given by the ratio of the maximum theoretical power delivery to the rated power in the system and is proportional to the fuel cell area. There are various factors which control the value of p_k . With respect to cost the upper value of p_k is considered in between 130 to 180%. Safety is also a concern with respect to the pressure difference between the flow of Hydrogen and Oxygen through the anode and cathode compartments of a fuel cell. Simulation studies show that the value ideal value of p_k is constricted to a value below 170%. Simulations also show that the value of r_{H_2O} should be 1.145 in order to maintain a safe pressure difference of 4 KPa. In order to maintain r_{H_2O} at 1.145 the oxygen flow is controlled by the air compressor. The dynamic model of the chemical response is modeled as a first-order transfer function with a time constant of 5sec as the chemical reaction parameters take time to change after the reactants flow, whereas the dynamic model of the electrical response is modeled as a first-order transfer function with a time constant of 0.8 sec due to the fast response of charge restoration as a result of charge drain by the load. The complete SOFC dynamic model is shown in figure 2.7.

The model used in this paper contains all the electromechanical dynamics and losses of a SOFC. An inverter interfaces the SOFC to the main grid. By using the PQ control dynamics to control the firing pulses of inverter the power factor can be maintained within a range of 0.8-1.

Figure 2.7 SOFC System Dynamic Model [12].

2.4 Storage Device

A single storage device can usually be a DC power source, with limited power capability and is connected to the main grid through an inverter interface. It is an important part of the microgrid especially during the island mode of operation as it takes up the portion of the power which was previously being generated by the main grid. In order to provide such high power many battery sources need to be stacked in parallel for back-up. As the battery has the capability of a bi-directional power flow, it can also absorb excess energy. In the microgrid considered in this paper the battery model is assumed to be a DC voltage source.

CHAPTER III

GRID CONNECTED MODE

3.1 PQ control

As previously mentioned the microgrid in this paper contains both directly interfaced and inverter interfaced micro-sources, their control scheme also varies. All the controllable inverter interfaced micro-sources are operated with a PQ control strategy when grid-connected.

There exist two methods to control the active and reactive power flowing out of an inverter. The first kind is the voltage-mode control, where the active and reactive power are controlled using the phase angle and magnitude of the inverter AC side with respect to same quantities on the PCC side. The advantages of using a voltage mode control is that it is simple and has a fewer number of control loops, while the main disadvantage of the voltage mode control is that it does not have a protection scheme against overcurrents when there is a rapid reference power change or fault in the AC system as a result of the lack of a current feedback loop. This drawback is compensated by the second control approach which is the current-mode control scheme. In this approach the active and reactive power are controlled by controlling the phase and magnitude of the inverter AC side currents with respect to the PCC current quantities [14]. There is a dedicated feedback control loop to achieve this process. The other advantages of using a current mode control scheme are higher control precision, better dynamic performance and toughness against the change of AC system and inverter parameters when compared to the voltage-mode control scheme.

3.2 Theory behind the P-Q control

The main function of an inverter in a microgrid which is in grid-connected mode is to control the active and reactive power flow between the microsource and AC system. In this section the variables which influence the flow of active and

reactive power through the inverter would be discussed. The power flow between two AC sources is represented by [15]:

$$P = \frac{VE}{X} \sin(\theta_V - \theta_E) \quad 3.1$$

$$Q = \frac{V^2}{X} - \frac{VE}{X} \cos(\theta_V - \theta_E) \quad 3.2$$

Where P and Q are the active and reactive power flowing between the inverter and the microgrid. V is the voltage at the AC side of the inverter and E is the voltage at the microgrid. θ_V and θ_E are the power phase angles at the AC side of Inverter and the microgrid side respectively. X is the impedance connected in between the inverter and the microgrid. From the equations it is observed that the active power is predominantly dependent on Inverter AC side and the microgrid power phase angle difference. Solving for $\theta = \theta_V - \theta_E$ and V from the equations (3.1) and (3.2) we get:

$$V = \sqrt{\frac{2Q}{X} - \frac{E^2}{X^2} + \sqrt{\frac{E^4}{X^4} - \frac{4QE^2}{X^3} + \frac{4P^2}{X^2}}} \quad 3.3$$

$$\theta = \sin^{-1}\left(\frac{PX}{VE}\right) \quad 3.4$$

Thus from the above equations it can be seen that for a reference active and reactive power the Voltage and power phase angle at the inverter AC side can be controlled with respect to the Voltage and power phase angle at the microgrid side.

3.3 Current-Mode Control

As discussed previously representing the dynamic model in dq-frame has more advantages when compared to $\alpha\beta$ -frame, the first step would be to derive the space-phasor representation in dq -frame [14].

3.3.1 Space-Phasor representation in d-q frame

Considering the space phasor $\vec{f}(t) = f_\alpha + jf_\beta$, the $\alpha\beta$ to dq frame transformation can be written as:

$$f_d + jf_q = \vec{f}(t)e^{-j\rho t} = (f_\alpha + jf_\beta)e^{-j\rho t} \quad (3.5)$$

Where $\rho(t)$ represents the angle of rotation in the rotating reference frame

3.3.2 Dynamic Model for Active-/Reactive-Power Controller

The voltage at the microgrid side can be written as:

$$\begin{aligned} V_{sa}(t) &= \hat{V}_s \cos(\omega_0 t - \theta_0) \\ V_{sb}(t) &= \hat{V}_s \cos\left(\omega_0 t - \theta_0 - \frac{2}{3}\right) \\ V_{sc}(t) &= \hat{V}_s \cos\left(\omega_0 t - \theta_0 - \frac{4}{3}\right) \end{aligned} \quad 3.6$$

where, $\hat{V}_s$ is the peak phase-to-neutral value, ω_0 is the frequency at the microgrid side, θ_0 is the initial power phase angle. The space-phasor equivalent of the microgrid side voltage is given by:

$$\vec{V}_s(t) = \hat{V}_s e^{j(\omega_0 t - \theta_0)} \quad 3.7$$

The space-phasor equation of the dynamics involved in between the AC side of the inverter and the microgrid is given by:

$$L \frac{d\vec{i}}{dt} = - (R + r_{on})\vec{i} - \vec{V}_t + \vec{V}_s \quad 3.8$$

Substituting (3.7) in (3.8) we get:

$$L \frac{d\vec{i}}{dt} = - (R + r_{on})\vec{i} - \vec{V}_t + \hat{V}_s e^{j(\omega_0 t - \theta_0)} \quad 3.9$$

By using the equations $\vec{i} = i_{dq} e^{j\rho}$ and $\vec{V}_t = V_{tdq} e^{j\rho}$ the above equation can be converted to dq-frame:

$$L \frac{d}{dt} (i_{dq} e^{j\rho}) = - (R + r_{on}) i_{dq} e^{j\rho} - (V_{tdq} e^{j\rho}) - \hat{V}_s e^{j(\omega_0 t - \theta_0)} \quad 3.10$$

Where $f_{dq} = f_d + jf_q$, the above equation can be rewritten as:

$$L \frac{d}{dt} (i_{dq}) = -j \left(L \frac{d\rho}{dt} \right) i_{dq} - (R + r_{on}) i_{dq} - V_{tdq} - \hat{V}_s e^{j(\omega_0 t - \theta_0 - \rho)} \quad 3.11$$

By splitting the above equation into real and imaginary components we have:

$$L \frac{di_d}{dt} = \left(L \frac{d\rho}{dt} \right) i_q - (R + r_{on}) i_d - V_{td} - \hat{V}_s \cos(\omega_0 t - \theta_0 - \rho) \quad 3.12$$

$$L \frac{di_q}{dt} = - \left(L \frac{d\rho}{dt} \right) i_d - (R + r_{on}) i_q - V_{tq} - \hat{V}_s \sin(\omega_0 t - \theta_0 - \rho) \quad 3.13$$

By introducing a new control variable ω into the above two equations where

$$\omega(t) = \frac{d\rho}{dt} \quad 3.14$$

The equations get converted into standard state-space form:

$$L \frac{di_d}{dt} = L\omega(t) i_q - (R + r_{on}) i_d - V_{td} - \hat{V}_s \cos(\omega_0 t - \theta_0 - \rho) \quad 3.15$$

$$L \frac{di_q}{dt} = -L\omega(t) i_d - (R + r_{on}) i_q - V_{tq} - \hat{V}_s \sin(\omega_0 t - \theta_0 - \rho) \quad 3.16$$

From the equations (3.14)-(3.15), we have that i_d , i_q and ρ are the state variables; V_{td} , V_{tq} and ω are the control inputs. As the equations (3.14)-(3.15) are non-linear, to simplify them ρ is assumed to have zero initial condition and $\omega(t) = 0$. Thus the equations can be rewritten as:

$$L \frac{di_d}{dt} = (R + r_{on})i_d - V_{td} - \hat{V}_s \cos(\omega_0 t - \theta_0) \quad 3.17$$

$$L \frac{di_q}{dt} = (R + r_{on})i_q - V_{tq} - \hat{V}_s \sin(\omega_0 t - \theta_0) \quad 3.18$$

In the equations (3.17) and (3.18), $\hat{V}_s \cos(\omega_0 t - \theta_0)$ and $\hat{V}_s \sin(\omega_0 t - \theta_0)$ are the excitation inputs. The advantage of using the dq -frame representation lies on the proper selection of ω and ρ . For the VSC system that we consider if $\omega = \omega_0$ and $\rho = \omega_0 t - \theta_0$, then the equations can be written as:

$$L \frac{di_d}{dt} = L\omega_0 i_q - (R + r_{on})i_d - V_{td} - \hat{V}_s \quad 3.19$$

$$L \frac{di_q}{dt} = -L\omega_0 i_d - (R + r_{on})i_q - V_{tq} \quad 3.20$$

The above two equations represent a second-order linear system that is excited by $\hat{V}_s$. In steady state V_{td} , V_{tq} , i_d and i_q can be considered as DC variable. For maintaining $\rho = \omega_0 t - \theta_0$ a PLL is used which would be discussed in the next section.

3.3.3 Phase-Locked Loop (PLL)

By substituting (3.5) in (3.1) we get,

$$V_{sd} = \hat{V}_s \cos(\omega_0 t - \theta_0 - \rho) \quad 3.21$$

$$V_{sq} = \hat{V}_s \sin(\omega_0 t - \theta_0 - \rho) \quad 3.22$$

Equations (3.14)-(3.16), can be rewritten as:

$$L \frac{di_d}{dt} = L\omega(t)i_q - (R + r_{on})i_d - V_{td} - V_{sd} \quad 3.23$$

$$L \frac{di_q}{dt} = -L\omega(t)i_d - (R + r_{on})i_q - V_{tq} - V_{sq} \quad 3.24$$

$$\frac{d\rho}{dt} = \omega(t) \quad 3.25$$

From (3.22) we get that V_{sq} must be equal to zero in order for ρ to be equal to $\omega_0 t - \theta_0$, which is achieved by the feedback law:

$$\dot{\rho} = H(p)V_{sq}(t) \quad (3.26)$$

Where $H(p)$ is the compensator and p is the differential operator. By substituting $V_{sq}(t)$ from eq into the above equation gives:

$$\frac{d\rho}{dt} = H(p)\hat{V}_s \sin(\omega_0 t - \theta_0 - \rho) \quad (3.27)$$

The above equation describes a non-linear dynamic system also called as Phase-Locked Loop (PLL). As the equation has non-linear characteristics, the PLL may exhibit sinusoidal behavior around zero for low-pass frequency response of $H(p)$, ρ does not track $\omega_0 t - \theta_0$ properly and the PLL falls into a limit cycle. To avoid the limit cycle from occurring, the control law must be modified as:

$$\dot{\rho} = H(p)V_{sq}(t), \quad \rho(0) = \rho_0 \text{ and } \omega_{min} \leq \omega \leq \omega_{max} \quad (3.28)$$

The value of ω_{min} and ω_{max} are chosen to be close to ω_0 , narrowing down the variation range for $\rho(t)$. As the purpose of the PLL is to track $\omega_0 t - \theta_0$, the value of $\omega_0 t - \theta_0 - \rho$ in steady state is around zero, hence $\sin(\omega_0 t - \theta_0 - \rho) \approx \omega_0 t - \theta_0 - \rho$ and the control law can be further simplified as:

$$\frac{d\rho}{dt} = \hat{V}_s H(p)(\omega_0 t - \theta_0 - \rho) \quad (3.29)$$

The above equation represents a classical feedback law with $\omega_0 t - \theta_0$ as the reference input, ρ is the output and $\hat{V}_s H(p)$ is the compensator as shown on Figure 3.1.

Figure 3.1 Control Block Diagram of a PLL [14].

Figure 3.2, shows the abc to dq transformation along with the PLL. The purpose of using PLL is to adjust the dq frame rotation speed ω , such that V_{sq} is forced to zero in steady state. The Voltage Controlled Oscillator (VCO) in the figure acts as resettable integrator to reset the output ρ to zero every time it reaches 2π .

Figure 3.2 Schematic for abc to dq -frame Transformation along with PLL [14].

3.3.4 Current mode control of Active-/Reactive-Power Controller

The active and reactive power flow from an inverter to the microgrid system at PCC is given by:

$$P_s(t) = \frac{3}{2} [V_{sd}(t)i_d(t) - V_{sq}(t)i_q(t)] \quad 3.30$$

$$Q_s(t) = \frac{3}{2} [V_{sd}(t)i_q(t) + V_{sq}(t)i_d(t)] \quad 3.31$$

Where V_{sd} and V_{sq} are the dq -frame voltages at the microgrid system side. At steady state the PLL makes sure that $V_{sq} = 0$. Therefore the active and reactive power transferred can be rewritten as:

$$P_s(t) = \frac{3}{2} V_{sd}(t) i_d(t) \quad 3.32$$

$$Q_s(t) = \frac{3}{2} V_{sd}(t) i_q(t) \quad 3.33$$

Therefore from the above equations it can be seen that by controlling the dq -frame currents the active and reactive power can be controlled as follows:

$$i_{dref}(t) = \frac{2}{3V_{sd}} P_{sref}(t) \quad 3.34$$

$$i_{qref}(t) = \frac{2}{3V_{sq}} Q_{sref}(t) \quad 3.35$$

From the above equation, by maintaining $i_d = i_{dref}$ and $i_q = i_{qref}$, we have that $P_s = P_{sref}$ and $Q_s = Q_{sref}$ i.e. the active and reactive powers are independently controlled using reference signals.

The dq -frame representation of a two-level Inverter can be written as:

$$V_{td}(t) = \frac{V_{DC}}{2} m_d(t) \quad 3.36$$

$$V_{tq}(t) = \frac{V_{DC}}{2} m_q(t) \quad 3.37$$

Where m_d and m_q are the modulating signal in dq -frame. As the equations (3.23) and (3.24) with $(t) = 0$, have $L = 0$ terms the dynamics of i_d and i_q are coupled, to decouple them we introduce the terms u_d and u_q which can be written as:

$$u_d = L \frac{di_d}{dt} + (R + r_{on}) i_d \quad 3.38$$

$$u_q = L \frac{di_q}{dt} + (R + r_{on}) i_q \quad 3.39$$

By rearranging the terms we have:

$$L \frac{di_d}{dt} = - (R + r_{on})i_d + u_d \quad 3.40$$

$$L \frac{di_q}{dt} = - (R + r_{on})i_q + u_q \quad 3.41$$

By replacing the Right hand side terms of (3.38) and (3.39) in the equations (3.23) and (3.24) with u_d and u_q and then substituting the terms V_{td} and V_{tq} in equation (3.36) and (3.37), we get:

$$m_d = \frac{2}{V_{DC}} (u_d - L\omega_0 i_q - V_{td}) \quad 3.42$$

$$m_q = \frac{2}{V_{DC}} (u_q - L\omega_0 i_d - V_{sd}) \quad 3.43$$

Equations (3.40) and (3.41) describes two decoupled, first-order, linear systems, where i_d and i_q , can be controlled by u_d and u_q , respectively. Figure 3.2 shows the block diagram of a d- and q- axis controller of the VSC system where u_d and u_q are the outputs of the two corresponding compensators which processes the errors $e_d = i_{dref} - i_d$ and $e_q = i_{qref} - i_q$, respectively. The modulating signals m_d and m_q , which depend on u_d and u_q are amplified in a VSC by a factor $V_{DC}/2$ to generate V_{td} and V_{sd} , which in turn controls i_d and i_q based on (3.23) and (3.24). The control-block diagram of a current-controlled VSC system is shown in figure 3.3.

Figure 3.3 Control Block Diagram of a Current-Controlled VSC System [14].

The complete schematic for a current-controlled real-/reactive-power controller in dq -frame is shown in figure 3.4.

Figure 3.4 Current-controlled Power Controller in dq -frame [14].

CHAPTER IV

ISLANDED MODE

In islanded mode the distributed sources operating with PQ control strategy lose their voltage and frequency references which were previously dictated by the main grid. The storage device which was previously being operated with a PQ control changes to V/f control. The storage device provides the power imbalance that was being supplied from the main grid to the microgrid before the islanding instant. Rest of microsources could either be operated at the same set points or may change their set points based on the supply and demand. It is assumed that the storage device has an adequate reserve to be able to provide the same power imbalance as the main grid. There is also the droop control method where multi-power sources participate in the power balance during the island mode [16]. These DG's follow frequency droop (f-P) and voltage droop (V-Q) characteristics to change the operating points in order to follow the power imbalance caused by the disconnection of the main grid.

4.1 V/f control

The V/f control scheme was taken from a paper and shown in Figure 4.1. The same inverter that connects the Storage device experiences a change in gating pulses which is now dictated by a V/f control scheme instead of the PQ control. The V/f control strategy is a tight closed loop control with the reference values of voltage, V_{ref} and frequency, f_{ref} being the nominal values of the LV test-bed [17]. The frequency is measured using a three-phase PLL. In the V/f control scheme two separate PI compensators are used to process the error caused by the difference of the measured value and the reference set-points and attempts to minimize the error by adjusting the process control units. The power imbalance is automatically detected by the storage system and it supplies the remaining power. Even in case of excess power generation within the islanded microgrid the storage device readily absorbs the power to charge itself. In case the power flow from the storage device exceeds its limits the battery

storage would have to shut down. In case there is extra power available from controllable power sources like a reserve storage device which for example could be HEV's batteries, their power settings can be modified in order to limit the Main storage power flow within its rated value. If all the power limits of the DG's are exceeded then load shedding of non-critical loads become inevitable. When the signal for resynchronization is given, the storage systems returns to its normal PQ control.

Figure 4.1 General V/f control Scheme in a Distribution Network [17].

The V/f control scheme as developed in Matlab/Simulink environment is shown in Figure 4.2.

Figure 4.2 V/f control Scheme in Matlab/Simulink Environment.

4.2 Master-slave operation

In master-slave operation of a microgrid during islanding period only one microsource acts as a reference DG to set the voltage and frequency constant while all the other sources, which are a combination of directly connected and inverter interfaced sources operate in the same way as during the grid-connected mode. It is assumed that the storage device has enough capacity to meet the power imbalance along with a fast response to power demand. The main disadvantage of the master-slave approach is that the whole microgrid in islanded mode depends on just one source as voltage and frequency reference as well as for meeting the power imbalance. In the case of failure of the storage device due to crossing of power limit for a certain period the voltage collapses which collapses the whole microgrid during the islanded mode.

4.3 Droop Control

In droop control all the microsources within the microgrid during the islanding period are transferred to droop control to share the load based on their respective droops. Each of the microsource is operated based on their respective droops i.e. f-P and V-Q droops. In f-P droop control the total increase in active power load is shared based on a frequency droop characteristics. In the same manner the V-Q droop control regulates the reactive power change based their respective voltage droop characteristics [18].

The sharing of load by each microsource based on their droop characteristics called a peer-to-peer concept where all the microsources are treated equally to regulate the power imbalance instead of depending on a single source to regulate the entire power imbalance. The advantage of the peer-to-peer level concept is that even with the dysfunction of one microsource, rest of the microsources ($n-1$) are able to satisfy the load by proportionally increasing their power levels. The other advantage of this method is that communication links between the microsources is avoided to share the load as the entire sharing concept is based on the voltage and frequency sensed at the terminals of each microsource. However there are disadvantage involved with droop control that include poor voltage regulation, high voltage distortion and loss of synchronism with the main grid which poses a problem while resynchronization with the main grid [19]. Droop control is also being widely used to control the microgrid mainly for automatic power sharing among the microsources rather than from a dispatch control unit.

4.4 Novel modified method for generation control

As previously mentioned in the microgrid model there are three microsources, out of which two are intermittent sources of energy being operated on random input profiles. As the renewable energy sources do not have a fixed power supply they can only be made sure to be operated at their maximum power point. The third

microsource i.e. a fuel cell is a controllable microsource which already operates at a reference power slightly below its rated value and depends upon the fuel consumption and charge discharge rate. In islanded mode there is a main storage device to meet the power imbalance by maintaining a constant voltage and frequency within the system. In case the excess power demanded by the load exceeds its predefined power limits with increase in load or decrease in the power supply from the intermittent sources the battery fails to operate. As far as controls are mentioned there is no other way that the controls can be modified to meet the excess power demand. An alternate way to meet the power imbalance in this case would be to introduce a second power reserve which could be operated at low reference power levels initially and then step up its power when the main storage device fails to meet the excess power demand by staying within its power limits. In order for the reserve storage device to automatically meet the demand when the main storage device fails, an algorithm needs to be introduced. Considering the fact that due to sudden power changes in the load, at times there may be an increase in the demanded power for a short duration of time (microseconds to milliseconds). In that case the main storage device may be within its operating power limits but may fail due to a wrong algorithm. It must be made sure that the excess demanded power is indeed for a longer period so as to activate the algorithm. In that case there is a delay of about 1 sec to be given for the algorithm activation after the excess demand is more than that for the main storage device to operate in a safe manner. Once the algorithm is activated the reference active or reactive power to the reserve storage device increases in steps per second until the main storage device is brought back to a level within its safe operating limits. Once the main storage device is within its safe operating limits the reserve storage device maintains the same power limit until the microgrid is in islanded mode. When brought back to grid-connected mode the main storage and reserve storage devices are operated at low power levels. The whole algorithm is developed within Matlab/Simulink environment and is shown in figure 4.3.

Figure 4.3 Algorithm for Main Storage Device Protection.

As can be seen from the figure 4.4, the instantaneous active and reactive power are calculated and compared with the power limits throughout the simulation time. The input 1 is true throughout the islanding period. During this period if either of the instantaneous powers calculated exceeds the power limit the relation operator produces a true signal. If this signal continues for more than 1 sec the Reference Power Setting subsystem receives a true signal to operate. The OR logic operator along with the memory is meant to produce a continuous true signal for the rest of the islanding period once it receives a true signal to activate the Reference Power Setting subsystem. The details of the Reference Power Setting subsystem is given in figure 4.4.

Figure 4.4 Reference Active Power Setter for Reserve Storage.

As seen from the figure 4.4, until the activation true signal is generated all the switches bypass the signals that are in the bottom end. Switch 1 gives an output 0 which keeps the switch 2 to receive signals from the bottom end. With 0 adding to 0 continuously the overall reference output remains zero until the activation signal to switch 1 is given. Once the signal is received the switch 1 passes the 20 kW through the switch 1 which keeps on adding to itself with a time delay of 1 sec i.e. the power increase rate is 20 kW/sec until the main storage device falls within its power limit and resets the input value to zero when in the islanding period. After the 0 input is received the summation stops and remains at a constant value due to the memory block. After the microgrid goes back to the grid-connected mode the reserve storage device goes back to receiving its original low reference power settings.

CHAPTER V

TIME DOMAIN SIMULATION RESULTS

5.1 Overview of simulation case studies

As the simulation test bed consists of a wind turbine, a fuel cell, a PV panel, a storage device along with a reserve storage device within the microgrid, it is assumed that the microsources start at time $t = 0$ sec and produce their respective powers. While the uncontrollable power sources (renewable energy sources) produce power randomly the controllable sources like the fuel cell and the storage device is considered to be producing power according to the demand needs and the power from the MV grid. The voltage from MV grid was brought down to a low voltage level by using a transformer. The nominal values at the LV test-bed are $V_{nom} = 480$ V and $f_{nom} = 60$ Hz. The controllable power source are generally operated at power levels lower than their rated values during grid connected mode to have an adequate reserve during peak time or during a fault occurrence. All the power ratings and settings of microsources are given in Table I in the appendix. The loads within the microgrid system are mentioned in Table II in the appendix.

5.2 Case Studies

The case studies were performed on the developed test bed for various cases so as to see the performance of the system for different conditions.

5.2.1 Case 1

In this case the islanding condition is considered with the storage device acting as the reference voltage and frequency source. When the microgrid shifts from grid-connected mode to islanded mode the storage device moves from P-Q control to V/f control strategy. The storage device now acts like a power balancer by either producing more power or by absorbing the excess power from the other microsources when certain load conditions are considered. When the power flows from the storage device to the rest of the microgrid the storage device discharges, while when power flows into the storage device it starts charging. The charging and discharging

characters are not shown as the storage device is considered a DC voltage source at a constant voltage value. Also for this case it is assumed that the storage device has enough power capacity to be able to cover up the power imbalance for as long as the microgrid is in islanded mode.

Simulations show the power characteristics of the storage device when it moves from grid- connected mode to islanded mode and then back to grid-connected mode. The voltage and frequency characteristics during this time interval has also been shown, where it can be seen that the voltage and frequency remains constant throughout the time interval, which are the desired characteristics.

Figure 5.1 shows the active and reactive power flow between the main grid and the microgrid. Between time $t = 20$ sec to $t = 30$ sec the microgrid is in islanded mode and the power flow between the main grid and microgrid reduces to 0.

Figure 5.1 Main Grid Output Power.

Figure 5.2 shows the power flow from the inverter interfaced main storage device. When in grid-connected mode, the storage device does not produce any power. When in islanded mode the storage device picks up the excess load to be met while maintaining constant voltage and frequency. When the microgrid is resynchronized to the main grid the storage device is disconnected and the power flow from storage device reduces to zero.

Figure 5.2 Main Storage Device Output Power.

Figure 5.3 shows the power flow from the wind turbine. As the fixed-speed wind turbine needs to absorb reactive power in order to operate, only active power is produced based on a random wind profile.

Figure 5.3 Wind Turbine Output Power.

Figure 5.4 shows the power flow from a PV array based on a random input irradiance profile. The PV array is operated at the MPP based on an MPPT algorithm. The reference power settings are based on the MPP. The irradiance value changes at time $t = 18.7$ sec and $t = 38.7$ sec.

Figure 5.4 PV Array Output Power.

Figure 5.5 shows the active and reactive power flow from a Fuel Cell. The Fuel Cell produces both active and reactive power based on the power settings. The active power and reactive power settings for a Fuel Cell remain constant during the islanded mode.

Figure 5.5 Fuel Cell Output Power.

Figure 5.6 shows the active and reactive power absorbed by the lumped load. Based on the load settings the load was satisfied by the microgrid sources and the main grid both during grid connected as well as during the islanded mode.

Figure 5.6 Lumped Load Power Absorbed.

Figure 5.7 shows the motor load power absorbed when a torque of 11.9 N-m was applied. After initial transients for a few milliseconds the load settles down to a constant active power of 2.4 kW while absorbing a reactive power of 1.92 kvar.

Figure 5.7 Motor Load Power Absorbed.

Figure 5.8 shows the voltage during the simulation time period. It can be seen that the voltage remains constant throughout the simulation time period at the low voltage level $V = 480V$.

Figure 5.8 Voltage at the PCC.

Figure 5.9 shows the frequency during the simulation time period. It can be seen that the frequency remains constant throughout the simulation time period at $f = 60$ Hz.

Figure 5.9 Frequency at the PCC.

Figure 5.10 shows the total active power flow in the microgrid. The green line depicts the total active power generated within the microgrid while the dark blue dotted line depicts the total active power demand within the microgrid. The total demand is met with some losses in the microgrid components.

Figure 5.10 Total Active Power Flow.

Figure 5.11 shows the total reactive power flow in the microgrid. The green line depicts the total reactive power generated within the microgrid while the dark blue dotted line depicts the total reactive power demand within the microgrid. The total demand is met with some losses in the microgrid components.

Figure 5.11 Total Reactive Power Flow.

Table 5.1 shows the total power generated during time instants $t = 10$ sec, 25 sec and 35 sec. Table 5.2 shows the total power demand within the microgrid for time instants $t = 10$ sec, 25 sec and 35 sec. It can be seen that for the respective time instants the total power generated is approximately equal to the total power demand in the microgrid. The difference in the power generated and the power demand is due to the losses in the microgrid components.

Table 5.1 Power generated within the microgrid.

Time	t = 10 sec		t = 25 sec		t = 35 sec	
Power	Active Power (kW)	Reactive Power (kvar)	Active Power (kW)	Reactive Power (kvar)	Active Power (kW)	Reactive Power (kvar)
Main Grid	242.9	20.3	0	0	298.8	11.77
Storage	0	0	282.59	13.9	0	0
Wind	178.8	-93.4	135.74	-86.68	120.02	-84.68
PV Array	40.14	0	42.95	0	42.95	0
SOFC	40	5	40	5	40	5
Capacitor Bank	0	120	0	120	0	120
Total Supply	501.84	51.9	501.28	52.2	501.77	52.09

Table 5.2 Power demand within the microgrid.

Time	t = 10 sec		t = 25 sec		t = 35 sec	
Power	Active Power (kW)	Reactive Power (kvar)	Active Power (kW)	Reactive Power (kvar)	Active Power (kW)	Reactive Power (kvar)
Lumped Load	499.1	49.1	498.84	49.88	498.9	49.8
Motor Load	2.4	1.92	2.4	1.92	2.4	1.92
Total Demand	501.5	51.02	501.24	51.8	501.3	51.72

5.2.2 Case 2

When the microgrid moves from grid connected to island mode there is a single power source which moves from PQ control to V/f control mode, which in this case is a single storage device. All other microsources are PQ controlled while the storage device operating with V/f control meets the power imbalance. At times the power to be drawn from the storage device exceeds its limits. The following simulations show the transients during this condition due to reduction in wind speed during the islanding period and implements an algorithm based on the section 4.4.

Figure 5.10 shows the active and reactive power flow between the main grid and the microgrid. Between time $t = 25$ sec to $t = 38$ sec the microgrid moves to islanded mode and the power flow between the main grid and microgrid reduces to 0.

Figure 5.12 Main Grid Output Power.

Figure 5.11 shows the power flow from the inverter interfaced storage device. When the storage device is grid connected the active and reactive flow is zero. When in islanded mode the storage device picks up the excess load to be met while maintaining constant voltage and frequency. The limit for the active and reactive power to be transferred from the main storage device is known beforehand. If any of the limits are exceeded the algorithm takes 1 sec to react so as to make sure the excess power demand is not due to any transients. Based on section 4.4, the algorithm is applied to reset the power setting for the reserve storage device until the power transferred from the main storage device is less than their respective limits. When the microgrid is resynchronized to the main grid the storage device is disconnected and the power flow reduces back to zero. From figure 5.11, it can be seen that at time $t =$

28.2 sec the active power limit is exceeded. After 1 sec the reference power to the reserve storage device changes from $P_{\text{ref}} = 0$ kW to 20 kW and hence reducing the power transferred from the main storage device. Even after 1 sec as the power flow from the storage device is above its limits again at time $t = 29.2$ sec the active power limit is exceeded due to further reduction in wind speed. At time $t = 30.2$ sec the algorithm is activated and the reference power to the reserve storage device changes from $P_{\text{ref}} = 20$ kW to 40 kW and remains constant until time $t = 33.5$ sec after which the reference setting changes from $P_{\text{ref}} = 40$ kW to 60 kW due to the main storage rating crossed at time $t = 32.5$ sec.

Figure 5.13 Main Storage Device Output Power.

Figure 5.12 shows the power flow from the wind turbine. As the fixed-speed wind turbine needs to absorb reactive power in order to operate, only active power is produced based on a random wind. It can be seen from the power flow from the wind turbine that there is a sudden decrease due to the reduction in wind speeds during time

instants $t = 28.2$ sec and $t = 32.5$ sec. The main storage device detects an increased power imbalance due to which it steps up its active power. It is during these time instants that the main storage device exceeds its active power limits, causing the activation of an increase in the reference power settings to the reserve storage device in order to be within its power limits.

Figure 5.14 Wind Turbine Output Power.

Figure 5.13, shows the Active and reactive power flow from the reserve storage device which steps up its power during time $t = 29.2$ sec, 30.2 sec and 33.5 sec based on the algorithm as discussed in section 4.4.

Figure 5.15 Reserve Storage Output Power.

All the other devices operate in the same manner as in the case I based on their reference settings and input profile. Both the lumped load and the motor load have the same values as in the previous case.

Figure 5.14, shows the power output of a PV array based on an input irradiance profile.

Figure 5.16 PV Array Output Power.

5.2.3 Case 3

When the microgrid moves from grid connected to island mode there is a single power source which moves from PQ control to V/f control mode, which in this case is a single storage device. All other microsources are PQ controlled while the storage device operating with V/f control meets the power imbalance. At times the power to be drawn from the storage device exceeds its limits. The following simulations show the transients during this condition due to reduction in the irradiance input to a PV array and implements an algorithm based on the section 4.4.

Figure 5.15, shows the active and reactive power flow between the main grid and the microgrid. Between time $t = 40$ sec to 50 sec the microgrid moves to islanded mode and the power flow between the main grid and microgrid reduces to 0.

Figure 5.17 Main Grid Output Power.

Figure 5.16, shows the power output of a PV array based on an input irradiance profile. During islanded mode the irradiance suddenly changes from 1300 W/m² to 100 W/m² at time $t = 38.7$ sec, which causes a decrease in power output from 43 kW to 3.1 kW. This causes an increase in the power supplied from the main storage device as seen from the next figure.

Figure 5.18 PV Array Output Power.

Figure 5.17, shows the power flow from the inverter interfaced storage device. When the storage device is grid connected the active and reactive is zero. When in islanded mode the storage device picks up the excess load to be met while maintaining constant voltage and frequency. The limits for the active and reactive power to be transferred by the main storage device are known beforehand. If any of the limits are exceeded the algorithm takes 1 sec to react so as to make sure the excess power demand is not due to any transients. After 1 sec based on sec the algorithm is applied to reset the power setting for the reserve storage device until the power transferred from the main storage device is less than their respective limits. When the microgrid is resynchronized to the main grid the power flow from the storage device reduces to zero. From Figure 5.17 it can be seen that at time $t = 41.5$ sec the active power limit is exceeded. After 1 sec the reference power to the reserve storage device changes from $P_{ref} = 0$ kW to 20 kW and hence reducing the power transferred from the main storage device. Even after 42.5 sec the power limit of the main storage device is exceeded,

hence at time $t = 43.5$ sec the reference setting is changed from $P_{ref} = 20$ kW to 40 kW. P_{ref} remains unchanged after $t = 43.5$ sec until the end of the islanding period.

Figure 5.19 Main Storage Device Output Power.

Figure 5.18 shows the Active and reactive power flow from the reserve storage device which steps up its power during time $t = 42.5$ sec and $t = 43.5$ sec based on the algorithm as discussed in section 4.4.

Figure 5.20 Reserve Storage Device Output Power.

Figure 5.19, shows the power flow from the wind turbine. As the fixed-speed wind turbine needs to absorb reactive power in order to operate, only active power is produced based on a random wind profile. As can be seen from the power flow from the wind turbine it can be seen that the power flow from the wind turbine is quite high and continuous.

Figure 5.21 Wind Turbine Output Power.

CHAPTER VI

CONCLUSION AND FUTURE WORK

6.1 Conclusion

In the thesis presented a number of Distributed Generators were developed in a microgrid. Their dynamic and steady state behaviors were examined in a Matlab/Simulink simulation environment. Simulations were carried out to examine the transients when the microgrid changes from grid connected mode to islanded mode and then back to grid connected mode. The two control modes used in this paper were PQ control and V/f control. A dedicated storage device with enough power capacity was assumed, which helped to smooth out the power imbalance during the islanded mode of operation. Whenever the power rating for the main storage was exceeded during some conditions the reserve storage device were set to produce power until the power rating for the main storage device was brought within limits.

Results indicated that all DGs apart from the storage device operated in a regular way, while the storage device experienced a change in its operation during the islanding mode to maintain the pre-islanded voltage and frequency values. Table 5.1 and Table 5.2 shows that the total power generated is approximately equal to the total power demand within the microgrid. It is also observed that the transition between the two modes of operations takes place with minimal transients.

6.2 Future Work

The islanding was intentional in nature and not caused by any fault at the main grid level. In the future work faults like LG, LLG, LLLG etc can be considered. There could be an islanding instant detection scheme included in the system so as to open the circuit breaker and then auto reclose when the fault is cleared. The reclosure is achieved when the main grid is in synchronism with the microgrid.

The battery assumed in the thesis was a constant DC source, but in reality considering the battery it would be limited by the energy stored in it in order to supply the extra power during islanded mode. In the future real battery characteristics can be

considered along with the state of charge concept. The case when the limits for the reserve power exceeds was not considered. In such a case load shedding could be performed for the non-critical loads in order to save the microgrid from collapsing. There is also a need to look into the optimization of the sources and energy balance.

REFERENCES

- [1] F. Katiraei, R. Iravani, N. Hatziargyriou, and S. Amires, “Microgrids: Control and Management”, IEEE Power & Energy Magazine, Vol. 6, No. 3, pp. 74-98, May/June 2008.
- [2] IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems.
- [3] R.H Lasseeter, “Smart Distribution: Coupled Microgrids”, Proceedings of the IEEE, Vol. 99, Issue 6, pp. 1074 1082
- [4] R. Lasseeter, P. Paigi, “Microgrid: A conceptual solution”, in 2004 IEEE 35th Annual Power Electronics Specialists Conference, 2004. PESC 04, volume 6, 2004.
- [5] B. Kroposki, R. Lasseeter, T. Ise, S. Morozumi, S. Papathanassiou, and N. Hatziargyriou, "Making microgrids work," IEEE Power Energy, vol. 6, no. 3, pp. 40-53, May 2008.
- [6] T. Ackermann, “Wind Power in Power Systems”, John Wiley and Sons, Ltd, West Sussex, 2005
- [7] F. Blaabjerg, Z. Chen, “Power Electronics for Modern wind Turbines”, Morgan and Claypool Publishers, San Rafael, 2006
- [8] K. Ishaque, Z. Salam, H. Taheri, “Accurate MATLAB Simulink PV System Simulator Based on a Two-Diode Model”, Journal of Power Electronics (JPE), Vol. 11, no. 2, pp.179-187, 2011
- [9] V. Galdi, A. Piccolo, P. Siano, “Dynamic Performance and Control of dispersed generators connected through inverter”, International Conference on Computational Intelligence for Modeling, Control and Automation.pp.1060-1065.Nov, 2005.

- [10] I. Laird, H. Lovatt, N. Savvides, D. Lu, V.G. Agelidis, “Comparative Study of Maximum Power Point Tracking Algorithms for Thermoelectric Generators”, Power Engineering Conference, 2008. AUPEC '08. Australasian
- [11] D. P. Hohm, M. E. Ropp, “Comparative Study of Maximum Power Point Tracking Algorithms” Progress in Photovoltaic's”, Research and Applications Prog. Photovolt: Res. Appl. 2003; 11:47-62.
- [12] Y. Zhu, K. Tomsovic, “Development of models for analyzing the load following performance of micro-turbines and fuel cells”, Electric Power System Research journal, December 2001.
- [13] J. Padulles, G.W. Ault, J.R. McDonald, “An integrated SOFC plant dynamic model for power systems simulation”, J. Power Sources 86 (2000) 495-500.
- [14] A. Yazdani and R. Iravani, “Voltage-Sourced Converters in Power Systems”, New York: Wiley, 2010.
- [15] S.S. Shi, Z.X. Lu, Y. Min, “Verification of the Equivalent Model of the Inverter in Microgrid”, 2010 2nd IEEE International Symposium on Power Electronics for Distributed Generation System, pp 691-695
- [16] M. Angelo Pedrasa, T. Spooner, “A Survey of Techniques Used to Control Microgrid Generation and Storage during Island Operation”, AUPEC2006.
- [17] T. Tran-Quoc et al., “Investigation of Dynamic Behaviors of Distribution Networks in Stand-Alone Mode”, International Institute for Critical Infrastructures, Grenoble, 2004.
- [18] M. C. Chandorkar, D. M. Divan, R. Adapa, “Control of Parallel Connected Inverters in Standalone ac Supply Systems”, IEEE Transaction on Industry Applications, Vol. 29, No. 1, Jan/Feb. 1993.
- [19] K.D. Wu, J.C. Wu, H.L. Jou, C.Y. Chen and C.Y. Lin, “Simplified Control Method for Parallel-Connected DC/AC inverters”, IEE Proc.-Electr. Power Appl., Vol. 153, No. 6, November 2006.

APPENDIX

Table A.1: DG Model Parameters

Parameters			Values	
SOFC	Rated Power		50 kVA	
	P_{refl}		40 kW	
	Q_{refl}		5 kVar	
	Line impedance		$0.05 + j0.3768 \Omega$	
	Series Cells No.		450	
PV Array	Series panels No.		3000	
	Parallel Panels No.		10	
	Rated Power		50 kVA	
	Temp		20^0 C	
	Line impedance		$0.05 + j0.03768 \Omega$	
Storage Device	P_{rated}		300 kW	
	Q_{rated}		225 kVar	
	DC link voltage		10 kV	
	Line impedance		$0.05 + j0.03768 \Omega$	
Wind Generator (Induction Generator)	S _n	V _n	275 kVA	480 V
	R _s	L _{ls}	0.016	0.06
	R _r	L _{lr}	0.015	0.06
	H	Pole pairs	2	2

* Impedance parameters of machines in p.u

Table A.2: Load Parameters

Loads	Values
Lumped Load	500 KW, 50 KVar
Asynchronous Motor	20 HP, 220 V, 60 Hz, 1780 RPM