MODELING AND PERFORMANCE ANALYSIS OF MICROGRID WITH FUEL CELL AND WIND BASED DISTRIBUTED GENERATION SYSTEMS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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Declaration

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled **MODELING AND PERFORMANCE ANALYSIS OF MICROGRID WITH FUEL CELL AND WIND BASED DISTRIBUTED GENERATION SYSTEMS** which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfillment of the requirements for the award of the **Doctor of Philosophy** in **Electrical and Electronics Engineering** is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Certificate

This is to certify that the Research Thesis entitled **MODELING AND PERFORMANCE ANALYSIS OF MICROGRID WITH FUEL CELL AND WIND BASED DISTRIBUTED GENERATION SYSTEMS** submitted by **Santhosha Kumar A.** (Register Number: **100529EE10F03**) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

Dr. D N Gaonkar
(Research Guide)
(Name and Signature with Date and Seal)

Chairman-DRPC
(Signature with Date and Seal)

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SANTHOSHA KUMAR A

With blessing of almighty dedicated to

My late grandparents

My Family and friends

All my teachers and Guides

Abstract

The deregulation of electric power utilities, advancement in technology, environmental concerns and emerging power markets are leading to increased interconnection of distributed generators to the utility system. Various new types of distributed generator systems, such as microturbines and fuel cells in addition to the more traditional solar and wind power are creating significant new opportunities for the integration of diverse DG systems to the utility. Inter connection of these generators will offer a number of benefits such as improved reliability, power quality, efficiency, alleviation of system constraints along with the environmental benefits. With these benefits and due to the growing momentum towards sustainable energy developments, it is expected that a large number of DG systems will be interconnected to the power system in the coming years.

Unlike centralized power plants, the DG units are directly connected to the distribution system; most often at the customer end. The existing distribution networks are designed and operated in radial configuration with unidirectional power flow from centralized generating station to customers. The increase in interconnection of DG to utility networks can lead to reverse power flow violating fundamental assumption in their design. This creates complexity in operation and control of existing distribution networks and offers many technical challenges for successful introduction of DG systems. Some of the technical issues are islanding of DG, voltage regulation, protection and stability of the network. Some of the solutions to these problems include designing of standard interface control for individual DG systems by taking care of their diverse characteristics, finding new ways to/or install and control these DG systems. In this regard a particularly promising and emerging solution is the microgrid concept of integrate large number of distributed generation resources to the grid.

The microgrid is a systematic way of operating a section of network, comprising sufficient generating resources in grid connected or autonomous mode in an efficient, deliberate and controlled way. The microgrid has larger power capacity and more control flexibilities to fulfill the system reliability and power quality requirements, in addition to all the inherited advantages of a single DG system. Along with generation sources microgrid also consists of storage devices such as flywheels, batteries and super capacitors. The operation and con-

trol of microgrid can be very challenging due to diverse characteristics of DG systems and storage devices integrated in the microgrid and also presence of ac and dc loads. Important aspect of the microgrid is the possible combination of renewable energy sources with inevitable uncertainty in the output such as wind and solar with reliable energy sources like fuel cell and microturbine systems along with storage devices. In this regard promising configuration of the microgrid is the combination of wind and fuel cell based DG system along with storage device.

In this work solid oxide fuel cell (SOFC) and wind based microgrid system along with battery, UC and electrolyzer as energy storage devices has been implemented. The dynamic models of SOFC, wind, ultra capacitor(UC), battery and electrolyzer are presented. The wind system considered in this work employs the permanent magnet synchronous generator (PMSG). The detailed modeling of the power electronic converters for interfacing the generation and storage devices considered in the microgrid are also given. In this work SOFC, wind system, UC, battery and dc loads are integrated at common dc-link to reduces multiple energy conversion losses. The battery and UC are integrated at common dc-link through bidirectional dc-dc converters. The electrolyzer and dc loads are connected to the dc link through the buck converter interface. The modelling of the control schemes to coordinate and manage the operation of the DG systems and storage devices in the microgrid are also presented in this work. The presented microgrid model is integrated to the utility network through the 3 phase voltage source inverter along with necessary control scheme. Matlab/Simulink/SimpowerSystem environment is used in this work implementing the microgrid system and study the performance of the same in grid connected and isolated mode of operation.

The performance of the microgrid in grid connected mode considering only wind system with and without storage device is presented in this work. The maximum power point tracking (MPPT) method is employed in the wind system to extract maximum power under different wind speed conditions. The performance results obtained through the simulation show the output power fluctuation due to variation in the wind speed. The wind system performance has been studied with battery and battery-UC coordinated operation. The frequent charge and discharge cycle of battery due to change in wind speed is also shown through the simulation results, which reduces life of the battery. In this work the battery instant discharge is controlled by using ultracapacitor for varying wind speed by coordinated operation of battery and UC. Dump load is also used to maintain the power balance between generation and demand in this work. The effectiveness of the coordinated control of UC and battery for wind system in microgrid is studied through simulation results.

The wind power output variation can be effectively compensated using the SOFC along with the ultracapacitor and electrolyser. Thus microgrid with SOFC, wind system, ultracapacitor and electrolyzer is implemented in this work. The electrolyser considered in this work can effectively utilize the wind power for producing hydrogen during increased wind speed. The hydrogen is required for fuel cell operation. The simulation results are presented and analysed to study the performance of the microgrid with above configuration. The simulation results show the effectiveness ultra capacitor in compensating slow dynamic response of the fuel cell. The ultracapacitor instant supplies the any increase in load demand while SOFC gradually increase the power delivery. The inherent slow dynamic response of the fuel cell can adversely effect the load. The effective control and coordination of SOFC and UC can supplement each other and avoid adverse effect on the load. The simulation are also presented to show the effective utilization of increased wind power output during high wind speed condition to produce hydrogen through electrolyser.

The performance of ac/dc microgrid based on SOFC, wind, ultracapacitor, battery and electrolyzer is studied in this work. In this study two separate DC loads one at 48V and another 380V is considered apart from the ac load at the grid side. The control schemes are implemented to coordinate the operation of energy sources and storage devices to supply the load efficiently. The performance of the microgrid is studied through simulation results both in grid connected and islanded mode of operation. Typical case studies are presented in this research work considering various scenarios of feeding ac and dc loads in the microgrid. The simulation results presented in the case studies highlight the changes in SOFC output power due to change in wind speed, limited options to charge the storage devices,load control during less generation and charging

of UC by battery. The simulation results show the effective operation of UC in compensating slow response of SOFC while controlling battery discharge rate. The results presented also show the performance of battery in supplying minimum load when SOFC is disconnected and also generation of hydrogen using electrolyser during more generation by wind and less load condition.

Keywords: Distributed generation;wind system;PMSG;SOFC;ultracapacitor.

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NOMENCLATURE

Symbol	Meaning
A_w:	area swept by rotor(m^2)
E_0 :	standard electrode potential (V)
V_{act} :	activation loss (V)
V_{con}:	concentration loss in (V)
V_{ohm} :	ohmic loss(V)
E :	fuel cell output voltage(V)
E_0 :	open cell voltage(v)
R :	gas constant
r :	ohmic losses of the stack
I :	fuel cell stack current
N_0 :	number cell connected in series
K_{H_2} :	Valve molar constant of hydrogen
K_{H_2} :	Hydrogen flow response time
ρ :	air density(kg^3
ω_m:	angular velocity of wind turbine rotor
E_{UC} :	energy delivered by the UC
V_i :	initial voltage
V_f :	final voltage
v_{cell}:	voltage drop
u_0:	thermodynamic cell voltage
T:	temperature (C)
$\frac{I_e}{A}$:	current density (A/m^2)
A :	cell electrode area (m^2)
$r1, r_2$:	ohmic resistance parameter
t_1, t_2, t_3 and u_1 :	over voltage parameters
n :	number of cells
V :	voltage across the electrolyzer
n_{H_2}:	hydrogen produced (mol/s)
η_F :	Faraday efficiency
I_e :	electrolyzer current
$P_b \& P_{bi}$:	tank pressure and initial tank pressure
z :	compression factor
N_{H_2} :	hydrogen sent to tank (mol/s)
R :	universal gas constant

ABBREVIATIONS

Abbreviation :	Expansion
ac :	alternating current
ac :	direct current
CHP :	combined heat and power
DG :	distributed generation
kV :	kilo volt
kVAr :	kilo volt ampere reactive
kW :	kilow watt
MPPT :	maximum power point tracking
PCC :	point of common coupling
MTG :	microturbine generation
PLL :	phase lock loop
PMSG:	permanent magnet synchronous generator
P_{load} :	load power
P_{wind} :	wind power
P_{SOFC} :	SOFC power
P_{total} :	total power
P_{bat} :	battery power
I_{bat_ref}:	battery reference current
I_{bat} :	battery current
$B_{soc\_TH\_U}$:	battery charge upper threshold limit
$B_{soc\_TH\_L}$:	battery charge lower threshold limit
B_{soc} :	battery state of charge
I_{wind} :	wind current
I_{UC_ref} :	UC reference current
I_{UC} :	UC current
V_{uc} :	UC terminal voltage
$V_{uc\_TH\_U}$:	UC terminal voltage upper limit
$V_{uc\_TH\_L}$:	UC terminal voltage lower limit
V_{dc} :	dc-link voltage
V_{dc_ref} :	dc-link reference voltage

Chapter 1

INTRODUCTION

1.1 Overview

The need for energy is never ending. This is certainly true of electrical energy, which is a large part of total global energy consumption. But growing in tandem with energy needs are the concerns about sustainable development and environmental issues, such as the movement to reduce greenhouse gas emissions. Traditionally electrical power is generated mainly by using fossils fuels. The effluents from these power plants are one of the major factors for the environmental pollution. Many countries formulated policies and guidelines to reduce greenhouse gas emission [Don et al. 2014, Xiaoli et al. 2015, Ajay et al. 2014]. The increased awareness towards the global warming, the environmental safety norms, time, space and economic constraints are few factors associated with construction of new traditional power plants[Francesco et al. 2011].

To meet the power demand while addressing the issues with traditional power generation is important.It has became necessary to look for alternative energy resources which are free from such issues. The renewable based energy resources are natural choice for alternative energy resources which are free from environmental issues and freely available.The world energy need can be satisfied by wind and solar[Jacobson and Delucchi 2011]. The renewal based power generation may include wind, photovoltaic(PV), geothermal,wave energy, mini hydro, biomass etc.The non-renewable based power generation may include fuel cell and microturbine(MT).The potential of these resources are utilized well by distributed generation (DG) which are small scale generation system connected near the loads. The deregulation of power sector is another influencing factor which bought attention for DG system[El-Khattam and Salama 2004, Barker and De Mello 2000]. The power electronics has high impact on DG technology development The DG interface has been become more flexible and convenient as power electronics system are advancing. The DG system becoming more controllable, efficient and enhancement in performance is possible with power electronic converts [Bimal 2013].

Along with environmental benefits the DG offers many benefits like reliability, utilization of local resources, sustainability, reduction in overloading and losses of transmission and distribution system. Erection of new large power plants can be minimized hence the new long, bulky and time consuming transmission and distribution line can be reduced. In many cases the power supply to remote areas becomes expensive or impractical. In such conditions the DG plays very important role.The DG can be placed near the load and can be operated locally. However the traditional power system configuration may experience many technical, operational and management issues with high penetration of DG system into the network. The interconnection, voltage rise, protection, safety,flicker, power quality and islanding are few issues [Pepermansa et al. 2005, Barker and De Mello 2000, Larsson 2002]. The operational, control, management and protection issues arises with high penetration of DG system into utility. The economic operation of power plants, scheduling of power plant operation and matching load with fluctuating power from DG is major concerns. The size and placement of DG is crucial for interfacing with utility. Although renewable resources are available freely, the prime issue is output power fluctuations. The fluctuating power may affect either load or the grid.

The power fluctuations are mitigated using storage devices.The flywheel, superconductor magnetic coil, battery, ultracapacitor etc are used as energy storage devices[John and David 2004]. Among these devises the batteries are commonly preferred because of its high energy capacity. The wind and PV based system are quite successful in such cases with storage. The different DG systems compliment each other to supply constant power. The different DG technology are combined and operated together.Hybrid generation system includes combination of PV , wind, fuel cell, MT and diesel generator. The hybrid system leads to reliable and sustainable energy. [Caisheng and Hashem 2008, Gyawali and Ohsawa 2010, Bhende et al. 2011, Colson and Nehrir 2011, Gyawali and Ohsawa 2010, Nehrir et al. 2011]. However the output from these sources is fluctuating. Many studies has shown that combination of different DG are beneficial. The unpredictably and power fluctuations are still the limitations faced by renewable based DG system. The renewable based DG systems can be combined together with diesel generator,microturbine or fuel cell to ensure the continuity of supply. Hence different combinations are explored with other DG systems to supply reliable power. A new concept of operating different distributed generation systems together has came up recently called microgrids.

The different DG are operated together to supply the section of utility are called as microgrids [Chris et al. (2008)]. The DG system benefits are maximized when they are operated collectively in microgrids. The microgrid can be of remote ones or grid connected. The microgrid connected to grid have benefits like voltage,frequency and reactive power support. However the synchronization, protection and stability are the issues. Along with ac loads the number of dc loads utilization are increasing and these loads fed with many conversion stages. The industries like data-centers, communication and commercial building requires dc power [Daniel and Ambra 2007, Daniel et al. 2008] in large portion. The nowadays appliances like LED lighting, BLDC motors, electric vehicles are based on dc power. The dc system has advantages like reduction of conversion stages and losses [David et al. 2013, Jackson et al. 2013]. The DG like fuel cell,PV and storages devices outputs are dc in nature. Hence the utilization of dc power directly can leads to increased efficiency reduced cost and size. In order to supply new coming loads based on dc power, the microgrid may required to have flexibility is supplying both existing ac load and dc loads. To address the issue with DG system and to supply sustainable and reliable power supply extensive research work and solutions are essential. As renewable based DG systems output is fluctuating and a controllable generation with eco friendly feature is needed. To fulfill this condition the fuel cell can be a one of the better option.

The fuel cell is one of the promising and developing technology which can be combined with other DG like wind and PV to produce better results. The fuel cell input can be generated using renewable resources which leads to environmental friendly system. The combined operation fuel cell with mature renewable technology like wind system is important. Hence the wind and fuel cell based microgrid can play a important role in reliable supply. Due to added benefits the microgrid are increasing. The development of dynamic model microgrids to study the behavior, control ,operational and interconnection aspects are necessary. Hence the modeling and performance of wind and fuel based microgrid is presented in this thesis.The control schemes to operate and control microgrid are given.Wind power fluctuations are mitigated using storage device. The controllers are presented use the wind power by battery or UC or to generate hydrogen as per the requirement or used by the battery or ultracapacitor. The control schemes or employed to mitigate the slow dynamic response of SOFC and battery discharge rate. The control schemes are presented to balance the ac and dc loads.

1.2 DG Technologies

The distributed generation systems comprises different technologies like sustainable power generation like wind, PV, wave, geothermal and nonrenewable resources like fuel cell, microturbine and internal combustion engines. The wind and PV are mature and established technology. The fuel cell and microturbine are getting more importance and technologically advancing. The different DG have different characteristics and studying the behavior of these technologies can make system design and analysis better. The major DG technologies are discussed in the following section.

1.2.1 Wind energy conversion system

Wind based power generation is one of the old and fastest growing technology of renewable energy. World installed wind power capacity has been crossed 318GW by 2014 and wind market is growing fast. In India the installed capacity of wind power is about 22GW by 2014. Wind speed is very unpredictable and hence whenever it is available has to used accordingly. The blowing wind encompasses kinetic energy with it.The kinetic energy in the blowing wind is converter to rotational power by the wind turbine blades. The blades are attached to shaft which acts as prime mover to electrical generator. Wind turbine technology developed over a period of time with different wind turbine and generators employed[Polinder et al. 2013, John and Zafirakis 2011]. Among the different wind turbines the horizontal axis, variable speed turbine are very successful. The advantages,classification and control of horizontal axis wind turbine are given below.[Ackermann 2012, Mukund 2006]

Fixed speed wind turbines:

In this type, the generator is normally Induction type due to their low cost,better environmental durability and superior mechanical durability with rapid wind speed. The generator is directly connected to grid. It includes the gear system which increases low speed to higher speeds of generator side(1000 to1500rpm).The turbine speed depends on size of wind turbine and rotor. As wind turbine size increases the rotational speed decreases.The fixed wind speed turbines are design to optimum efficiency for a particular wind speed. To capture more energy few turbines have two rotational speeds by adapting two generators are two windings.

Variable speed wind turbines(VSWT):

The variable speed wind turbines are of two types;one is limited variable speed wind turbine and variable speed wind turbine. In the limited variable-speed wind energy conversion system (WECS), a resistance bank at the rotor is included for limited control of the speed. The wound rotor induction generator (WRIG) is used in this types for direct grid integration. Capacitor bank are connected near the generator for reactive power compensation.The rotor resistance is varied by connecting an additional resistance optically controlled by converter mounted on rotor shaft.This enables the slip control hence the power output can be controlled. The variable speed range depends on size of variable resistor. The variable speed wind turbine operates in wide speed range unlike fixed speed turbines. The energy capture is enhanced. It requires converters to interface with load or the grid.The variable speed turbine coupled with DFIG or PMSG.The DFIG based system requires gear system as speed is around 1000 to 1500 rpm. The variable speed turbine can be used without gear system along with PMSG.

Advantages of VSWT

- Captures more energy compared to fixed to speed.
- With proper power electronic converter contributes to stability of the system by controlling the reactive power.
- Less mechanical stress.
- With direct drive train system do not require gear box and can operate at lower speeds.
- With reduced size nacelle design is simple.

The major disadvantage of variable speed wind turbine is increased cost and complexity due to power electronic converters.

Wind turbine control

- **Stall control:**In stall control the pitch of the angle of the blade is constant. The blades are fixed to the hub they do not rotate along the axis. The turbine output is controlled by stall effect. This arrangement is robust and less expensive. As blades are fixed aerodynamic power is limited. The turbine do not produce rated power even when sufficient wind speed is available.

- **Active stall control:** To produce rated power available in the wind active stall control is used.The turbine blades are slightly pitched as per wind speed to get the desired power.The wind system performance is enhanced during high wind speeds. The turbine stopping or starting can be achieved easily.However it requires flexible connection of blades to hub hence mechanical and control complexities increases.
- **Pitch control:** It is similar to active stall. The turbine blades are pitched to obtain the desired output power.The blade can be turned into or out the wind as per wind speed.it provides the starting and emergency stopping of wind turbine. The control mechanism is complex.

The wind energy conversion system are interfaced with load using power electronic converter[Blaabjerg et al. 2004, Ackermann 2012, Mukund 2006]. The DFIG and PMSG are two types of generators used for WECS. Nowdays the direct drive PMSG are becoming more prominent[Polinder et al. 2006]. The small and medium scale wind turbine are connected to low voltage or medium voltage system individually or in group. The large capacity (megawatt range) turbine are connected to high voltage line in groups called wind farms.The wind system with different configuration is shown in Figure1.1.

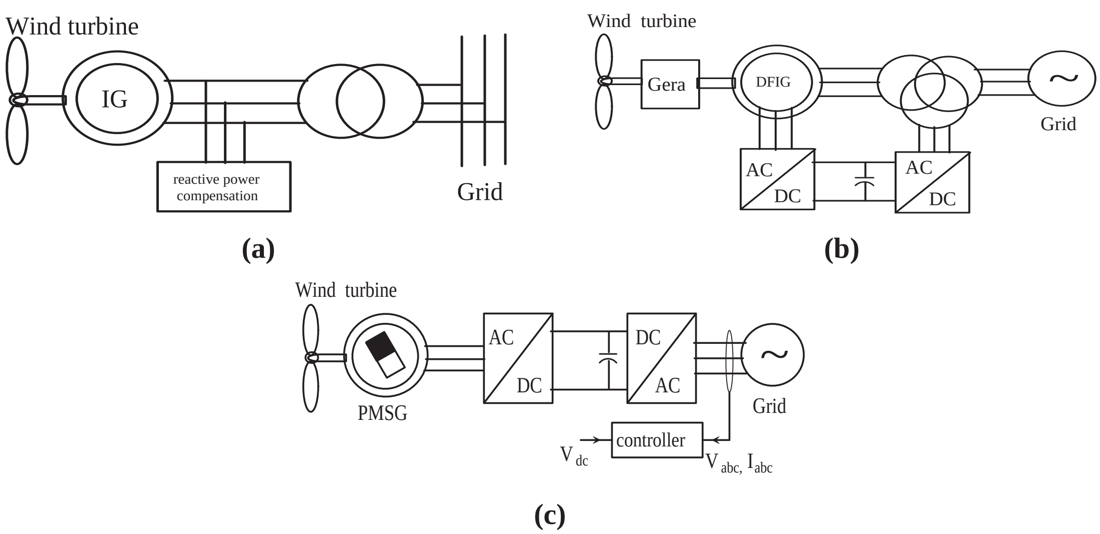


Figure 1.1: Wind system with (a)Induction generator (b)DFIG (c)PMSG

The PMSG utilization with wind system has increased. The PMSG offers many advantages like increase the power capture, reduced noise problems and higher efficiency and no external excitation requirement.The direct drive PMSG based wind system drawing more attention due to gearless construction, reduced weight, reduced size of nacelle,more stability to the structure. The PMSG based system requires full scale power electronic converters it is a disadvantage as compared to DFIG. In contrary it provides more control,operation in low speed, less maintenance and fast response.

1.2.2 Photovoltaic

Photovoltaic cell is a large semiconductor p-n diode which converter sun light into dc voltage and current. The number of cells are grouped in series and parallel to form arrays for the desired working power ratings. The PV technology cost were very high initially however the technological advancement reduced price of PV very drastically over the decade. The PV is an unregulated dc power source. It needs power electronic interface for two main tasks: one is to convert the generated DC voltage into a suitable AC current for the utility; the other is to control the terminal conditions of the PV module(s) so as to track the maximum power point (MPP) for maximizing energy capture[Eltawit and Zhao 2010].

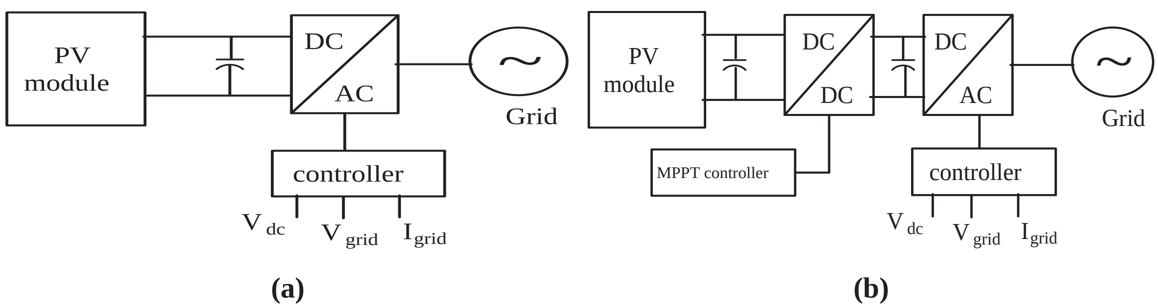


Figure 1.2: Schematic diagram of PV system (a) directly connected to grid (b)with dc-link voltage regulation.

A battery storage system may be present at the dc bus, mainly in autonomous and small installations. Most of the individual range of PV module ranges from 20W to 100kW The disadvantages of PV systems are significant area requirements due to the diffuse nature of the solar resource, higher installation cost than other DG technologies, and intermittent output with a low load factor. [Jhunjunwala et al 2013, Mukund 2006] The schematic diagram PV system connected to grid is shown in Figure 1.2.

1.2.3 Fuel cell

Fuel cells are electrochemical devices which converters chemical energy directly into electrical energy. It is similar to battery but differs as, a battery stores energy within it and releases when load connected. The battery needs to be recharged by external source or discarded once the stored energy is depleted. In other hand the fuel cell produces power as long as fuel is supplied. The fuel cell do not have any moving parts. It is zero emission device with water and heat as by product. In fuel cell the combustion do not occurs. It consists two electrodes and electrolyte between them. Hydrogen is supplied to the anode and oxygen is supplied to the cathode of the fuel cell. The hydrogen is split into an electron and a proton as chemical reaction takes place. Each takes a different path to the cathode. The electrons pass through external circuit to produce electricity for a given load. The proton passes through the electrolyte and both are reunited at the cathode. The electron, proton, and oxygen combine to form water as byproduct [Chris and Scott 2003, Hashem and Caisheng 2009]. Fuel cell can be the one of alternative solution for difficulties in power generation by wind and solar based DGs. The Fuel Cell can work in parallel with other distributed generation units. Fuel cells differs from conventional heat engines in that they produce electricity directly from chemical energy without an intermediate conversion into mechanical power. Fuel cell based power system can be operated in parallel with other DG system unaffected by climatic conditions and is very promising technology in present days among the alternative energy. The fuel cell produces power as long as fuel is supplied. The types of fuel cell, advantages and disadvantages are discussed below[Laughton 2002, Chris and Scott 2003, Hashem and Caisheng 2009]

Advantages of fuel cells

- **Efficient:** As fuel cells directly convert fuel and oxidant into electricity through an electrochemical process, they can achieve high electrical efficiencies upto 40 to 60 % [Laughton 2002]. The combined operation of fuel cells with MT or gas turbine for combined heat and power applications (CHP), the system efficiency can reach 70 to 80%.

- **Simple in design:** The fuel cell are simple in design which helps is achieving longevity. In fuel cell there are no moving parts (except for the axillary devices). It contributes in simplistic manufacturing process and higher operational time.

- **Ultra low emission:** Since the output of an ideal fuel cell is pure water, the emissions are extremely low. Depending on the type of fuel cell and the fuel used the actual emissions of fuel cells fall well below any current standard of emissions. It emits less than 1ppm of NOx, 4ppm of CO, and less than 1ppm of reactive organic gases, while the standards are an order of magnitude greater for NOx, two orders of magnitude greater for reactive organic gases, and several orders of magnitude larger for CO.

- **Silent operation:** The fuel cell converts energy though a chemical process, as opposed to a mechanical process like in an internal combustion engine, thus the sound emissions are virtually zero. This is an important advantage especially in on site and in vehicle applications.

Types of fuel cells

Fuel cells are classified based of the electrolyte used. The electrolyte and materials used determines the chemical reactions taking place in the fuel cell, the catalyst required and operating temperature. Depending on the type of fuel cell, operating temperature and fuel required, applications of fuel cell differs. Different fuel cell are under development and each has their own advantages,disadvantages and applications. Among the different types of fuel cells the most preferred ones along with other types are given below.

- **Alkaline fuel cells (AFCs)** uses alkaline solution like potassium hydroxide in water as electrolyte. Commonly nickel is used as catalyst. These are first fuel cell and used in space programs. These fuel cells can be categorized depending on their pressure temperature and electrode structures. Have high electrical efficiency. Generally requires pure hydrogen and oxygen as they are very sensitive to poisoning. High-temperature AFCs operate at temperatures between 100°C to 250°C and lower temperatures Alkaline fuel cells operates around 23°C to 70°C.

- **Molten carbonate fuel cells (MCFCs)** uses molten mixture of alkali metal carbonates. The electrolyte is usually a binary mixture of lithium and potassium, or lithium and sodium carbonates which is kept in ceramic matrix.They operate at extremely high temperatures around 650°C, hence precious metals are not required as catalysts at the anode and cathode, reducing costs. Best runs continuously due to high temperature. MCFCs are used for large stationary power plants and CHP application can be utilized.

- **Phosphoric acid fuel cells (PAFCs)**use liquid phosphoric acid as an electrolyte.The phosphoric acid is contained in silicon carbide matrix using capillary action. A finely dispersed platinum catalyst on carbon is used. It is resistant to poisoning by carbon monoxide. It's operating temperature is around 180°C. Phosphoric acid fuel cells were the first commercially available fuel cells and cost is very high to be economically competitive. Electrical efficiency is relatively low however the overall efficiency can reach above 80% if CHP is used. Used in stationary power generation(100kW to 400kW)

- **Polymer electrolyte fuel cells** are also know as proton exchange membrane fuel cell (PEMFCs) are low temperature type and it is a main feature of attraction. PEM uses water based acidic polymer membrane as electrolyte. Platinum based catalyst are used on both electrodes. They have operating temperature around 100°C. It has ability to deliver high power density at lower temperature. Hence they can be made smaller which reduces overall weight, cost to produce and specific volume. It has immobilized electrolyte membrane hence the production process is simple and in turn reduces corrosion and longer stack life. It requires pure hydrogen. PEM are suitable for vehicular and portable applications as they have features like quick start up, low temperature and modular. These fuel cell can also be used for stationary power generation.

- **SOFC** is a high temperature fuel cell and has promising future. Based on a negative-ion conductive electrolyte, SOFCs operate between 600 to 1000 °C, and convert chemical energy into electricity at high efficiency, which can reach up to 65% .They have higher system efficiency and higher power density. The SOFC are simpler design compared other fuel cells based on liquid electrolytes. Utilization of the exhaust heat for co-generation application in industries is very advantageous. The overall efficiency of an integrated SOFC-with CHP can even reach upto 70 to 85%. SOFC allows for internal reforming of gaseous fuel inside the fuel cell, hence hydrocarbons gases (natural gas and methane) can be used directly along with hydrogen. It is low start-up system and more thermal stresses occurs due to due to the high operating temperature.The SOFC has structure of tubular or planar. The SOFC are best suited for stationary power generation and some cases for transportation[Fuel Cell Handbook (2002), Yamamoto (2000), Caisheng (2006)].

  The SOFC has higher cell efficiency because of high temperature operation.Flexibility in fuel choices. Suitable for Distributed Generation (DG) application because of its high conversion efficiency. Integration flexibility with other power generating systems, such as automotive engines or gas turbines of various sizes. Solid oxide fuel cells can be scaled from kW-size units to MW-size units for large high-power applications, including industrial and large-scale central electricity generating stations. They can also be used in vehicles. Solid oxide fuel cells are being considered for a wide variety of applications, especially in the 5-250 kW size range in the following areas: Residential, cogeneration,Small commercial buildings and Industrial facilities. However SOFC have large start up time, slow dynamic response to load change and high cost.The schematic diagram of fuel cell connected to grid is shown in Figure 1.3.

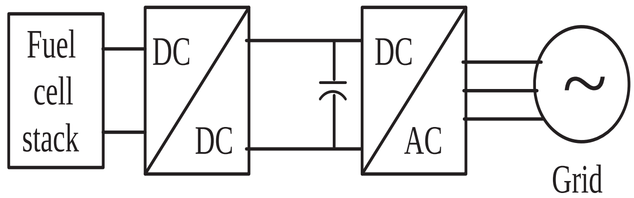


Figure 1.3: Block schematic diagram of fuel cell connected to grid.

1.2.4 Internal combustion engines

The electrical power can be generated using internal combustion (IC) engines which act as prime mover to the electrical generator. The IC engines works on the principle of combustion of fuels which gives moment to reciprocating piston. The reciprocating motion then converted to rotational power. The IC engines drives the generator in a distributed generation[Pandiaraj and Fox 2000]. These engine uses diesel, natural gas,propane, or gasoline as fuel.The Diesel generators are most popular which serves better in remote areas. These are reliable, convenient usage,less installation cost,modular and compact.These IC engines are used extensively however these system have becoming expensive due to increased fuel cost,maintenance, need to be operated with rated load for maximum efficiency, requires continuous supply of fuel and major concern is greenhouse gas emission.

1.2.5 Microturbine

Microturbine are small scale modified version of gas turbines. The MTG are high speed devices and power ranges from 25 to 500kW. The DG system are ultra low emission and feasible for stationary power generation. In most configurations, the microturbine is a single shaft machine with the compressor and turbine mounted on the same shaft as the electric generator. With a single rotating shaft, gearboxes and associated parts are eliminated. Thus, helping to improve operational reliability and reducing manufacturing costs. The rotational speeds vary in the range of 50,000 to 120,000 rpm, depending on the output capacity of the microturbine. This high-frequency output is first rectified and then converted to 50 or 60 Hz. Figure 1.4 shows the interconnection of microturbine generation system to grid [Lasseter 2001, Gaonkar et al. 2008, Saha et al. 2009].

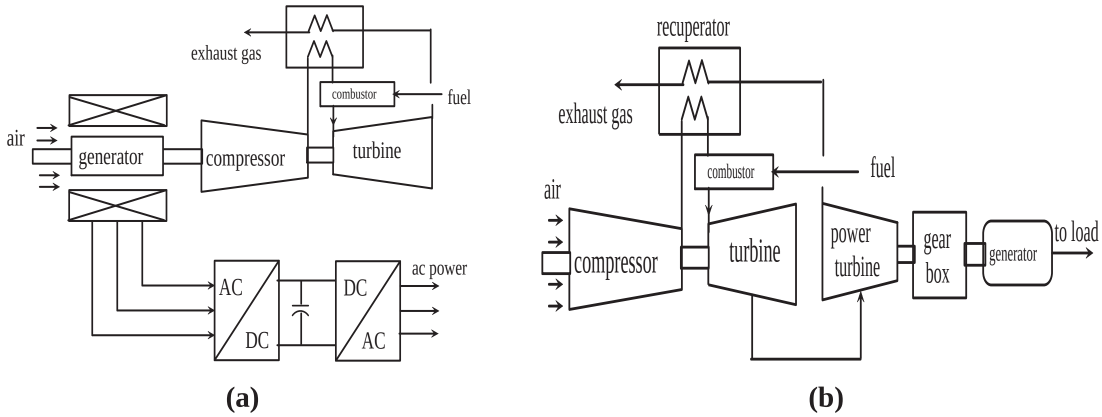


Figure 1.4: Schematic diagram of MTG system (a) single shaft MTG system (b)split shaft MTG system.

1.2.6 Other DG systems

Apart from the wind, PV, fuel cell, IC engines and MTG other technologies like geothermal,wave energy , small hydro, biomass etc are gaining importance.

Solar thermal

Solar thermal power plants make use of the thermal part of solar spectrum. Popular solar thermal application is household solar water heaters. The sunlight is concentrated by trapping the heat. The sunlight can be concentrated using different device called solar thermal collectors. The heat is then used to increase the temperature of working fluid to produce steam. The sun to heat a working fluid , which drives an engine or steam-turbine generator. Solar thermal systems use solar radiation for a heat engine to generate electricity. Applications of concentrating solar power are now feasible from a few kilowatts to hundreds of megawatts. Solar-thermal plants can be operated in parallel with grid or distributed standalone applications.

Small hydro power plants

The location where the rain fall is more and in hilly areas small rivers and seasonal water flow is available a small hydal power plant can implemented which serve local requirement. For these plants the the reservoir is optional however without storage the water is not fully utilized.In such plants the generator runs continuously in full load condition. The small hydro plant ranges upto 10MW and further divide into mini hydro and micro hydro.The generators used are can be either synchronous or asynchronous machines.The application of small hydro plants ranges from single family to small community[Ekanayake 2002, Borges and Pinto 2008].

Wave energy

Ocean wave energy is a renewable energy source with a large potential that may contribute to the increasing demand for power worldwide. Almost 75% of the earth is filled with water, a large proportion of which are the world's seas and oceans. These oceans contain a huge amount of energy in the form of ocean waves and tides. Both kinetic and potential energy associated with these traveling water waves can be exploited. For a given wave, the power is approximately proportional to its square of amplitude and to the period. The high concentration of continuously oscillating water results in high energy densities, making it a favorable form of hydro power. Wave power conversion technologies involve three main designs, on-shore or embedded near the harbor, near shore in close proximity to the seashore standing on the sea bed and off-shore in the deep waters. For large scale deployments, off-shore installments are found to be more appropriate. Wave energy can be used to generate electricity much in the same way as a traditional hydroelectric power plant by constructing a dam or barrage across a narrow bay. The turbines and gates are installed at different points along the barrage, and when there is a difference in hydrostatic head on both sides of the dam, the gates open and water flows in, rotating the turbines which are connected to generators to generate electrical power [Previsic, M. et al. (2005)].

Geothermal

Geothermal is energy available as heat emitted from within the earth, usually in the form of hot water or steam. Geothermal as a recoverable energy resource is very site specific. Geothermal power plant can range from hundreds kW to hundreds MW. [Bloomquist (2002)]. After hydropower and biomass, geothermal energy is the third most exploited energy source worldwide, with a projected installed capacity of 13.5 GW by 2012. Geothermal power can play a fairly significant role in the energy balance of some area of the world. Geothermal power plants use natural hot water and steam from below the earths surface to rotate turbine generators to produce electricity. Unlike fossil fuel power plants, no fuel is burned in these plants. Hence, geothermal power plants emit water vapors but produce no smoky emissions. Geothermal electricity can be used for the base load power as well as the peak load power demand.

There are three basic designs of geothermal power plants, all of which extricate hot water and steam from earths crust, utilize the heat content and return the warm water to the heat source to extend its life [Barun and McCluer (1993)]. In the simplest design, the steam goes directly to the turbine and then to condenser where it is condensed into water. In the second approach, the steam and hot water are separated as they exit the well, and while steam is used to drive the turbine, the water is sent back to underground. In the third approach known as Binary system, the hot water and steam is passed through a heat exchanger where the heat is extracted to heat up a second liquid (organic fluids like Iso-butane) in a closed loop and then is used to drive the turbine. The choice of the approach to be used to generate electricity is determined solely by the type of the resource, and the availability of steam or water from it.

Biomass

The biomass comprises all organic material from plants, land and water based vegetation and all organic wastes. Green plants produce biomass by converting sunlight to sugars and further to plant material through photosynthesis. The energy of sunlight is stored in chemical bonds and released to produce energy by digestion, combustion or decomposition[McKendry 2002]. Biomass comes from a huge variety of different sources. These include especially the energy stored in trees, grass crops, forestry, vegetative coal, urban wastes, agricultural wastes and forestry wastes. The wood and other forms of biomass are used as fuels for generating electricity and heat. Biomass is locally produced, cheap, and renewable source. With recent development of technologies the biomass can be used efficiently with low levels of emissions biomass becoming an attractive source. The majority of biomass electricity is generated using a steam cycle where biomass material is first converted into steam in a boiler. The resulting steam is then used to rotate a turbine that is connected to a generator. Biomass can also be used with coal to produce electricity in an existing power plant. Cofiring, as it is known, is the most economical near-term option for introducing new biomass electricity generation and lowers the air emissions from coal-fired power plants [Saifur 2003]. Municipal waste may also be used in many of the new processes developed. In terms of resource; biomass is very large, providing about 15% of the worlds primary energy. Biomass has a dominant position for the poor people in the world, who are dependent on wood fuel for cooking and heating. In fact, it plays an important role in developing countries that have large poorest regions. But it is also important in a number of industrialized countries, e.g. the United States, which obtains 4% of its energy from biomass, and Sweden with 14% [Hatziargyriou et al. (2000)].

1.3 Storage Technologies

The electrical power is always associated with stored energy. In most of cases power generation is from stored energy. The traditional power plants basically converts stored chemical energy into electrical power in difference ways. The hydel power plants are uses stored energy in the form reservoir. These forms of energy transformation is predictable controllable and output can be quantifiable.However the electrical power can not stored as it is, it has to be consumed as and when it is produced. The storage systems are used for different applications like peak load shaving, UPS and ancillary services to the grid. In case of renewable based power generation storage is essential and integral part. Hence storage of electrical power storage became very important. The storage devices are used with DG system to mitigate power fluctuations,excess energy can be stored which can avoid the curtailment renewable resources. The stored energy can be used when the generation is less than the demand. The storage are used for load transient mitigation and power balance[Sergio et al. 2010, John and David 2004, Mukund 2006].

The battery,supercapacitor,compressed air, superconducting magnetic energy storage (SMES),pumped hydro,flywheel, electric vehicles are some of storage technologies. The energy storage system can be classified on different basis. The storage devices are classified based on supply duration. The short term (in terms of minutes and second) , medium term (few hours)and long term duration (days). The long term storage comprises of biomass, hydrogen, large hydro, battery. The medium term storage may include hydrogen, compressed air,pumped hydro,flow batteries, other battery types. The ultracapacitors, redox flow cell, flywheel and SMES can be categorized in short term storage devices. The classification of energy storage technologies based type of storage is mechanical(pumped hydro,compressed air,flywheel),electrochemical (battery and hydrogen), electromagnetic (UC and SMES) and thermal (molten salt and solar pond). Among all the storage devices the battery is universal choice in most of the DG and other application. The batteries are energy dense devices and commercially available in difference type and ratings. Another emerging technology in storage is ultracapacitor which is power dense device suitable for short term high power requirement. The combination of battery and UC getting more attention due to added benefits [Sergio et al. 2010, John and David 2004].

1.3.1 Battery

The oldest storage technology is battery and dates back to 18^{th} century. The battery energy storage system (BESS) is natural choice in most applications. For the DG system it is an essential device and most essential in standalone applications. The battery used to store the excess power when generation in more and load is less. The energy can be released when generation is less and load is more, for load transients mitigation and to ensure the continuity of power supply. The battery supports in power balance and maintaining the dc-link voltage for many inverter based system. The lead acid, lithium ion (Li-ion), Nickel cadmium/Metal hydride (NiCd/NiMH),Sodium sulpher (Nas), flow batteries [Zinc bromide(ZnBr), vanadium redox (VRB),Ploysulphate(PSB)a and Zinc-air] (FBs) are different types of batteries. The most common types of battery used in electrical application is the lead acid battery. The batteries are used to smooth power fluctuations and load transient mitigations.With renewable source the battery also undergoes severe and instant discharge cycle which is detriment to battery life. The battery is best suited for constant load applications[Sergio et al. 2010, Mukund 2006].

1.3.2 Ultracapacitor

The Ultracapacitors is also known as electrochemical double layer capacitor(EDLC) and supercapacitor. It works in similar way of normal capacitor but has much higher capacitance (in terms of farads) due to its different construction from capacitor.The energy is stored by charge separation.The permitivity of dielectric and electrode surface area are high in case of UC. However the ultracapacitor has low voltage ratings. The UC has high life cycle, higher efficiency and power density. The UC can discharge completely and leads to large voltage difference which directly proportional to SOC. The ultracapacitor can be charge very quickly and discharge burst of power instantly. The UC is a very high power device and can supply power for short time duration. With proper power electronic interface UC can operate for wide range of voltages. In renewable based DG power varies very frequently and ultracapacitor can mitigate the power fluctuations effectively. The UC can be used effectively with other storage devices like battery.The battery is high energy dense device and UC is high power dense device.The battery-UC combination can easily accommodate instant and large power requirement. The battery and ultracapacitor combination is extensively used nowadays in DG application and electric vehicles [Sergio et al. 2010, Scott 1998].

1.3.3 Hydrogen storage

The fuel cell requires hydrogen to produce electricity and hydrogen is very clean burning fuel.Hydrogen do not available naturally and freely. It has to be produced from other sources of energy hence it often called as energy carrier. It is efficient mode to store and transport energy.Hydrogen can produced directly from fossil fuels or from biomass. It can also be produced from water electrolysis. Most of the hydrogen is produced from steam reforming of natural gas. The natural gas is good fuel and is exhausting fast and becoming more expensive. As it is fossil fuel produces the greenhouse gases. The properties which makes hydrogen as favorable coming age fuel are

- It is a most abundant and lightest element.
- High energy content per weight.
- The combustion of hydrogen do not produce harmful effluents.
- Hydrogen has wide flammability range.
- Can satisfy transportation, electrical and thermal needs.
- It can be generated from renewables by water electrolysis

With many benefits hydrogen usage as fuel has many issues. The regulatory guidelines, lack of infrastructure, high cost of initial building infrastructure are some of issues. The leakage may lead to explosion as it has wide explosive mix with air of all gases. Hydrogen is odorless and leakage can not be smelled. The flame and gas detectors are very essential[Mukund (2006)].

1.3.4 Other storage devices

The flywheel, pumped hydro, compressed air, superconducting magnetic energy storage and thermoelectric energy storage are few other storage technologies.The compressed air energy (CAE) storage stores the energy in the form of compressed air. The compressed air then used to rotate the turbine which acts as the prime more to the electrical generator. The CAE is complex system due to absorption and release of heat while air is compressed or expanded.The compressed air technology used in many applications. In case of grid support the energy is stored during low demand and released when load demand is high.It also used with DG applications. The pumped hydro is another storage technology where the water is lifted to higher altitude reservoir from lower water resources during lower power demand. The stored water is then released to generate power during high load demand. The power generation during the energy release is similar to hydel plants.The type of storage are used in support of grid as well with DG also. The flywheel stores energy in form of rotating mass.

It has very fast response,infinite number of charge and discharge cycles and can have very high peak power. Flywheel are of different kinds as low speed and high speed system and has one machine which act as generator cum machine to discharge and charge. These are high power system and employed in transportation and power quality improvements. The energy is stored in the form of magnetic field in case of super conducting magnetic coil. The system may consists of one or more solenoid.It is highest power densities among the storage devices. It has high efficiency and high dynamic response time. The different storage have different characteristics,configuration and different form of output. The storage device are selected depending upon application location and availability of sources [Sergio et al. 2010].

1.4 DG Interfacing Technologies

Broadly the DG outputs can be of two types. The first one is the rotating type which requires electrical generator (wind, MTG,wave, small hydro etc).The second one produces power in the dc power directly (PV and FC). The induction generator, synchronous generator and power electronic converter interface are used as per requirement.

1.4.1 Synchronous generators

Synchronous generators are rotating electric machines that convert mechanical power to electrical power. Synchronous generators are typically utilized by the following DG technologies: internal combustion engines, gas turbines, solar thermal, biomass and geothermal. Synchronous generators have the advantage, that they can be controlled to provide reactive power by adjusting their excitation. During short circuits a synchronous generator contributes large fault currents for a relatively long time. Fault currents four to five times of the rated current are normal [Krause et al. 1995].

1.4.2 Induction generators

Like synchronous generators, an induction generator is a rotating electrical machine that converts mechanical power into electrical power. Induction generators are extensively used in wind farms and small hydroelectric plants. Induction generator combined with a converter interface is currently becoming common in wind power DG. They are cheap in investment and need relatively little maintenance work. The drawback is that they cannot control voltage level in the grid they are connected to. They also need reactive power from the grid or from shunt capacitances or power electronic based reactive power generators for magnetization.

1.4.3 Power electronic converters

The power electronic converters (PECs)are integral part of DG systems. in grid connected DG systems frequency and voltage are controlled by grid. However in many DG technologies the output can not be used directly like variable wind system, PV and fuel cell. In such cases PE converter properly condition to suit the load or grid requirement. With PECs the frequency, voltage, active and reactive power are controlled with controlled distortion. The different converters are used for different DG systems. The partial power electronic converts are used in wind with DFIG system where the rating of the converter is 30% of rated wind power capacity. In case of PMSG based wind system the full scale converter are used. In case of PV and fuel cell the DC-AC(inverter), DC-DC (boost, buck or buck-boost) are used. The bidirectional converters (DC-AC-DC), matrix converters (AC-AC) are also used in many cases[Blaabjerg et al. 2004, Bimal 2013].

1.5 Microgrid System

The distributed generation is an effective and alternative solution to many issues associated with traditional power generation. DG offers environmental,economical and social benefits. The DG benefits can be enhanced my operating then both in grid connected mode and as well islanding mode. The section of grid which has sufficient generation and controlled and managed locally is termed as microgrid(MG) [Eklas et al. 2014]. The microgrid dates back to end of 19^{th} century and gained importance and commercialization taking place recently.The practical test bed of microgrid are implemented by CERT [Lasseter et al. 2011]. The microgrid consists group of DG systems with storage. The microgrid can supply power to grid in case of low demand. In microgrid the local loads are supplied uninterrupted even when grid fails. The MG offers many benefits like higher efficiency,reduction in distribution system losses and improved power quality.

The microgrid is mix of different DG system with divers characteristics and different loads. The integration,control, coordination and management is important for operation of MG. It may consists of single or combination of wind, PV fuel cell, MTG. The storage system like battery, UC and hydrogen are common systems. The microgrid can have different topologies depending upon network combination, type of DG , and voltage level. The microgrid differentiated as low voltage and medium voltage. The low voltage MG has low voltage loads and group of small generation units. In case medium voltage MGs the large generating units are connected and interface with HV line and feed both LV and MV grid. The power electronic converter are extensively used for maximum benefits.The storage improves the reliability by supplying stored energy during the low power generation from DG in case of islanded operation[Ivn et al. 2015].

The many DG in microgrid produce power in dc form. The many load requires dc power and are supplied with multiple conversion stages. The dc power based loads are increasing day by day. With the microgrid the dc loads can supplied with less number of convert stages and losses can be reduced.The dc system has major drawbacks as CB operations are complex. Many existing loads are ac hence the it is better to supply the both ac and dc loads. Microgrid can be categorized as ac,dc and hybrid. To have sustainability and reliability, the renewable energy (wind and PV) sources and controllable sources like fuel cell and MTG are employed together. The energy storage is additional and necessary component to mitigate the transients and provide backup[Estefana et al. 2015].

The microgrid test systems are successfully implemented. However microgrid poses many technical issues. The renewable makes system output fluctuating. The different energy resources, storage, load management, islanding operation, balancing of ac and dc load, interfacing are technical issues. The regulatory and economic barriers are also comes into picture. The commercial success of MG depends mainly on price, reliability, safety and convenient operation of the system. Hence the better combination of DGs, better storage, operation, coordination and management issues are need to be addressed.

1.6 Literature Review

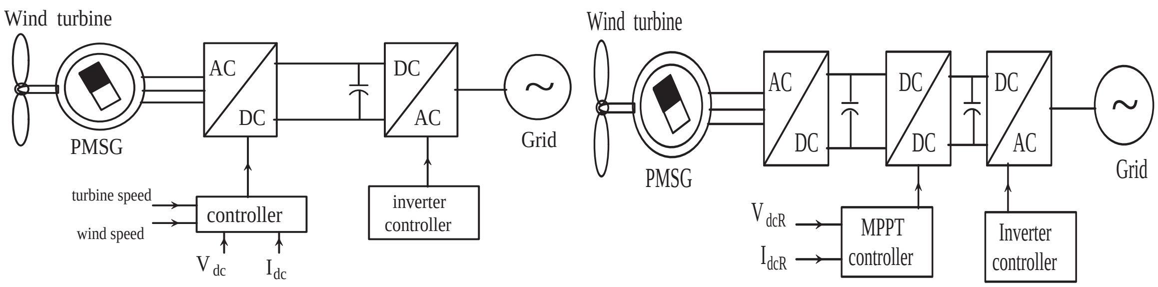
The wind based power generation is a well established technology. The wind energy conversion system (WECS) mainly consists of wind turbine, gear system (optional) and electrical generator and power electronic converter. The large wind turbines grouped together to from wind turbine and connected to medium or high voltage line. In [Jenkins 1993] introduction to the engineering of wind farms and discusses their particular implications for the distribution system. The wind generation systems are classified depending upon wind turbine control (pitch control and stall control), and type of generator used.

The wind turbine are coupled with induction generator, doubly fed induction generator, synchronous generator or permanent magnet synchronous generator to produce electrical power. The wind turbine and its control strategies with power electronic converter schemes are presented in [Blaabjerg et al. 2004]. A DFIG wind turbine model in which the power converter is simulated as a controlled voltage source, regulating the rotor current to meet the command of real and reactive power production is reported in [Lei et al. 2006]. A dynamic model of a gearless VSWT with power electronic interface was proposed for computer simulation study and the model is implemented in transient analysis program, PSCAD/EMTDC [Kim and Kim 2007].

Nowadays most WECS system employs the DFIG or PMSG. In recent years PMSG gained more importance due to several advantages. The construction is simple and do not require gear system. Hence WT construction containing no gearbox offers several advantages, namely higher overall efficiency and reliability, reduced weight and less maintenance. Due to the magnets there is no need for the external magnetization, which is important especially in stand-alone wind power applications and also in remote areas where the grid cannot easily supply the reactive power required to magnetize the induction generator [Haque et al. 2008] . Due to the small resistance losses are small.Iron losses are also small, due to the laminated stator core and the absence of the armature reaction. The overall axial length of the generator is small and correspondingly the nacelle of the wind power plant becomes simpler than with the traditional.The variable speed wind turbine with PMSG offers many advantages like higher energy conversion and efficiency[Higuchi et al. 2000] The control issues with small wind turbine is given in [Natalia et al. 2013] The standalone operation of wind turbine with MPPT capability is presented in [Nishad et al. 2012].The wind power can be effectively utilized by connecting to utility. However the grid connection of variable speed wind turbine affects the voltage and power quality [Chen and Spooner 2001] The wind system comprises of maximum power point tracking technique to yield more power by operating the system at a optimal point.

The MPPT achieved by regulating turbine rotor speed and using power converters [Arifujjaman et al. 2006, Chinchilla et al. 2006, Raza et al. 2000]. Wind system with MPPT has different control schemes mainly the most of the systems employs the generator side controller and grid side converter control. The generator side converter controller basically include the MPPT algorithm which calculates the optimum power is calculated using actual wind speed measurement or by estimation techniques. The sensor less MPPT techniques are employed which do not require wind speed measurement or the rotor position[Senjyu et al. 2004, Kelvin and Sayed 2000]. A simple sensorless MPPT is presented in [Mahmoud et al. 2012] where the rectifier outputs are used to calculate optimum power and dc-dc boost converter is controlled accordingly. The Figure 1.5 shows schematic of wind system with

MPPT.



(a) **(b)**

Figure 1.5: Schematic diagram of wind system with MPPT (a) by wind speed measurement (b)sensorless technique

The storage systems are used for peak load shaving,UPS systems,storing the energy for later use and mitigation of power fluctuations from renewable resources etc. The energy storage is integral part of the DG system. The storage device are required to store the generated power, to mitigate the fluctuation and balance power during variation in availability of natural resources and also during the load transient. The different energy storage like battery, flywheel supercapacitor technologies and their interfacing systems are discussed in [Ribeiro et al. 2001]. The different energy storage system and configuration for grid and transportation applications is given in [Sergio et al. 2010].The reference [Anurag et al. 2012] shows favorable impact on typical feeder by the storage devices with DG system. The different storage device, discharge duration with economic analysis is given in [John and David 2004].

The wind is a volatile resource, to supply the constant power and to feed the isolated system, storage units are employed.The battery is most common choice for energy storage device. The direct integration of battery and wind system with utility is presented in [Jayasinghe et al. 2011]. The wind system with battery storage in discussed in [Abedini and Nikkhajoei 2011, Lu et al. 1995]. The battery is suitable constant power delivery,however with wind system batteries undergoes deep discharge or over charge state and experiences the rapid charge/discharge profile, which results in reduced performance and life. Hence frequent replacement of batteries may required. To protect the battery from several instant discharge conditions the UC are employed along with battery. The UC or also called as double layer capacitor are high power dense devices which deliver high power for short duration of time. These devices has very high charging and discharging cycles [Burke 2000]. The combination of battery and UC has advantage over using one of them. The battery is energy dense device which can supply power for longer period while UC can deliver large burst of power for short duration of time. The two devices are required in renewable energy based power generation system. The combined operation and control methodology has been described in [Gao et al. 2005]. The wind and ultracapacitor combination is given in [Muyeen et al. 2009]. The combined use of battery and UC with wind system are shown in[Nishad et al. 2014, Wei et al. 2010]. The capacitors and flow battery combination is presented in [Ali et al. 2013]. Along with battery and UC the other storage device are used for energy storage. The flywheel, pumped hydro, superconducting magnetic coil, compressed air are few technologies used with renewable resources. These systems usage is limited with operational difficulties, multiple conversions stages, integration etc. The battery is most versatile device, nowadays with UC its performance is improved. However the batteries are limited with storage capacity, high weight to energy ratio, maintenance, release of toxic gases etc. hence a better storage medium is necessary and to store for longer periods and easy usage. The schematic of WEC system with storage is shown Figure.1.6.

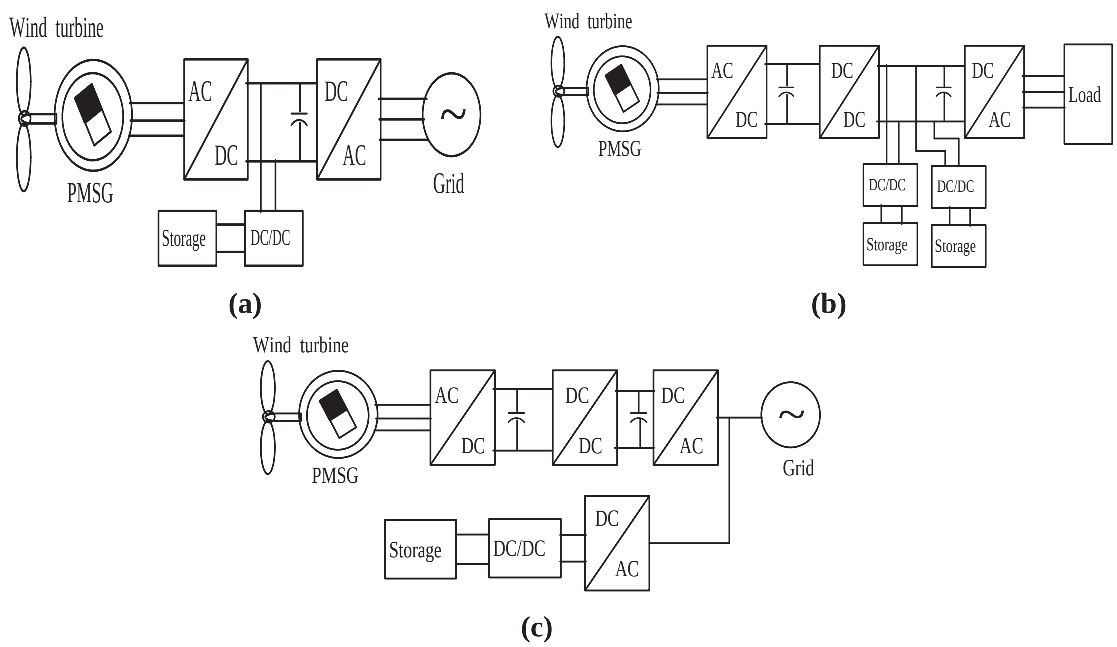


Figure 1.6: Schematic diagram of wind system (a) with single storage device (b)Multiple storage devices (c)storage directly connected to PCC.

Nowdays the hydrogen energy is gaining more importance. The hydrogen can be generated with different sources and in few industries(production of chlorine,sodium-chlorate, ethylene) it is a by product and it has been vented or burnt. However to reach sustainability in power generation renewable based hydrogen generation is preferred. The wind and PV are used generate hydrogen using water electrolyzers. The wind system with hydrogen generation is presented in [Valenciaga and Evangelista 2010, Rion et al. 2010]. With advancement in fuel cell technology and hydrogen generation by renewable resources power generation is becoming more eco friendly.The status of water electrolysis and future anticipation is given in [Alfredo et al. 2012]. The advantage of hydrogen from renewable resources is discussed in [Seyyed and Chan 2014]

Fuel cell is a electrochemical device which utilizes the hydrogen as fuel and produces dc electrical power with heat and water. The basic operating principle, types of fuel cell, advantages of fuel cell are discussed in [Cook 2002, Hashem and Caisheng]. The dynamic and transient analysis of distribution system with SOFC is given in [Kourosh and Ali 2004]. The SOFC in grid connected mode for short time overloading capacity is given in [Caisheng and Hashem 2007].The SOFC operation in islanded mode is presented in [Li et al. 2005] and in grid connected mode in [Li et al. 2007].The stability analysis of grid connected SOFC is discussed in [Du W et al. 2012]. The emission reduction by using the SOFC with storage and CHP application is shown in [Colson and Nehrir 2011].

Combining the different energy sources and operating together along with storage has the benefits over the operating them individually. The combined operation gives the more sustainability and reliability to generation system.The hybrid system has combination of fuel cell, wind, PV , microturbine, diesel generator etc. The operation of these energy sources together is complex as each has different characteristic. Another issue with hybrid system is proper load sharing between them. The hybrid system consisting of wind, fuel cell (PEM) is proposed in [Iqbal 2003]. The power control strategies of a grid-connected hybrid generation system with versatile power transfer is proposed in [Seul-Ki et al. 2008]. The hybrid system is combination of photovoltaic (PV) array, wind turbine, and battery storage via a common dc bus.

The DG system consists of energy storage system to compensate the power deficiency during transients due to slow dynamic response of system. And other reason for using energy storage is uncertainty in availability of natural resources. The battery and Ultracapacitor are most used for energy storage. The battery has high energy density and UC offers high power density. The UC provides power during transient period during which high power is required for short period. The battery supplies the power during the non availability or insufficient natural resource (wind and solar radiation). To interface the energy storage to common dc link and control power flow the bidirectional DC/DC converter is used. A schematic block diagram of Hybrid system is shown in Figure 1.7

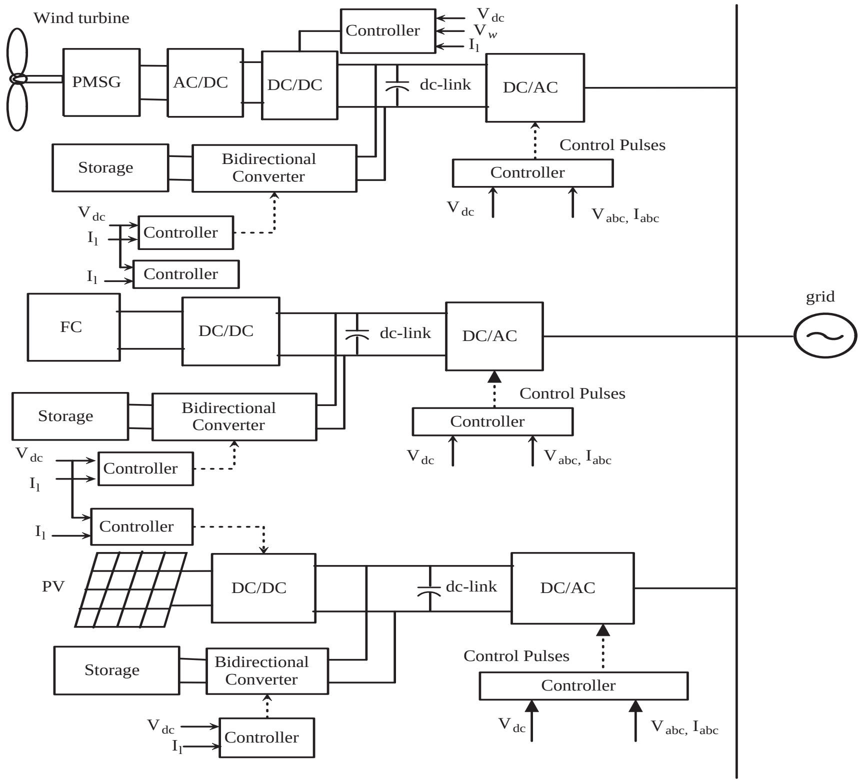


Figure 1.7: Schematic diagram of hybrid system with storage connected to dc-link.

Hybrid wind/ photovoltaic (PV)/fuel cell (FC) alternative energy system for stand-alone applications is proposed in [Caisheng and Hashem 2008]. Wind and PV are the primary power sources of the system, FC as a backup and a long-term storage system. An electrolyzer used to produce hydrogen and a common ac link is used connect the load. An overall power management strategy is designed for the proposed system to manage power flows among the different energy sources and the storage unit in the system. The fuel cell battery and UC combination is used in vehicular applications. A comparison study of three topologies of fuel-cellbattery, fuel-cellultracapacitor, and fuel-cell battery ultracapacitor for vehicular application are discussed in [Bauman and Kazerani 2008]. A control method for bidirectional converter to integrate UC with fuel cell is presented in [Samosir and Yatim 2010]. Reference [Khaligh and Li 2010] presents state-of-the-art energy-storage topologies for HEVs and plug-in HEVs (PHEVs). Battery, UC, and FC technologies are discussed and compared in this paper. In addition, various hybrid ESSs that combine two or more storage devices are addressed.

In [Gyawali and Ohsawa 2010] the control and operational aspects of fuel cell/electrolyzer /ultracapacitor (FC/ELZ/UC) unit into a micro hydro power system are given. The storage tank, electrolyzer, and UC models are presented. The control of hybrid fuel cell energy-storage distributed generation systems under voltage sag in distribution systems is proposed in [Amin et al. 2010]. The proposed control strategy makes hybrid DG system work properly when a voltage disturbance occurs in distribution system, and it stays connected to the main grid. The FC/UC hybrid system control is proposed in [Fathi et al. 2011] for industrial distribution system in island mode.

In [Wang and Lee 2010] the load-tracking performance of an autonomous hybrid power generation/energy storage system with two solid-oxide fuel cells, a diesel engine generator, a battery , two dc/dc converters, and a dc/ac inverter is addressed. This paper proposes a control scheme using the output dc current of the SOFC or the current magnitude of the ac load to modulate the hydrogen flow rate of the SOFC generation system. The SCs as a fast-dynamic energy storage system and fuel cell with electrolyzer and hydrogen tank as a longterm energy storage system is studied.The structure of the control system is divided into three levels. Two power-balancing strategies have been presented and compared for the PCU: the grid-following strategy and the source following strategy. For both of them, the dc-bus voltage and the grid power can be well regulated. The combination of fuel with PV,wind and electrolyzer leads to more efficient and environmental friendly DG system . The different combinations of PV,wind, battery,electrolyzer and UC based hybrid system are discussed with operation, control and management aspects in [Kaushik 2005, Onar et al. 2006, Bhende et al. 2011, Osman et al. 2013]

The combined operation of different DG system utilization can be maximized by operation them in grid connected mode and in islanded mode. Micrograds are part of electrical network, which have local generation and loads and can operate in islanded mode. Articles [Hatziargyriou et al. 2007, Ventakaramanan and Marnay 2008] presents an overview of research, development and demonstration of microgrid projects. The various architectures, demonstration projects, operational and control principles, field trial to date, and economic and regulatory issues are discussed. A review of the major characteristics of hybrid systems that integrates fuel cells and other technologies in electrical microgrids is discussed in [San Martin et al. 2010].These microgrids combine energy systems to produce a superior overall efficiency, compared with their separated operation. This is so, because this configuration allows compensating the limitations of some technologies in terms of: fuel flexibility, utilization of waste heat, pollution,etc. Reference [Peas Lopes et al. 2006] describes and evaluates the feasibility of control strategies to be adopted for the operation of a microgrid when it becomes isolated. The microgrid provides the more flexibility in control and operation and able to provide reliable, sustainable and quality power. The microgrid operation control and management strategies are discussed in [San Martin et al. 2010, Eduardo et al. 2014] The different control methods; active power and frequency control principles [Seon-Ju et al. 2010], robust hierarchical control system [Mohamed and Radwan 2011] are proposed to control, operate and co ordinate the multiple DG system and microgrids. A method for inner controllers of inverter-based distributed energy resources to have a suitable response for different dynamics is proposed in [Sao and Lehn 2008]. Parallel inverters in distribution networks were considered to be controlled by nonlinear robust voltage and current controller.

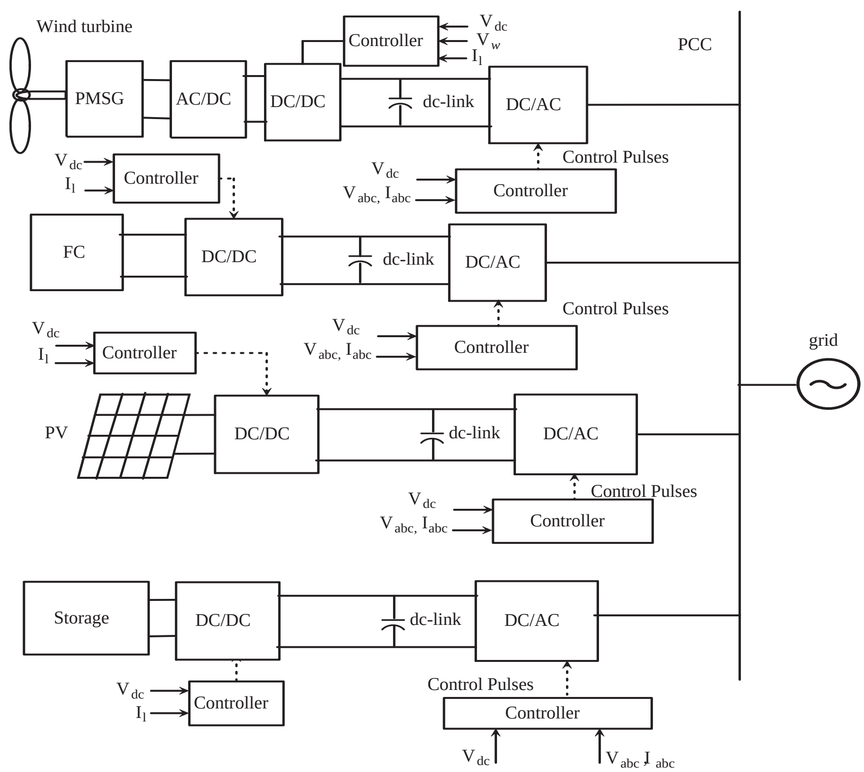


Figure 1.8: Schematic diagram of hybrid system with storage connected to grid.

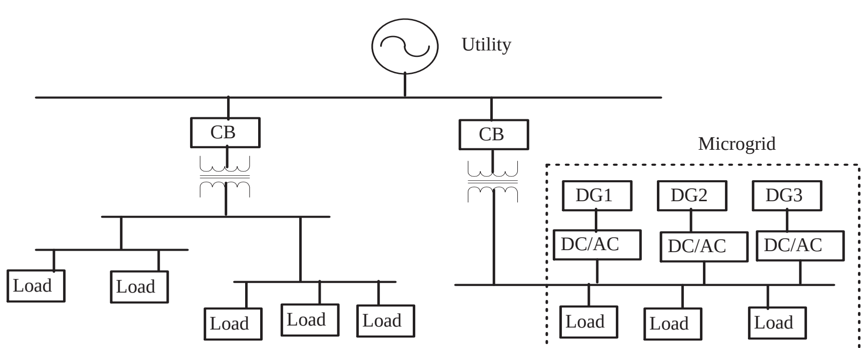


Figure 1.9: Schematic representation of microgrid.

The microgrid schematic with multiple inverters is shown in Figure 1.8. A block schematic representation of microgrid is shown in Figure 1.9

The dc loads are supplied with many conversion stages. The industries like data-centers, communication and commercial building required dc power[Daniel and Ambra 2007, Daniel et al. 2008]. The nowadays appliances like LED lighting, BLDC motors, electric vehicles are based on dc power. The dc system has many advantages[David et al. 2013, Jackson et al. 2013]. In order to supply new coming loads based on dc power, the microgrid can have flexibility is supplying both existing ac load and dc loads as well. The different ac-dc microgrid structures with DG system and storage are presented in [Hiroaki et al. 2010, Lie and Dong 2011, Poh et al. 2013]

A hybrid ac/dc micro grid to reduce the processes of multiple dc/ac/dc or ac/dc/ac conversions in an individual ac or dc grid is proposed [Guerrero et al. 2011]. The hybrid microgrid consists of both ac and dc networks connected together by multi-bidirectional converters. AC sources and loads are connected to the ac network whereas dc sources and loads are tied to the dc network. Energy storage systems are connected to dc or ac links.

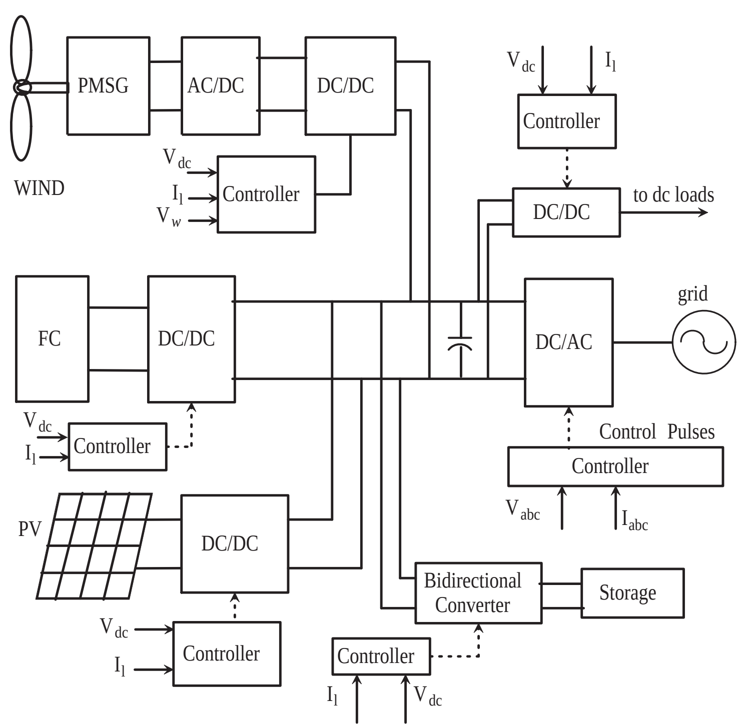


Figure 1.10: Block diagram of hybrid system with single inverters.

The microgrid schematic with single inverter to interface ac loads is shown in Figure 1.10

Microgrids are proposed and researched for the good connection with dc output type sources such as photovoltaic (PV) system, fuel cell, and secondary battery. Moreover, if loads in the system are supplied with dc power, the conversion losses from sources to loads are reduced compared with ac microgrid [Kakigano et al. 2010]. A low-voltage bipolar-type dc microgrid, which can supply super high quality power with three-wire dc distribution line is claimed in this paper. Droop control strategy, namely current feed forward control strategy, is adopted for a dc grid based multi-terminal non-grid-connected wind power system which consists of several wind turbines, high-energy-consuming (HEC) loads, energy storage devices, and a grid-connected port is proposed in [Chen et al. 2009]. A schematic of ac-dc microgrid is shown in Figure 1.11

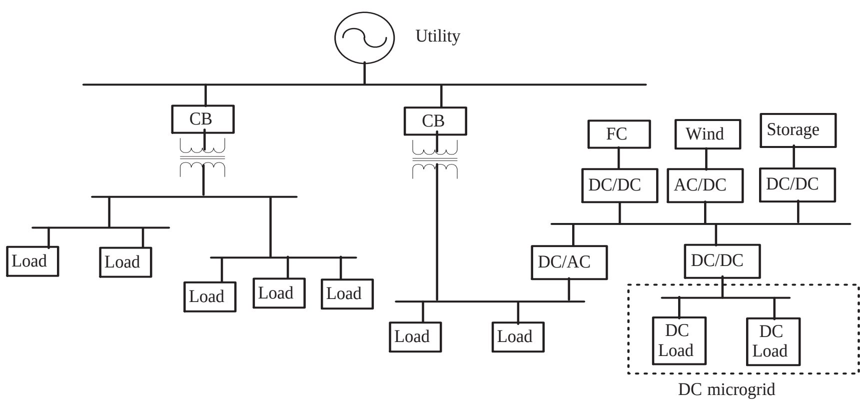


Figure 1.11: Schematic representation of dc microgrid connected to grid.

Reference [Tanaka 2009] presents a method for coordinated control of a dc power feeding system with using detailed model which considers the loss of dispersed generators and switching operation of the power converter. The proposed technique controls the dc bus voltage and the reactive power of ac system by the dc/dc converter and the ac/dc converter which is connected with each dispersed generators, dc load and infinite bus . Reference [Kurohane et al. 2011] presents a dc microgrid with renewable energy. The proposed method is composed of a gearless wind power generation system, a battery, and dc loads in a dc distribution system. The battery helps to avoid the dc over-voltages by absorbing the power of the permanent magnet synchronous generator PMSG during line-fault. The effectiveness of the proposed method is examined in a MATLAB/Simulink environment.

In [Kwasinski 2011] quantitative method to evaluate dc microgrids availability by identifying and calculating minimum cut sets occurrence probability for different microgrid architectures and converter topologies is presented. The stability issues in dc microgrids with instantaneous constant-power loads (CPLs) has been addressed in [Kwasinski and Onwuchekwa 2011]. dc microgrids typically have distributed power architectures in which point-of load converters behave as instantaneous CPLs to line regulating converters located upstream. In [Kurohanel et al. 2010] an islanding operation method of dc smart grid is presented. The power system consists of photovoltaic, wind generators and controllable loads. In this paper, the DC bus voltage fluctuations of DC grid are reduced by the photovoltaic, the wind generators and the controllable loads.

1.7 Motivation

The huge gap between generation and increasing demand, environmental issues and economical constraints are few factors influencing utilization of renewable energy resources.The deregulation of power sector and environmental, economical and many technical benefits offered by DG systems motivated the use more renewable base power generation. The wind and solar based power generation are adapted extensively as the resources are available abundantly and freely. Albeit all the benefits the renewable poses major issues as they are dependent on the nature. The fluctuating output poses many challenges to system operation.The supplying reliable and quality power along with satisfying load and grid requirements. The different DG are combined together to enhance the performance of the DG system. In order to mitigate the fluctuations the energy storage device are employed. The microgrids are gaining importance due to added benefits along with improved DG exploitation. Most renewable technologies based power generation and storage are natively direct current (dc), while the traditional utility infrastructure is almost entirely alternating current (ac). Hence the most power is being converted one or more times from ac to dc or dc to ac. With storage the conversion stages are increased more for the same original power. In converting dc to ac also many topologies are proposed where multiple inverters are used. Few studies are shown the single inverter with common dc-link. The supplying the dc and ac power with minimum conversion stages is became important. The renewables and fuel cell based microgrid is promising combination as the input for the fuel can be generated using renewable resources using electrolyzer. The combination leads to more sustainable and environmental friendly system. The use of energy storage devices can be used to store the energy for later use and to mitigate power fluctuations, load transients and improve the load following performance. The fuel cell, renewable sources and storage device based ac/dc microgrid can serve the purposes like, green power generation, smooth power delivery, reduced losses,reliable,sustainable and quality power.

1.8 Author Contributions

- The mathematical modeling of SOFC-wind based microgrid with dc load is implemented in Matlab/Simulink platform.The presented system has salient feature of connecting all sources and storage device to common dc-link. The three phase inverter is used to interface microgrid system to grid.The necessary control schemes for operation, control and coordination of dc-dc converters are implemented. The inverter control schemes for grid and isolated operation are presented.

- The performance of the wind system directly connected to grid, with battery and battery-UC combination is presented in this thesis. The effective mitigation of wind power fluctuations using battery-UC combination is shown. From the performance analysis the limitations of storage devices and the inefficient usage of wind power by adopting dump load to maintain the power balance is shown. The limited dispatchable capacity of wind system with battery and ultracapacitor combinations is given.

- The microgrid comprising of SOFC,wind, electrolyzer and UC is presented in this work. The slow dynamics response of SOFC and its effect on the load is given. The mitigation of slow dynamic response of SOFC by UC is presented. The load following capability of SOFC with ultracapacitor is presented. The effective mitigation of wind power fluctuations and its efficient usage by the electrolyzer is shown through simulation results. The dispatchable capacity of wind-SOFC with UC and electrolyzer is also presented.

- The ac/dc microgrid consisting of SOFC ,wind electrolyzer, battery and UC is implemented in Matlab/Simulink environment in this work.The battery is used for critical load supply when SOFC is out of service. The hybrid system components are connected to common dc-link to reduce multiple conversion stages. The advantage of using common dc-link for utilizing wind power by different storage devices is presented. The performance of the microgrid when the wind and SOFC are sharing the load is presented and the effects of power sharing on the SOFC performance is shown through simulation results.The control and operation of energy resources and storage devices to cater the required load for varying wind speeds and load change is given. The ac and dc loads are considered, the effects of these load change on performance of the microgrid is presented.

- The effective use of ultracapacitor to mitigates the slow dynamic response of the SOFC and to control the discharge rate of battery as per the requirement is presented in this work. The work focuses on mitigation of wind power fluctuations by electrolyzer to generate the hydrogen which can be used as input for fuel cell which leads to environmental benefits. The microgrid presented in this thesis is able to work in both grid connected mode and islanded mode of operation. The performance results presented also shows that the microgrid can supply reliable, sustainable and quality power supply with less loss.

1.9 Organization of the Thesis

Chapter 1: The general introduction of the DG systems is given in this chapter. The different wind systems, different storage technology associated with it are presented. The fuel cell technology is reported. The hybrid DG systems with different combination, storage, operation and benefits are presented. The brief literature review of hybrid DG system and microgrids are given in this chapter. The author contributions and organization of the thesis is presented.

Chapter 2: The mathematical modeling of microgrid components like wind system, solid oxide fuel cell and electrolyzer is given in this chapter. The modeling of energy storage devices battery and UC is presented. The control schemes for dc-dc boost converter is given in this chapter. The dc-dc bidirectional converter control schemes for ultracapacitor and battery operation is given. The control strategy for electrolyzer operation is presented. The buck converter control for dc loads is given in this chapter. The inverter control for grid connected mode and islanded mode of operation is presented.

Chapter 3: The wind system connected to grid is presented in this chapter. The necessity of storage device to mitigate power fluctuations to supply the constant power is presented. The wind system performance along with the battery storage is given in this chapter. The performance of wind system with battery and ultracapacitor for different wind speed and load change are presented. The performance of the control schemes for managing and controlling the charging/discharging of battery and UC is given. The usage of dump load is given. The dispatchable capacity of wind system with battery and UC is presented in this chapter.

Chapter 4: The microgrid system consisting of solid oxide fuel cell, wind system, UC and electrolyzer is presented in this chapter. The performance of microgrid system for different wind speeds and load variation is discussed for grid connected mode. The effective mitigation of wind power fluctuation by electrolyzer is given. The mitigation of slow dynamic response of SOFC by UC is presented. The effective dispatchable capacity of SOFC- wind hybrid system with electrolyzer and UC is presented in this chapter.

Chapter 5: The performance of microgrid consisting of SOFC,wind hybrid system along with the electrolyzer, battery and UC is presented in this chapter. In this chapter two case studies are considered. First one is the system performance for power sharing between SOFC and wind, second one is the SOFC is supplying load and wind power is utilized either by electrolyzer or by UC and battery as per requirement. The microgrid operation for varying wind speed, change in dc and ac loads is given. The effective control of dc-link voltage, dc load voltage, inverter voltage for islanded mode of operation is given. The microgrid operation for grid resynchronization is presented in this chapter.

Chapter 6: In this chapter conclusion and scope for future work.

Chapter 2

MODELING OF SOFC-WIND BASED MICROGRID SYSTEM

2.1 Introduction

The microgrid is a combination of different energy sources, storage devices and loads collectively operating. The different sources have different characteristics, loads have different requirement.Hence coordinated operation, control and management of the system is complex. The power output smoothing is important in renewable based microgrid. The different storage and DG systems with different combinations are used to mitigate power fluctuations.The evaluation of the system for different climatic conditions, response of the controllers and coordinated operation of different components is required. In [Osman et al. 2013]the operation and control strategies for wind and fuel cell based hybrid system in isolated mode along with battery and electrolyzer is presented. The wind system, fuel cell and diesel generator based hybrid system with electrolyzer is given in [Tomonobu 2005].The wind power fluctuations are mitigated by diesel generator and fuel cell, the hydrogen generated by the aqua electrolyzer is used for fuel cell.

The wind power and SOFC based hybrid system with battery and electrolyzer as storage devices for standalone application is reported in [Bhende et al. 2011]. In this wind system is considered as main source, and slow dynamic response of SOFC is mitigated using battery. As wind power fluctuates randomly, the battery is subjected to fluctuating charging or discharging cycle and SOFC output also varies randomly to cater required load. A microgrid based on wind system and battery with ac and dc load is discussed in[Lijun et al. 2013]. The PV and fuel cell produces the dc power, the wind system output is converter to dc power.

However the dc power is converter to ac to supply ac load and dc to cater dc loads.

The DG like PV and fuel cell produces dc power. The storage devices like battery and UC also delivers power in dc form. These system are interfaced with loads with different conversions stages. The loads like LED lighting, battery, electric vehicles, BLDC based motor loads, commercial building and datacenters requires power in dc form. These loads are supplied with multiple conversion stages. To avoid these redundant stages the dc microgrid can be adapted. A dc microgrid based on wind,PV, battery and gas turbine of a campus is presented in [Liang and Mohammad 2014].The control operation, merits and demerits of using dc microgrid is given.The dc microgrid consisting of PV , wind, fuel cell,battery and dc loads is presented in [Yu-Kai et al. 2013]. The fuzzy based controllers are used for energy management.

Nowadays the dc loads are increasing however the ac loads also need to supplied along with dc loads. The ac/dc microgrid can suffice the requirement.A smart hybrid ac/dc microgrid is presented in [Kyohei et al. 2010]. The system consists of wind system, battery, dc/ac loads and a diesel generator.A hybrid ac/dc microgrid is presented in [Xiong et al. 2011]. The energy resources with ac output are connected to ac line and resources with dc output are connected to dc bus. The ac loads are connected to ac sub grids and dc loads are to dc subgrids. The ac and dc subgrids are interfaced through bidirectional inverters. The energy management and operational modeling of hybrid ac/dc microgrdi is discussed in [Tommaso and Paolo 2014].An operational model with system and device level is presented.

In this chapter the modeling of microgrid components wind, SOFC and storage devices is given. The microgrid is implemented using Matlab/Simulink package. The controller schematic for converters of SOFC ,wind, storage devices,loads and inverter are presented.The wind system uses the PMSG, diode rectifier with MPPT controller for boost converter. The boost converter is utilized to interface the SOFC to dc-link. The battery and UC are connected to common dc-link by bidirectional dc-dc converters.The buck converters are used to feed electrolyzer and dc loads. By connecting the resources, storage devices and dc loads to common dc-link the the utilization of power from different devices may be an easy task and the switching between devices can be also convenient. The multiple conversion can be reduced. A three phase voltage source inverter (VSI) is used to interface dc-link to ac load. The different control schematic of inverter control are given. The control schemes for grid connected and islanded operation of microgrid is presented.

2.2 Modeling of Microgrid

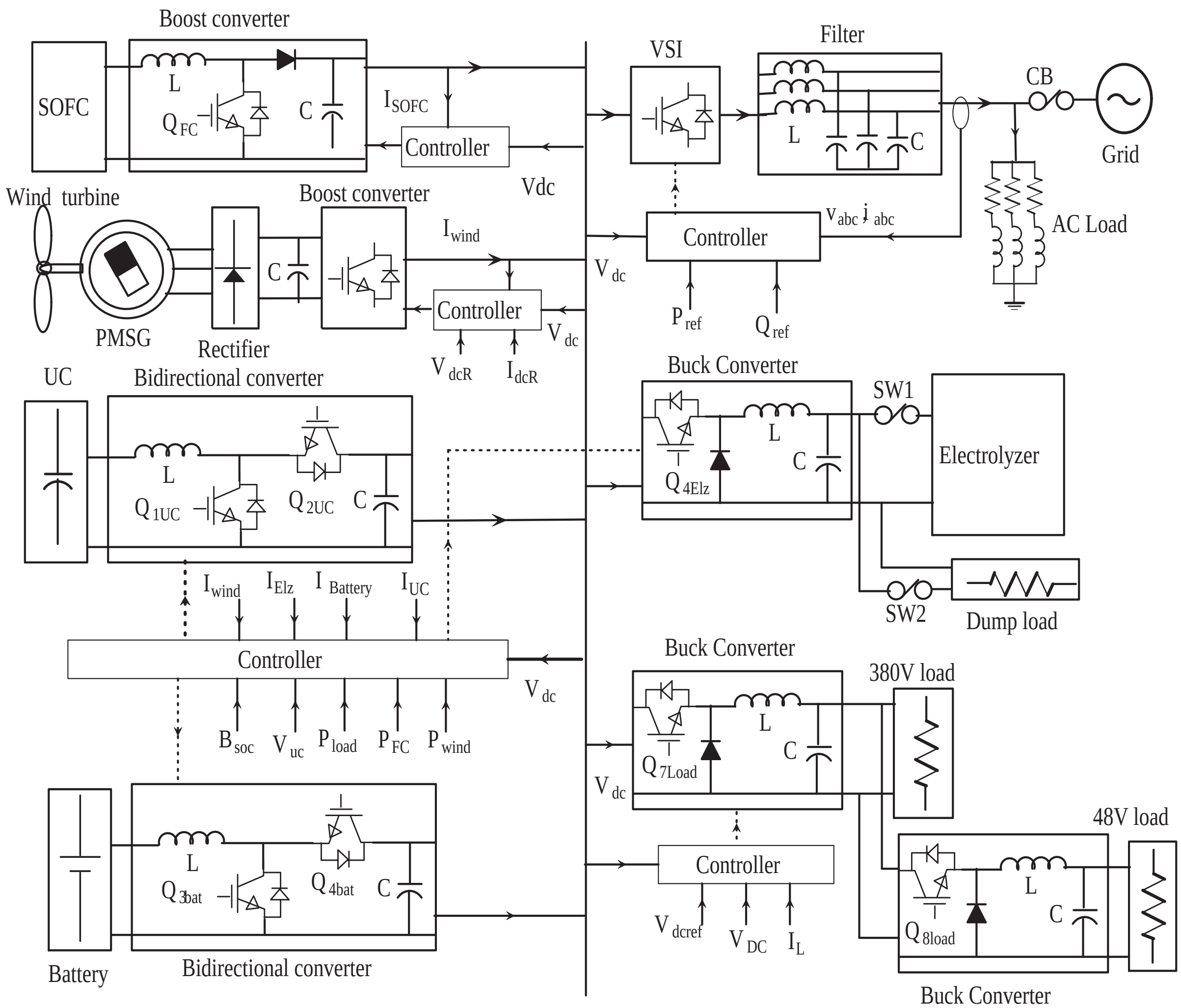


Figure 2.1: Block diagram of microgrid.

The schematic diagram of Wind-SOFC based microgrid is shown in Figure 2.1.The microgrid model consist of solid oxide fuel cell, wind turbine,battery,UC and electrolyzer. The wind turbine is coupled with PMSG. The battery and UC are used as storage devices are interfaced with dc-link through bidirectional dc-dc converter.The dc loads are connected to common dc-link. The dc loads are connected to common dc-link through buck converter. An electrolyze is used generate hydrogen from wind power. The UC plays major role in mitigating slow dynamic response of SOFC and controlling battery discharge rate. It instantly supplies the power for any increase in the load.The battery supplies minimum load when SOFC is disconnected and UC controls instant discharge of battery. A three phase voltage source inverter is used for interfacing the dc-link with ac loads. The microgrid system can be operated in grid and islanded mode. To ensure proper operation of of the system efficient control schemes need to be employed. The different situation arises in microgrid operation which are need to be anticipated. Wind power varies as wind speed varies, the SOFC voltage drops as load current increases , the terminal voltage of UC and battery decreases as the power consumed from them. The wind power variation need be followed by the battery,UC or electrolyzer. Different storage devices activated at different timing as per the situation. The transition between devices need to be smooth. The dc-link voltage has to be maintained well within the limits. The voltage and frequency are to be maintained constant at inverter side. The microgrid consist of different components and each have different characteristics. The modeling of microgrid is crucial for design and study. It is necessary to have dynamic model of system components to plan, design and study the system.

2.2.1 Wind system modeling

Wind generation system consist of wind turbine which converts the kinetic energy in wind into mechanical power.The turbine is coupled with permanent magnet synchronous generator which converts turbine mechanical power into electrical power.The PMSG output is rectified using uncontrolled diode rectifier and a boost converter is used to connect the system to common dc-link. The boost converter is controlled using MPPT technique.

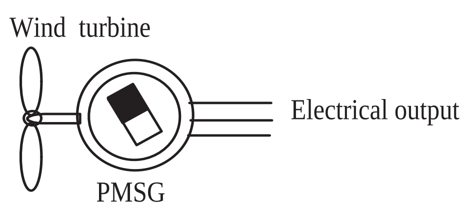


Figure 2.2: Schematic diagram of wind system.

2.2.1.1 Wind turbine

The turbine consists of aerodynamically designed blades which connected to hub. The kinetic energy in the blowing wind is converted in to rotating mechanical power by the turbine. The kinetic energy in air of mass m and speed V_w can be written as [Ackermann 2012, Mukund 2006]

$$E_w = \frac{1}{2} m V_w^2 \tag{2.1}$$

The mass of air passing through a given area$A$ at speed V_w for time period t,is

$$m = \rho A V_w t \tag{2.2}$$

The wind power from equation 2.1 and 2.2.

$$P = \frac{1}{2}\rho A V_w^3 \tag{2.3}$$

The mechanical power capture by the wind turbine can be written as [Slootweg et al. 2003]

$$P_w = \frac{1}{2}\rho A V_w^3 C_p(\lambda, \beta) \tag{2.4}$$

where ρ= air density(kg^3),A is area swept by the rotor,V is the wind speed(m/s) and C$_p$is power coefficient of the wind turbine.
The torque produced by wind turbine is given by

$$T_w = \frac{P_w}{\omega_m} = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3} C_P(\lambda, \beta) \tag{2.5}$$

where ω_m is the angular velocity of wind turbine rotor.
The tip-speed ratioλ is given in terms of rotor speed and wind speed as

$$\lambda = \frac{R\omega_m}{V} \tag{2.6}$$

where R is wind turbine rotor radius in meters ω_m=rotor speed in rad/s.

$$C_p\left(\lambda, \beta\right) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \tag{2.7}$$

Where$\lambda_i = \left[\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right]^{-1}$

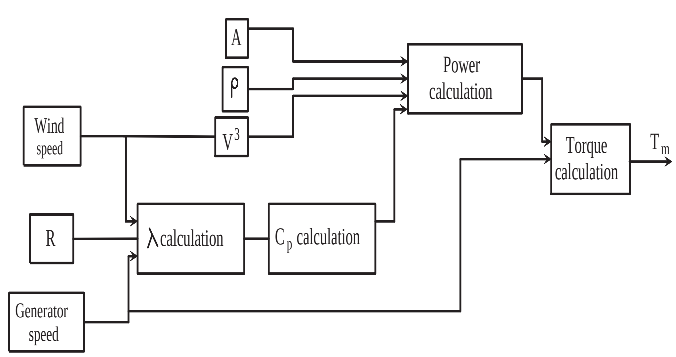


Figure 2.3: Wind turbine model.

The schematic of wind turbine simulink implementation using above expressions is shown in Figure 2.3.

2.2.1.2 Permanent magnet synchronous generator

The PMSG model is analyzed in the single phase assuming the three phases are balanced. The machine single phase model is shown in Figure 2.4

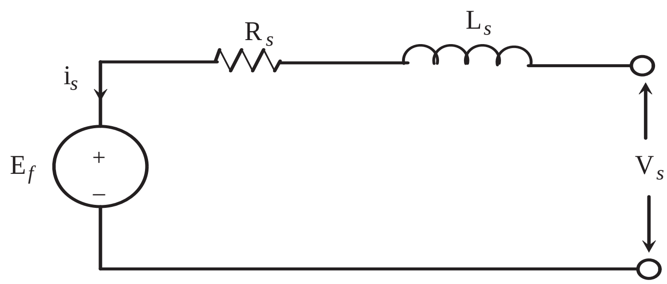


Figure 2.4: Equivalent circuit of PMSG.

The stator resistance (R_s) is the resistance of the winding and it is relatively small. The synchronous inductance (L_s) of the machine is inductance of the winding and is comprises air gap inductance,slot leakage inductance and the end turn inductance. The back electromotive force(emf) E_f is produced by the flux linkage in the stator winding from rotating magnetic field of the machine. The V_s is stator terminal voltage.

The induced emf (E_f) is given as [Polinder et al. (2006)]

$$E_f = k_{pm}\lambda_m\omega_e \tag{2.8}$$

Where:

k_{pm}= magnetic strength, λ_m=permanent magnet flux linkage,ω_e=electrical rotor angular speed. The E_f can also be expressed as

$$E_f = k_{pm}\lambda_m\frac{p}{2}\omega_m = V_s - i_sR_s - L_s\frac{di_s}{dt} \tag{2.9}$$

the electrical rotor speed is related with mechanical rotor speed as

$$\omega_e = \frac{p}{2}\omega_m \tag{2.10}$$

The terminal stator voltage of the PMSG can be presented as

$$V_s = i_sR_s + L_s\frac{d_s}{dt} + k_{pm}\lambda_m\frac{p}{2}\omega_m \tag{2.11}$$

The rate of change of total flux linking with each other stator winding (λ_s) is presented as

$$\frac{d\lambda_s}{dt} = L_s\frac{di_s}{dt} + k_{pm}\lambda_m\frac{p}{2}\omega_m \tag{2.12}$$

Substituting equation 2.12 into 2.11, the terminal voltage equation of PMSG can be expressed as

$$V_s = i_sR_s + \frac{d\lambda_s}{dt} \tag{2.13}$$

Assuming zero sequence quantities are not present and applying Parks transformation the expression 2.13 can be written in d-q frame [Borowy and Salameh (1997)]. The machine model voltage equation in d-q rotating frame where d-axis is fixed to the permanent magnet rotor flux direction are written as [Monica et al. 2006, Luminita et al. 2013]

$$V_s = v_{sd}jv_{sq}; i_s = i_{sd} + ji_{sq} \tag{2.14}$$

$$v_{sd} = R_si_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_m\lambda_{sq} \tag{2.15}$$

$$v_{sq} = R_si_{sq} + \frac{d\lambda_{sq}}{dt} - \omega_m\lambda_{sd} \tag{2.16}$$

$$\lambda_{sd} = L_{sd}i_{sd} + \lambda_m \tag{2.17}$$

$$\lambda_{sq} = L_{sd}i_{sq} \tag{2.18}$$

Putting equation 2.17 and 2.18 in 2.15 and 2.16 respectively.

$$v_{sd} = R_si_{sd} + L_{sd}\frac{di_{sd}}{dt} = \omega_mL_{sq}i_{sq} \tag{2.19}$$

$$v_{sq} = R_si_{sq} + L_{sq}\frac{di_{sq}}{dt} = \omega_mL_{sd}i_{sd} + \omega_m\lambda_m \tag{2.20}$$

In generating mode the power flows in reverse mode. Hence the sign conversion need to be considered in the generator model.As a result the voltage of PMSG in d-q frame can be written as

$$v_{sd} = -\left(R_si_{sd} + L_{sd}\frac{di_{sd}}{dt}\right) + \omega_mL_{sq}i_{sq} \tag{2.21}$$

$$v_{sq} = -\left(R_s i_{sq} + L_{sq}\frac{di_{sq}}{dt}\right) - \omega_m L_{sd} i_{sd} + \omega_m \lambda_m \tag{2.22}$$

The electrical torque (T_e) can be expressed as follows

$$T_e = 1.5p\left(\lambda_{sd} i_{sd} - \lambda_{sq} i_{sd}\right) \tag{2.23}$$

Substituting 2.17 & 2.18 in 2.23 the torque can be presented as

$$T_e = 1.5p\left(\lambda_m i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}\right) \tag{2.24}$$

By considering the PMSG is non salient, the air gap is uniform and d-q inductances are same. Hence the torque equation can be expressed as

$$T_e = 1.5p\lambda_m i_{sq} \tag{2.25}$$

The wind turbine and PMSG parameters are referred from [Goel et al. 2010].

Maximum Power Point Tracking

Maximum power can be extracted from turbine when turbine operates at optimum C_p. Hence it is necessary to adjust the rotor speed at optimum λ [Mahmoud et al. 2012].

$$\begin{aligned} P_{opt} &= 0.5\rho A C_{p\_opt}\left(\frac{\omega_{r\_opt} R}{\lambda_{opt}}\right)^3 \\ &= K_{opt}^{\omega_{r\_opt} 3} \end{aligned} \tag{2.26}$$

where

$$K_{opt} = 0.5\rho A C_{p\_opt}\left(\frac{R}{\lambda_{opt}}\right)^3 \tag{2.27}$$

$$\omega_{r\_opt} = \frac{\lambda_{opt}}{R} v_w = K_w v_w \tag{2.28}$$

The generator side converter can be controlled to extract maximum power from wind. It is necessary to adjust the rotor speed at λ_{opt} to extract maximum power. The control scheme consists of uncontrolled rectifier followed by dc-dc boost converter. The control scheme has to adjust duty ratio of boost converter to achieve the maximum power. The generator speed can be estimated by using the output voltage (V_{dc_R}) and current (I_{dc_R}) of the rectifier. The generator speed,PMSG parameter and voltage and current can be given as

$$\omega_g = \frac{2\pi(V_{dc\_R} + 2R_s I_{dc\_R})}{60\left(\frac{3\sqrt{3}}{\pi}K_m - \frac{P}{2}L_s I_{dc\_R}\right)} \tag{2.29}$$

The reference power can be estimated as

$$P_g^* = K_{opt}^{(\omega_g)3} \tag{2.30}$$

From the reference power the reference current can be calculated as

$$I_{dc}^* = \frac{P_g^*}{V_{dc}} \tag{2.31}$$

The error between the reference current and the measured current used to generate control signal.

2.2.2 Solid oxide fuel cell

Fuel cell is a electrochemical device which utilizes the hydrogen as fuel and produces dc electrical power with byproduct as heat and water. The chemical reaction between fuel and oxidant lead to the flow of electrons through the closed circuit between electrodes.The anode and cathode electrodes which are dipped in electrolytes. The process of flow of electron remains as long as fuel and oxidant are provided to the fuel cell. The fuel cells are extremely efficient, simple, have virtually no emissions and they run silent. Currently different types of fuel cells are being widely explored for various applications.

One of the most promising fuel cell technologies is the solid oxide fuel cell in power production, due to its solid state design, internal reforming of gaseous fuels, high temperature operation (1000°C) in addition to its high efficiency [Kaushik 2005]. The numbers of cells are connected in series to form a stack and get the desired output power. The schematic of internal structure of fuel cell is shown in Figure 2.5. The basic operating principle, types of fuel cell, advantages of fuel cell are discussed in [Cook 2002, Chris and Scott 2003, Fuel Cell Handbook 2002, Hashem and Caisheng 2009]. To design, develop and evaluate the performance of the fuel cell based power system the dynamic model of fuel cell is required.

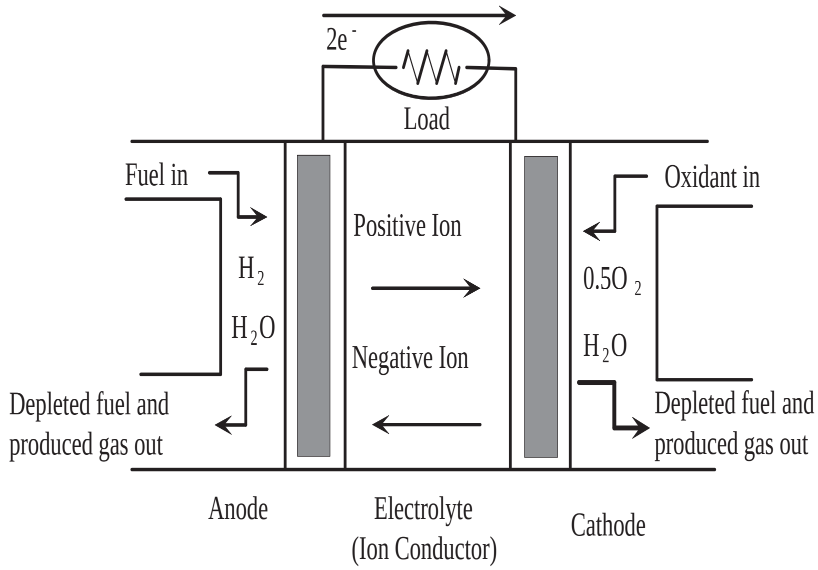


Figure 2.5: Schematic diagram of SOFC.

Transient model considering the temperature dynamics is presented in [Hall and Colclaser 1999] and a fuel cell stack model with power electronic converter interface is developed in [Padulls et al. 2000]. An analytical model for evaluation of fuel cell efficiency is developed in [Thorstensen 2001]. The types of fuel and fuel reforming processes are given. A thermodynamic model of tubular SOFC with internal reformer is proposed. The reference [Zhu and Tomsovic 2002] presents the dynamic model of SOFC with control strategies. The combined operation and control of SOFC-MT are presented considering the system in stand alone mode. The dynamic model of SOFC considering the thermal and electrochemical properties along with the ohmic, activation and concentration losses is given in [Kourosh and Ali 2004]. A physically based dynamic model of tubular SOFC using the material conservation, electrochemical , temperature and diffusion equations is proposed in [Caisheng and Hashem 2007]. The model emphasizes on the fuel cell electrical characteristic. The dynamic model of fuel cell are developed considering different parameters as per study requirement.

For mathematical model of solid oxide fuel cell the following limitations are considered [Padulls et al. 2000]

- Fuel cell is supplied with hydrogen and oxygen
- Ideal gases are considered, their chemical and physical properties are not affected by pressure.
- Nernst equation is applicable.

- The pressure drop across the electrode channels is negligible.
- Fuel cell temperature is constant
- The ratio of pressure between the inside and outside of the electrode channels is sufficient to consider choked flow.
- Ohmic, activation, and concentration losses are considered.

The fuel cell is a electrochemical device with no moving part generates electricity by electrochemical reaction. It quite modular and reliable device. Fuel cell uses hydrogen as fuel and oxygen as oxidant from air for chemical reaction.The water and heat are by products of the fuel cell.The fuel cell has higher efficiency in comparison with internal combustion engines.The electrochemical reaction occurs in the solid oxide fuel cell is given below

$$anode \tag{2.32}$$
$$H_2 + O^2 \rightarrow H_2O + 2e^-$$
$$cathode \tag{2.33}$$
$$\frac{1}{2}O_2 + 2e \rightarrow O^{2-}$$
$$overallreaction \tag{2.34}$$
$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

An choked orifice can be represented by following relation

$$\frac{W}{P_u} = K\sqrt{M} \tag{2.35}$$

Where,

- W= mass flow rate (Kg/s)
- K = valve constant (depending upon area of orifice)
- P_u = upstream pressure
- M = Fluid molar mass

The utilization factor (U_f) is defined as the ratio of amount of fuel that reacts to the amount of fuel injected.

$$U_f = \frac{m_f H_2^r}{m_f H_2^{in}} \tag{2.36}$$

Where,

- U_f=Utilization factor
- $m_f H_2^r$= Hydrogen which reacts with oxygen
- $m_f H_2^{in}$= Hydrogen which enters anode

From the utilization factor definition the equation 2.35 can be written as

$$\frac{Wan}{P_{an}} = K_{an}\sqrt{(1-U_f)M_{H_2} + U_f M_{H_2O}} \tag{2.37}$$

Where,

- Wan= mass flow through the anode valve (kg/s)
- K_{an}=the anode valve constant $\sqrt{kmolkg/(atms)}$
- M_{H_2} = molecular masses of hydrogen (kg/kmol)
- M_{H_2O} = molecular masses of water
- P_{an}= the pressure inside the anode channel (atm)

By considering the molar flow of any gas through valve to be proportional to partial pressure inside the channel, the following relations can be deduced [Padulls et al. (2000)].

$$\frac{q_{H_2}}{P_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = k_{H_2} \tag{2.38}$$

$$\frac{q_{H_2O}}{P_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = k_{H_2O} \tag{2.39}$$

Where,

- q_{H_2} & q_{H_2O} : molar flows of hydrogen and water respectively.
- P_{H_2} & P_{H_2O} : the partial pressures of hydrogen and water respectively(atm).
- K_{an}:anode valve constant
- K_{H_2} & K_{H_2O}: valve molar constant for hydrogen and water respectively.

From above equations the following expression can be deduced.

$$\frac{m_f}{P_{an}} = K_{an}\left[(1-U_f)\sqrt{M_{H_2}} + U_f\sqrt{M_{H_2O}}\right] \tag{2.40}$$

The partial pressures calculations: From the ideal gas law the partial pressure of hydrogen can be given as [Padulls et al. (2000)],

$$P_{H_2}V_{an} = n_{H_2}RT \tag{2.41}$$

Where,

- V_{an} =volume of the anode channel
- n_{H_2}= hydrogen moles in the channel
- R=universal gas constant
- T=operating temperature of the fuel cell stack

From equation 2.41

$$P_{H_2} = \frac{n_{H_2}RT}{V_{an}} \tag{2.42}$$

by taking the derivative of equation2.42

$$\frac{d}{dt}\left(P_{H_2}\right) = \frac{d}{dt}\left(\frac{n_{H_2}RT}{V_{an}}\right) \tag{2.43}$$

$$= \frac{q_{H_2}RT}{V_{an}} \tag{2.44}$$

Where,q_{H_2} is the time derivative of n_{H_2} and it represents the molar flow (kmol s^{-1}) of hydrogen.

The The hydrogen molar flow is further divided into three parts and as input, output and reacted flow and is represented as

$$\frac{d}{dt}P_{H_2} = \frac{RT}{V_{an}}\left(q_{H_2^{in}} - q_{H_2^{out}} - q_{H_2^{r}}\right) \tag{2.45}$$

Where $q_{H_2^{in}}$= input molar flow rate of hydrogen, $q_{H_2^{out}}$ =input molar flow rate of hydrogen and $q_{H_2^{r}}$= molar hydrogen flow rate that reacts in the channel in (kmol/s).

From the electrochemical relationships the molar flow of hydrogen that reacts is given as

$$q_{H_2^r} = \frac{N_0 I}{2F} = 2K - rI \tag{2.46}$$

Where,

- N_0= number of cells connected in series in the stack
- F=Faradays constant(C/kmol)
- I=fuel cell stack current (A)
- K_r= modeling constant which is given as follows

$$K_r = \frac{N_0}{4F} \tag{2.47}$$

From equations 2.45 and 2.46, the time derivative of hydrogen partial pressure can be given as

$$\frac{d}{dt}\left(P_{H_2}\right) = \frac{RT}{V_{an}}\left(q_{H_2^{in}} - q_{H_2^{out}} - 2K_r I\right) \tag{2.48}$$

Replacing the output flow by equation 2.38, the expression for partial pressure of hydrogen can be expressed by taking the Laplace transform both sides followed by isolation of hydrogen partial pressure.

$$P_{H_2} = \frac{1/K_{H_2}}{1 + \tau_{H_2} s}\left(q_{H_2^{in}} - 2K_r I\right) \tag{2.49}$$

Where K_{H_2}=Valve molar constant of hydrogen, K_{H_2}=Hydrogen flow response time, K_r= constant,I_{fc} = Fuel cell current and τ_{H_2}= system pole associated with hydrogen flow and given as

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2} RT} \tag{2.50}$$

In similar way the partial pressure oxygen and water can be written as

$$P_{O_2} = \frac{1/K_{O_2}}{1 + \tau_{O_2} s}\left(q_{O_2^{in}} - 2K_r I\right) \tag{2.51}$$

$$P_{H_2O} = \frac{1/K_{H_2O}}{1 + \tau_{H_2O} s}\left(2K_r I\right) \tag{2.52}$$

Where, K_{O_2} and K_{H_2} are valve molar constant for oxygen and water respectively.

The fuel cell voltage is very small, around 1.2 V. Due to low output voltage the number of fuel cell are connected in series to get the required power rating. There are many factors contributes to losses in the fuel cell.

The expression for stack output voltage V_{stack} of a fuel cell can be obtained applying Nernsts equation and also taking into account the voltage losses such as the ohmic, activation and mass transportation (concentration) losses.

The fuel cell stack voltage can be written as

$$V_{stak} = nE_0 - V_{act} - V_{con} - V_{ohm} \tag{2.53}$$

Where n is number of cells connected in series, E_0 is the standard electrode potential in (V),V_{act} is the activation loss in (V), V_{con} is the concentration loss in (V), V_{ohm} is the ohmic loss within the fuel cell in (V).

$$E = \left[E_0 + \frac{RT}{2F} log\left[\frac{P_{H_2} P_{0_2}^{1/2}}{P_{H_2}O}\right]\right] - rl \tag{2.54}$$

Where P_{H_2}, $P_{H_2}P_{0_2}^{1/2}$ and $P_{H_2}O$ are the partial pressures of hydrogen oxygen and water respectively. E=fuel cell output voltage, E_0=open cell voltage (based on the Gibbs free energy) R= gas constant, r=ohmic losses of the stack, I= fuel cell stack current. The schematic SOFC simulink model is shown in Figure 2.6. The SOFC parameters are referred from the [Zhu and Tomsovic (2002)]

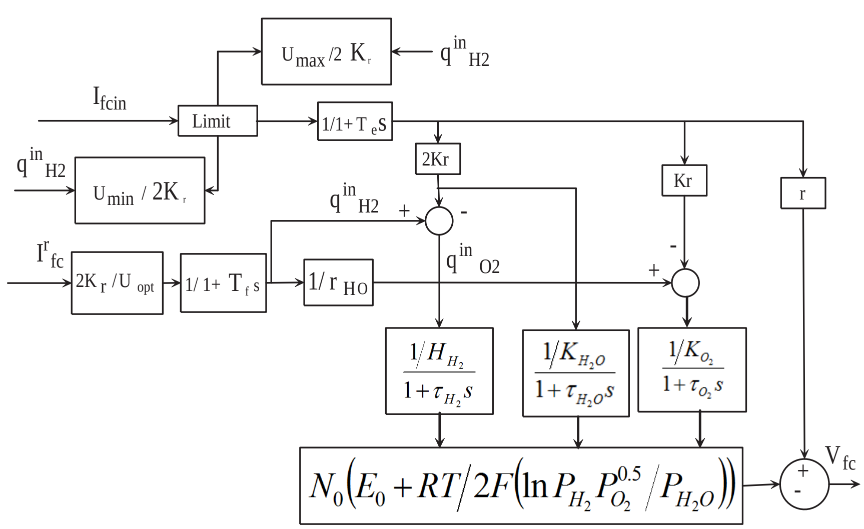


Figure 2.6: Simulink implementation of SOFC model.

Storage devices

The electrical power is most predominant form of power as it can be efficiently converted into other forms. However it can not be stored easily in bulk.Most of electrical power is consumed as it is generated which can be regulated. The renewable based power generation faces difficulties as load and generation both varies. The storage devices are integral part of renewable sources to supply the constant power. The storage devices are necessary to ensure the continuity of the power supply. The most common storage device is the battery.To supply the burst of power for short period the UC are used. The battery and UC can serves the power requirement satisfactorily. In recent days the hydrogen is also used for energy storage which can store for long periods.

2.2.3 Ultracapacitor

The ultracapacitor is an electrochemical device which stores energy in the form of electrostatic charge. The UC has large capacitance value ranging from Farad to thousand of Farads and are used where burst of power required for short duration. Ultracapacitor stores energy in a polarized liquid layer at the interface between a conducting ionic electrolyte and a conducting electrode.The electrodes have high surface area, porous material having pores of nanometer size. The surface of UC is much higher than the normal capacitor. The basic schematic of ultracapacitor construction is shown in Figure 2.7.

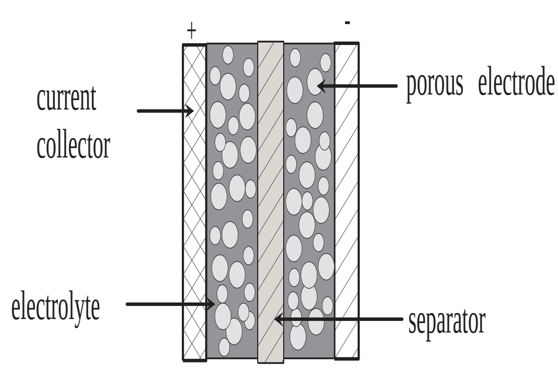


Figure 2.7: UC basic construction.

The basic operating principle , construction, design are described in [Burke 2000, Namisnyk 2003]. The double layer capacitor technology and circuit models are presented in [Spyker and Nelms 2000 , Nelms et al. 2003]. The UC model is presented by classical equivalent circuit using capacitance and resistance is given in [Onar et al. 2006, Uzunoglu and Alam 2006, product giude 2009].

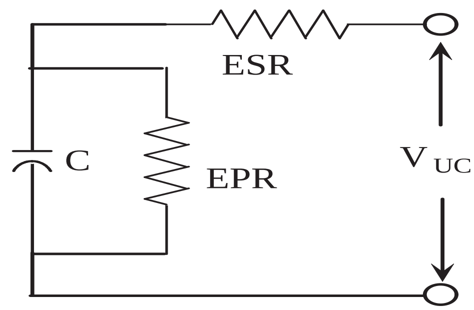


Figure 2.8: Equivalent circuit UC.

The UC model is presented by classical equivalent circuit using capacitance and resistance as shown in Figure 2.8.In the figure C is capacitance, ESR and EPR represents the equivalent series and parallel resistances. The energy delivered by the ultracapacitor is given as in 2.55

$$E_{UC} = \frac{1}{2}C\left(V_i^2 - V_f^2\right) \tag{2.55}$$

Where E_{UC} is the energy delivered by the UC, V_i and V_f are initial and final value of terminal voltages of UC respectively and C is capacitance.The UC comes in small voltage range hence to have required capacitance voltage the UC are connected in series and parallel combination.By taking a particular rating of capacitor from the data sheet and taking the number of ultracapacitors in series (n_s) and parallel (n_p) the total capacitance and resistance are calculated as

$$R_{UC\_total} = n_s \frac{R_{esr}}{n_p} \tag{2.56}$$

$$C_{UC\_total} = n_p \frac{C}{n_s} \tag{2.57}$$

2.2.4 Battery

Battery is most commonly used storage device in most of the applications. It stores the energy in electrochemical form. There are two types of batteries primary and secondary. The primary battery types are non reversible and discarded once fully discharged. The secondary batteries also known as rechargeable batteries where chemical reaction is reversible. The battery can be recharged many times. It may range from fraction of ampere-hour to hundreds.The lead acid batteries are regularly used in power application. The schematic of basic construction of battery is shown in Figure 2.9.The lead acid battery consists of two electrodes, one is anode and other one is cathode. The Active matter in positive plate cathode is made of lead dioxide PbO_2. The negative plate anode is made up of lead Pb.The electrolyte is sulphuric acid. Depending upon the process (charging or discharging) the cathode can serve as anode or vice-versa. The battery capacity is represented in Ampere-hours(Ah). The battery capacity is not constant, varies according to how quickly it is discharged.

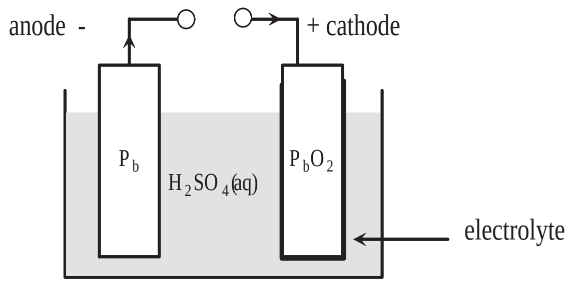


Figure 2.9: Basic construction of battery.

The different battery models have been presented in literature. The battery mathematical and equivalent circuit model are presented in [Gu, H. 1990, Casandra and Salami 1992, Salami et al 1992]. A new dynamic model of battery is presented in [Ceramic 2000]. The battery model based on mathematical and circuit oriented approach in given [Li and Kr (2011)]. Thevenin battery model is simple one and is represented with capacitance and resistance consisting of controlled voltage source in series with constant resistance.

The Thevanin equivalent circuit diagram [Salameh et al. 1992] of battery is shown in Fig.2.10

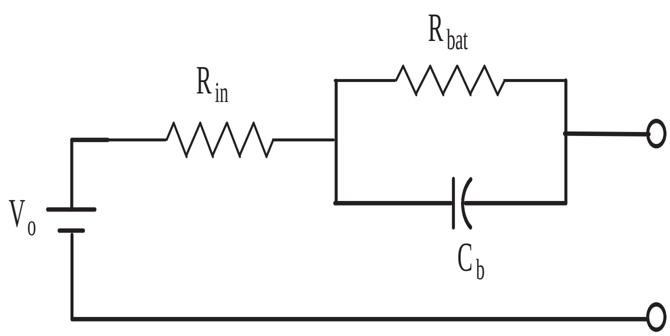


Figure 2.10: Equivalent circuit diagram of battery.

The C_b is the capacitance,R_b is the resistance and R_{in} is the internal resistance.The equivalent capacitance C_b is given as

$$C_b = \frac{kw \cdot \Delta h * 3600 * 1000}{0.5\,(V_{ocmax}^2 - V_{ocmin}^2)} \tag{2.58}$$

Where:$kW \cdot h$=battery rating, V_{ocmax}^2=maximum voltage (V),V_{ocmin}^2= minimum voltage (V)

2.2.5 Electrolyzer

The electrolyzer is electrochemical device which converts electrical energy into chemical energy which produces hydrogen. Hydrogen can be produced by water electrolysis.The water electrolysis can be carried out with different electrolyzers like alkaline and acidic.

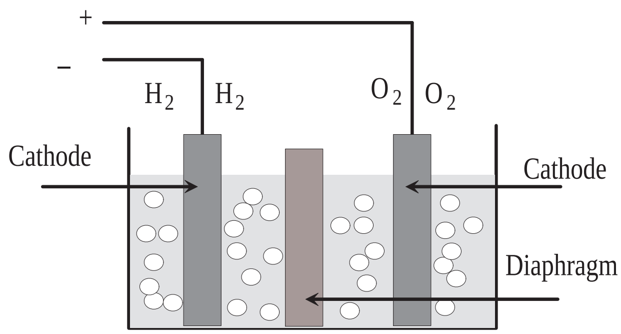


Figure 2.11: Schematic of electrolyzer operation.

As the water molecule is composed of hydrogen and oxygen atoms, it is decomposed by passing direct electric current (dc) through electrodes separated by a electrolyte (KOH) with good ionic conductivity. The water is poor ionic conductor hence the conductive electrolyte is used, so that reaction can take place at acceptable voltage.The half and overall reaction are given as follows.

$$Anode \quad halfreaction: \qquad (2.59)$$

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

$$Cathode \quad halfreaction: \qquad (2.60)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

$$Overall \quad reaction: \qquad (2.61)$$

$$H_2O+ \rightarrow H_2\frac{1}{2}O_2$$

The empirical relation between current and voltage of the electrolyzer is given by 2.62 [Gyawali and Ohsawa 2010].

$$v_{cell} = u_0 + \frac{r1 + r_2T}{A}I_e + u_1 log\left(1 + \left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)\left(\frac{I_e}{A}\right)\right) \qquad (2.62)$$

Where, v_{cell} = voltage drop, u_0 = thermodynamic cell voltage, T = temperature (C), $\frac{I_e}{A}$ = current density (A/m^2), A= cell electrode area (m^2), $r1, r_2$ = ohmic resistance parameter, t_1, t_2, t_3 and u_1= over voltage parameters. n= number of cells. V=voltage across the electrolyzer.

According to Faradays law the rate of hydrogen produced is directly proportional to current passing through it. The molar hydrogen production rate can be is given as [Onar et al. 2006]

$$n_{H_2} = \frac{\eta_F n I_e}{2F} \tag{2.63}$$

Where n_{H_2} = hydrogen produced (mol/s), η_F = Faraday efficiency, n = number of electrolyzer cells in series, F=Faraday constant, I_e =electrolyzer current.

The ratio between actual and theoretical maximum hydrogen produced in electrolyzer is known as the Faradays efficiency and ca be written as

$$n_F = 96.6e^{\left(96.6/I_e - 75.5/I^2\right)} \tag{2.64}$$

The hydrogen produced from electrolyzer is stored in a storage tank. The hydrogen stored is either in the form of liquid or in compressed gas. The pressure in hydrogen storage tank is given as

$$P_b - P_{bi} = Z\frac{N_{H_2} R T_b}{M_{H_2} V_b} \tag{2.65}$$

Where, $P_b \& P_{bi}$ are tank pressure and initial tank pressure respectively. z = compression factor, N_{H_2}= hydrogen sent to tank (mol/s), R= Universal gas constant, T_b =temperature, M_{H_2}= Molar mass of hydrogen (kg/kmol). The electrolyzer parameters are referred from [Gyawali and Ohsawa 2010]. The simulink implementation of electrolyzer is given in Figure 2.12

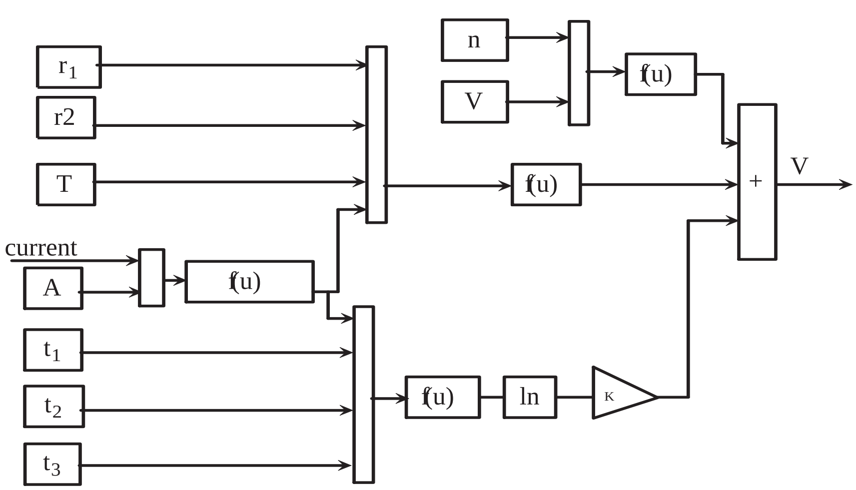


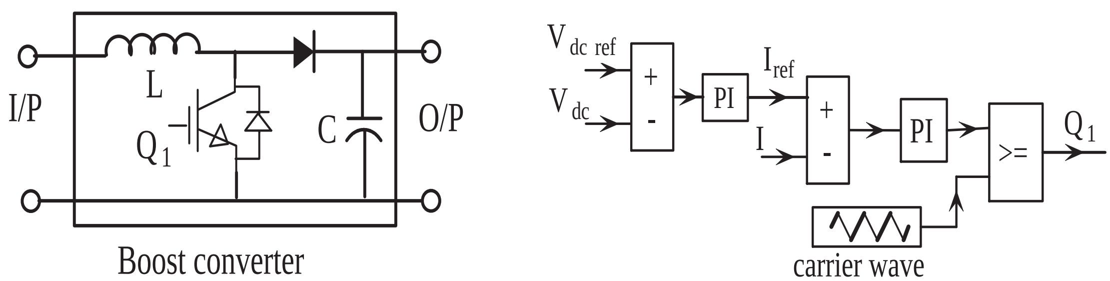
Figure 2.12: Simulink implementation of electrolyzer.

2.3 Power Electronic Converters

The power electronic converters are integral part of DG system. The converters facilitates the operation, control and coordination of different devices together. The main converters are boost,buck-boost,buck and inverter. To increase or decrease and regulate the output voltage boost or buck converter are required. To facilitate the bidirectional flow of power dc-dc buck-boost converters are used. To convert the dc to ac voltage the inverter is used.

2.3.1 Boost converter

The boost converters are use to step up voltage to higher level and for regulation of output voltage. The SOFC produces the lower voltage and it decreases as load increase. A boost converter is necessary to regulate and increase the input voltage to higher voltage level.The step up converter mainly regulates the dc-link voltage. It is a class of converter consists of at least two semiconductor device and at least one storage element [Andujar et. al. 2008, Choe et al. 2007]. The filters are used to reduce output voltage ripple. The schematic diagram of boost converter is shown in Figure 2.14.



(a) **(b)**

Figure 2.13: Schematic diagram of (a) boost converter (b)controller.

For the time period DT when switch is on, the inductor voltage cab be given as [Daniel 2010, Ned et al. 2003]

$$V_L = V_s = L\frac{di_l}{dt} \qquad or\frac{di_l}{dt} = \frac{V_s}{L} \tag{2.66}$$

The change in the inductor current is given as

$$(\triangle i_L)_{cl} = \frac{V_s DT}{L} \tag{2.67}$$

The switch is open for (1-D)T time period.Assuming the output voltageV_0 is constant, the voltage across inductor can be written as

$$V_L = V_s - V_0 = L\frac{di_L}{dt} \quad or \frac{d_L}{dt} = \frac{V_s - V_0}{L} \tag{2.68}$$

Change in the inductor when switch is open is given as

$$(\triangle i_L)_{op} = \frac{(V_s - V_0)(1-D)T}{L} \tag{2.69}$$

The net change in inductor current must be zero, from equation 2.67 & 2.69

$$(\triangle i_L)_{cl} + (\triangle i_L)_{op} = 0 \tag{2.70}$$

$$V_0 = \frac{V_s}{1-D} \tag{2.71}$$

Equation 2.71 represents the output voltage as a function of the duty cycle. The equivalent resistance of load can be given as

$$R = \frac{V_{out}^2}{P_{rated}} \tag{2.72}$$

The duty ratio is

$$D = 1 - \frac{V_{in}}{V_{out}} \tag{2.73}$$

The inductor current is given as

$$I_L = \frac{V_{in}}{(1-D^2)R} \tag{2.74}$$

From specified input current ripple (20%) and switching frequency (f_s).

$$\frac{\triangle i_L}{I_L} = \frac{D(1-D)^2 R}{f_s L} \Longrightarrow L \geq \frac{5D(1-D)^2 R}{f_s} \tag{2.75}$$

The small signal model of boost converter [Akshay]

$$\begin{bmatrix} sL & 1-D \\ 1-D & -\left(sC + \frac{1}{R}\right) \end{bmatrix} * \begin{bmatrix} i_L(s) \\ \hat{v_0}(s) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} * \hat{d}(s) + \begin{bmatrix} V_0 \\ I_L \end{bmatrix} * \hat{v_{in}}(s) \tag{2.76}$$

$$\begin{bmatrix} i_L(s) \\ \hat{v_0}(s) \end{bmatrix} = \begin{bmatrix} sL & 1-D \\ 1-D & -\left(sC + \frac{1}{R}\right) \end{bmatrix}^{-1} * \begin{bmatrix} V_0 \\ I_L \end{bmatrix} * \hat{d}(s) + \begin{bmatrix} sL & 1-D \\ 1-D & -\left(sC + \frac{1}{R}\right) \end{bmatrix}^{-1} * \begin{bmatrix} 1 \\ 0 \end{bmatrix} * \hat{v_{in}}(s) \tag{2.77}$$

$$\frac{\hat{i_L}(s)}{\hat{d}(s)} = \frac{(V_0)s + 2)(1 - D)I_L}{(LC)s^2 + \frac{L}{R}s + (1 - D)^2} \tag{2.78}$$

voltage loop transfer function

$$\frac{v_0(s)}{i_L(s)} = \frac{(1 - D)}{Cs + \frac{1}{R}} \tag{2.79}$$

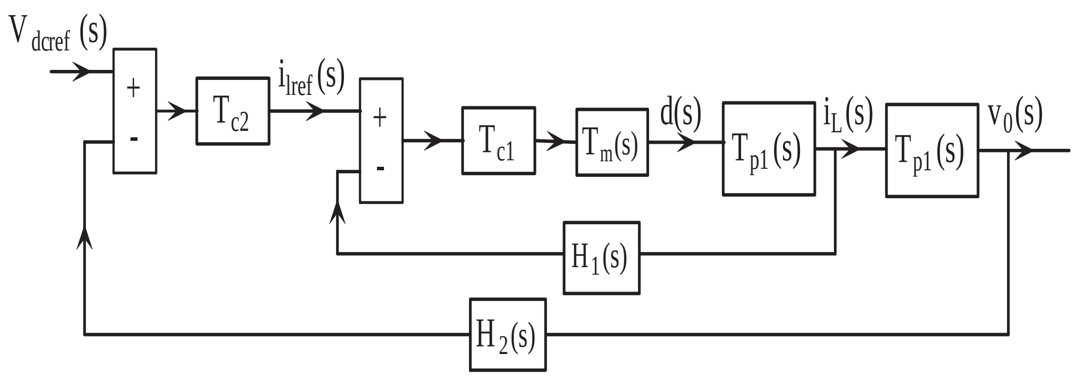
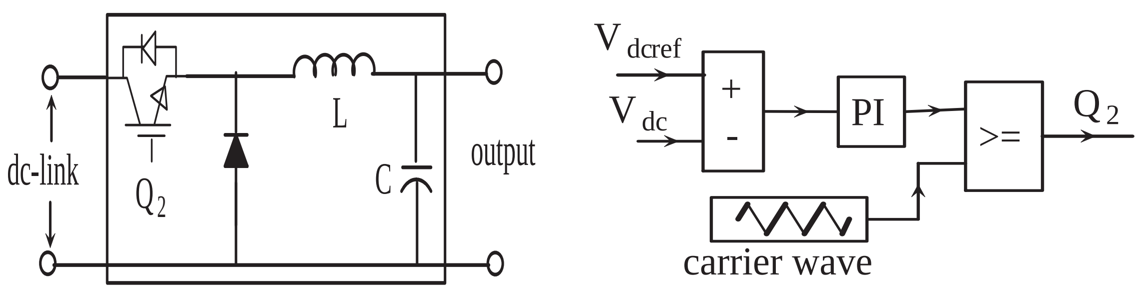


Figure 2.14: Schematic digram of control system.

2.3.2 Buck converter

The buck converter are use to step down the voltage. The electrolyzer, dc load and dump loads are fed by the buck converter. The bidirectional converter acts as buck converter during the charging of UC/battery.



(a) **(b)**

Figure 2.15: Schematic diagram of (a) buck converter(b)controller scheme.

The circuit operates in two conditions when switch is on and off. The switch is operated by switching pulses. When the switch is on,diode is reverse biased and conducts the inductor in forward direction.During this the positive voltage builds across the inductor and

increases gradually[Xu et al. 2004.].The modeling buck converter as follows [Daniel 2010, Ned et al. 2003].
Output voltage and current during on period is given as

$$V_L = V_d - V_0 \tag{2.80}$$

$$i_L = \frac{1}{L} \int V_L dt \tag{2.81}$$

Change in the inductor current can be derived as

$$V_L = V_d - V_0 = L\frac{d_i}{dt} \tag{2.82}$$

$$\frac{di_L}{dt} = \frac{v_d - V_0}{L} \tag{2.83}$$

Assuming ideal conditions, change in the inductor current by time duration can be given as

$$\frac{di_L}{dt} = \frac{\triangle i_L}{\triangle t} = \frac{\triangle i_L}{DT} \tag{2.84}$$

from 2.83 and 2.84

$$\triangle i_L = \frac{V_d - V_0}{L} \cdot DT \tag{2.85}$$

When the switch is off diode will be forward biased. Current will flow through diode. The voltage across the inductor is given as

$$V_L = V_0 \tag{2.86}$$

$$V_L = -V_0 = L\frac{di}{dt} \tag{2.87}$$

$$\frac{di_L}{dt} = \frac{-V_0}{L} = \frac{\triangle i_L}{\triangle t} = \frac{\triangle i_L}{(1-D)T} \tag{2.88}$$

$$\triangle i_L = \frac{-V_0}{L}(1-D)T \tag{2.89}$$

For steady state operation, change in inductor current is zero over period of time. Hence from equations 2.85 & 2.89

$$\frac{V_d - V_0}{L}(DT) + \left(\frac{-V_0}{L}\right)(1-D)T = 0 \tag{2.90}$$

Equation 2.90 can be reduced to

$$V_0 = DV_d \tag{2.91}$$

Small signal model can be deduced similar to the boost converter. The output voltage to to duty ratio is given as

$$\frac{v_0 s}{d(s)} = \frac{V_{in}}{LC\{s^2 + [(\frac{s}{RC}) + (\frac{1}{LC})]\}} \tag{2.92}$$

The inductor can be calculated as

$$L \geq \frac{(1-D)}{2f}R \tag{2.93}$$

The capacitance to reduce output voltage ripple can be calculated as

$$C = \frac{(1-D)}{8Lf^2 r} \tag{2.94}$$

Where

$$r = \frac{\triangle V_0}{V_0} \tag{2.95}$$

The bidirectional converter boost and buck mode operation is controlled separately.The buck operation of bidirectional converter and buck converter of electrolyzer are operated using current mode control scheme. The dc load buck converters are operated using voltage mode control. The dc loads are consider as resistances. The controller parameters are chosen from procedures given in Akshay, Deepak and Mariesa 2014, Caisheng 2006], trail and error methods and fine tuned for required performance.

2.3.3 Voltage source inverter

The voltage source inverter (VSI) are used to converter dc power to ac and act as interface between the dc-link and ac link. The inverter consists of six power electronic switches.The schematic of three phase VSI is shown in Figure 2.16. The inverter is of typical three phase six switch PWM voltage source inverter. The VSI converts the power from the dc voltage source to three phase ac outputs. Pulse width modulation techniques are used control the voltage source inverter output. In SPWM three balanced sinusoidal control voltages are compared with the same triangular voltages. The triangular waveform is at a switching frequency, which is generally much higher than the frequency of the control voltages and is called as carrier frequency. The three phase sinusoidal control signals with the same frequency are used to modulate the duty ratios of switching pulses for the switches.The resistive and inductive elements are used for ac load representation.

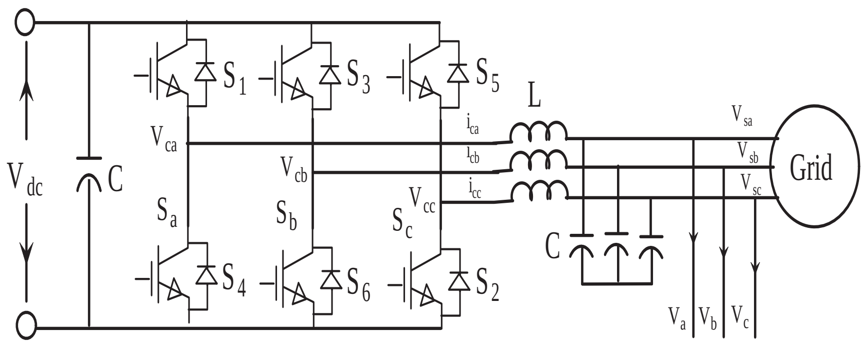


Figure 2.16: Schematic diagram of control system.

Power flow analysis is used on the simplified circuit, where the impedance represents the combined filter and transformer inductance. The active and reactive power flows from the converter are controlled by magnitude and phase of the converter output voltages relative with grid parameters. The active power flow is controlled by varying the phase difference and reactive power flow is by varying the magnitude of inverter output. The phase difference and amplitude are varied with reference to constant grid voltage. The control of modulation index controls amplitude, and synchronization and phase angle control of modulating sine wave controls the phase variation. The real and reactive power delivered to the utility is given by following relations.

$$P = \frac{EV_s}{Z} Cos(\Theta_Z - \delta) - \frac{E^2}{Z} Cos(\Theta_Z) \tag{2.96}$$

$$Q = \frac{EV_s}{Z} Sin(\Theta_Z - \delta) - \frac{E^2}{Z} Sin(\Theta_Z) \tag{2.97}$$

Where:

$$Z = \sqrt{R^2 + Z^2} \tag{2.98}$$

$$\Theta_Z = tan^{-}1(\frac{1}{XR}) \tag{2.99}$$

To operate an inverter, mainly two kinds of control can be adopted: the active and reactive power control scheme (PQ control), when the inverter is operated to meet a given real and reactive power set point and the control of active power and voltage (PV control), when the inverter is controlled to supply the load with fixed values of voltage and frequency.

2.3.3.1 Active power and reactive power control

The PQ or active and reactive control scheme is used with grid connected systems. The voltage and frequency references are supported by the grid. A LC filter is connected at the terminals of inverter to minimize the harmonics. The schematic of inverter is shown in Figure 2.16. In this scheme real and reactive powers injected into the grid are completely depend on the amplitude and angle of the sending-end voltage source.The dc bus voltage is mainly determined by the inverter ac output voltage and the voltage drop across the filter. A lower bound on the dc bus voltage can be determined from the following relation (2.100) at a unity power factor[Ned et al. 2003].

$$\frac{\sqrt{3}}{2\sqrt{2}} maV_{dc} \geq \sqrt{V_{LL}^2 + 3(\omega L_f I_{ac})^2} \tag{2.100}$$

Where:

(V_{acll})=Line- line RMS voltage on the inverter side, (L_f)=Filter inductance, (I_{ac})=Maximum possible RMS Value of the ac load current, ma=Modulation index of the inverter.

The three phase voltages can be written as

$$\begin{aligned} V_{ca} \frac{V_{dc}}{3}(2S_a - S_b - S_c) \\ V_{cb} \frac{V_{dc}}{3}(-S_a + 2S_b - S_c) \\ V_{cc} \frac{V_{dc}}{3}(-S_a - S_b + 2S_c) \end{aligned} \tag{2.101}$$

The three phase current can be given as

$$\begin{aligned} \frac{di_{ca}}{dt} = i_{ca} = -(R_c/L_c)i_{ca} + (v_{sa} - V_{ca})/L_c \\ \frac{di_{cb}}{dt} = i_{cb} = -(R_c/L_c)i_{cb} + (v_{sb} - v_{cb})/L_c \\ \frac{di_{cc}}{dt} = i_{cc} = -(R_c/L_c)i_{cc} + (v_{sc} - v_{cc})/L_c \end{aligned} \tag{2.102}$$

The total instantaneous power in the three phase system can be written as

$$p(t) = v_a i_a + v - b i_b + v_c i_c \tag{2.103}$$

The active power can be represented in synchronous frame as

$$P = \frac{3}{2}(V_{gd} i_d + V_{gq} i_q) \tag{2.104}$$

The reactive power can be represented in synchronous frame as

$$Q = \frac{3}{2}(V_{gq} i_d + V_{gd} i_q) \tag{2.105}$$

When the reference frame is synchronized with voltage, the active and reactive power can be written as

$$P = \frac{3}{2}(V_{gd} i_d) \tag{2.106}$$

$$Q = \frac{3}{2}(V_{gd} i_q) \tag{2.107}$$

The d and q axis components is synchronous frame with decoupling terms are given as

$$u_d = R_c i_d + L_c \frac{di_d}{dt} + V_{gd} - \omega L_c i_q \tag{2.108}$$

$$u_q = R_c i_q + L_c \frac{di_q}{dt} + V_{gq} - \omega L_c i_d \tag{2.109}$$

In the PQ control, the real and reactive power exchanged with the grid are variables controlled by the inverter, since they have to meet the reference power. The PQ control will fail on an isolated grid due to the absence of a voltage reference. In order to have a faster response the active and reactive power channels of the inverter are decoupled. In particular, a Park transformation of the inverter output currents and voltages from the physical a-b-c reference frame to the stationary d-q reference frame allows to make use of the correlation existing between active power and direct current component (i_d) and between reactive power and quadrature current component (i_q) [Gaonkar et al. 2008]. The current are given to PI controllers which produces the voltage set points $v_{d_{ref}}$ and $v_{q_{ref}}$. These voltage references are properly compensated to get voltage references u_d and u_q in the dq frame. The u_d and u_q then converted into a-b-c form which will be given to PWM generator. The PLL provides angel reference which is required to abc-dq and dq-abc conversion and to synchronize with grid. The schematic implementation of PQ control scheme is shown in Figure 2.17.

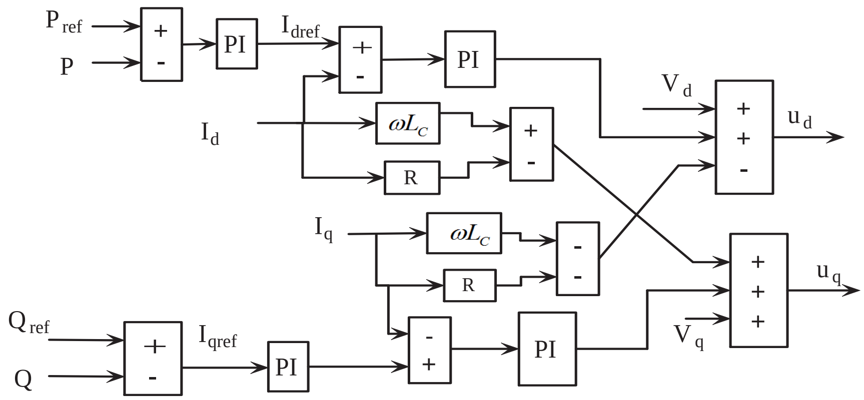


Figure 2.17: PQ control scheme

2.3.3.2 Voltage and frequency control

The islanded mode operation of microgrid has different requirement. The absence of grid the output voltage and frequency need to be maintained constant [Gaonkar et al. (2008)].The frequency of the system can be controlled by controlling the amplitude and frequency of control signal to the inverter.The schematic of control system is shown in Figure 2.18.

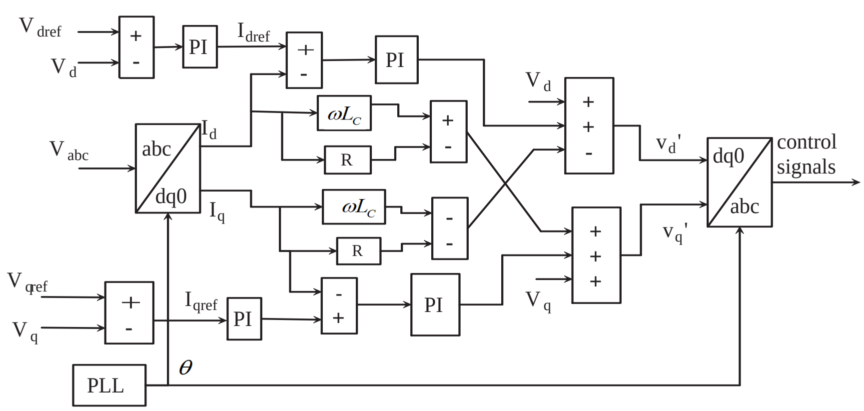


Figure 2.18: v/f control scheme

The Inverter supplies the load at fixed frequency and voltage.By using the park transformation the direct and quadrature reference voltage (V_{dref}) and (V_{qref}) can be calculated. An internal voltage signal at required frequency can be used to generate the reference signal. The voltage at inverter inverter terminal can be written as

$$\begin{bmatrix} V_a \\ V_b \\ Vc \end{bmatrix} = \begin{bmatrix} V_{a1} \\ V_{b1} \\ Vc1 \end{bmatrix} + R_c \begin{bmatrix} I_a \\ I_b \\ Ic \end{bmatrix} + L_c \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ Ic \end{bmatrix} \tag{2.110}$$

Where R_c is resistance, L_c is inductance of the filter and I_a,I_a,I_a are load currents. The d-q-axis load voltage can written as

$$V_d' = V_d + i_d R_c + L_c \frac{di_d}{dt} - \omega L_c i_q \tag{2.111}$$

$$V_q' = V_q + i_q R_c + L_c \frac{di_q}{dt} - \omega L_c i_d \tag{2.112}$$

The voltages V_d' and V_q' are used as control signals to generate the PWM pulses. The voltage and current loops parameters are obtained as given in the [Caisheng 2006, Hashem and Caisheng 2009]

The LC filter is used to minimize high frequency components.The cutoff frequency of LC circuit is given by [Milan and Timothy 2003 , Wang et al. 2003, Samul and Fernando 2007, Khaled et al. 2007]

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{2.113}$$

The current and voltage ripple can be chosen as 10%- 15% of rated current and power for inductor and capacitance calculations.

$$\triangle i_{Lmax} = \triangle i_L \times V_{dc} \times L \times f_s \tag{2.114}$$

$$C = \frac{\%Q \times P_{rated}}{2 \times \pi \times f \times V_{rated}^2} \tag{2.115}$$

2.4 Conclusion

The dynamic model are built to study the microgrid performance. In this chapter the modeling of wind,solid oxide fuel cell along with battery, ultracapacitor, electrolyzer is given.The modeling of power electronic converters are presented with control schemes. The Matlab/simulik model has been implemented using the theoretical equations. The microgrid model presented can be used to study the performance in grid connected and islanded mode operation.The system uses a common dc-link to interface all components. Hence multiple stages can be reduced and utilization of wind power among different device is convenient. The model presented has feature of mitigating SOFC slow dynamics and battery discharge rate control using ultracapacitor. The wind power is used to charge the UC, battery and to generate hydrogen. The dc and ac loads both are considered for the study.

Chapter 3

PERFORMANCE STUDY OF MICROGIRD WITH WIND AND STORAGE SYSTEMS

3.1 Introduction

The wind based power generation is increasing fast and more and more wind based power generation systems are integrating into electrical system. The technology has evolved significantly and well developed over period of time. The wind system produces fluctuating power due to random wind speed variations depending upon natural conditions. The fluctuating wind power may cause adverse effect on the connected system [Larsson 2002]. In grid connected systems the deficit power can be met by grid, hoverer in stand alone mode it is difficult to supply the load with wind system alone. To mitigate the fluctuating power generation and supply the constant power the energy storage devices are employed along with wind system.

To smooth wind power output the storage system are adopted. The storage devices like battery, UC, compressed air, flywheel, pumped storage etc are employed to store the wind power[Sergio et al. 2010]. Among the storage devices the battery is most common choice due to high energy density [Abedini and Nikkhajoei 2011, Gamini et al. 2011].The battery is not suitable for fluctuating loads as it has operating limitations like, deep and instantaneous discharge issues which affects life of the battery. It has high weight to energy ratio, releases toxic gases.For better life of battery its discharge rate need to be controlled or maintained constant [Anthony et al. 2013].

Another significant storage device which can overcome few drawbacks of battery is ultracapacitor which has high power density and can deliver fluctuating power instantly [Abbey and Geza 2007, Gamini et al. 2013].However UC is not suitable for long duration power requirement. The battery and UC combination can provide better solution to address the drawbacks of each device in supplying varying generation and load. The combination of battery and UC which can support each other as instant power requirement is supplied by the UC and long duration power requirement is supplied by battery [Ali et al. 2013]. The combined operation of battery and UC to support each other a proper and efficient control scheme is necessary. The UC has to compensate the deficit power for the time duration, from time instant the power requirement is increased till battery reaches the desired power level gradually. The coordinated control operation of battery-UC combination has to control discharge rate of battery as ultracapacitor suffices the requirement by releasing the power instantly for any load change and decreases as the battery power increases.

In this chapter the performance of wind system connected to grid without and with storage is presented. The wind based power generation model for grid connected mode has been implemented.The PMSG is adapted with uncontrolled rectifier. A comprehensive analysis of wind system with battery, battery-UC combination and without storage in grid connected mode is given. The performance of the wind system without storage in grid connected mode is presented with Matlab/Simulink simulation results. The system performance for inverter output, PCC voltage and frequency presented for variation in wind speed and change in load are discussed.

The wind system with storage in grid connected mode is presented in subsequent sections considering the two cases. The performance of wind system with battery presented for different wind speeds, load variations, charging and discharging of the battery. For case study two wind system connected to grid with battery and ultracapacitor is considered. The performance analysis is given for UC-battery coordination and control to supply the load for varying wind speed, control of battery discharge rate and charging/discharging of battery and UC. The control schemes are presented and dump load is considered for both case studies. An effective control scheme is presented to operate the battery -UC combination to make wind system dispatchable to overcome the storage devices limitations. The performance of system is presented with simulation results for the wind system operation in grid connected mode.

3.2 Microgrid with Wind System

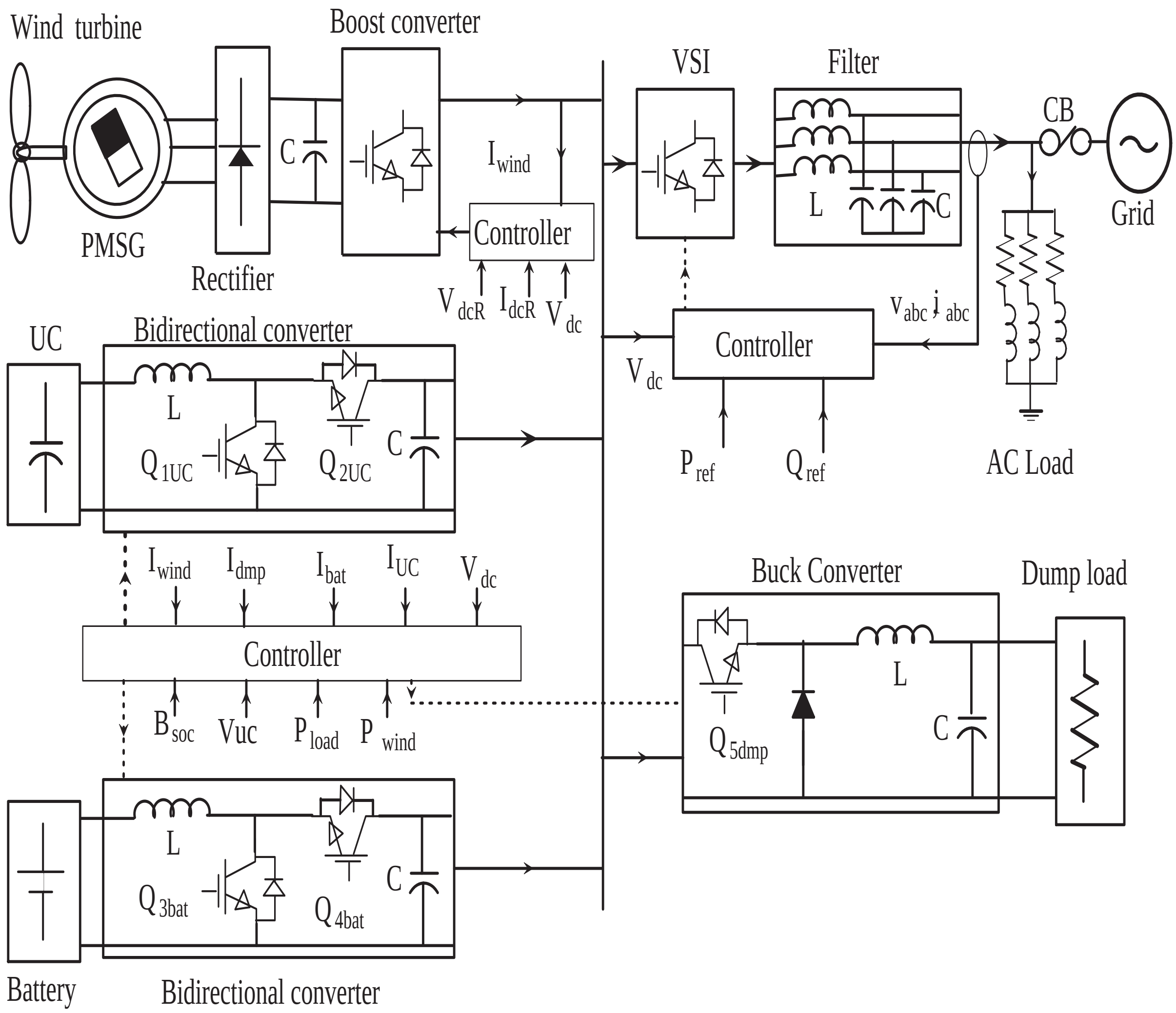


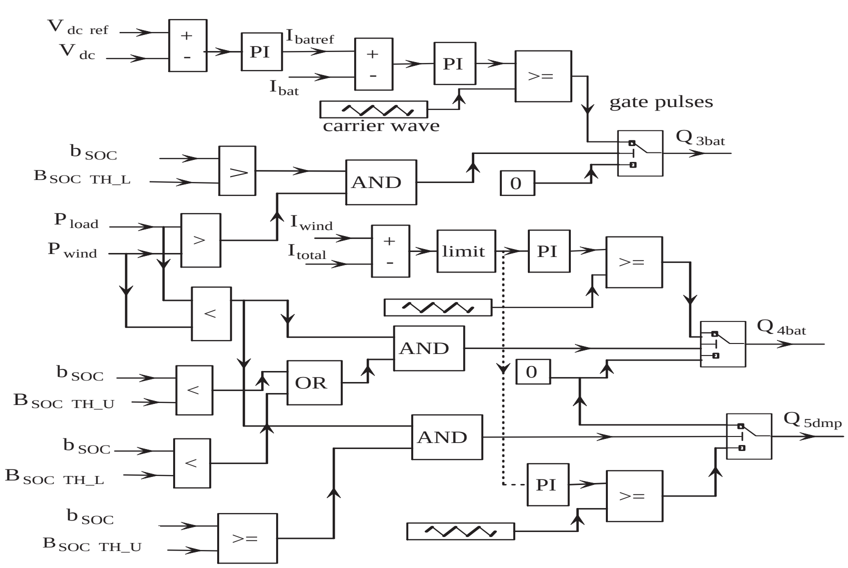
Figure 3.1: Microgrid with wind system.

The Figure 3.1 shows the schematic diagram of wind system connected to grid with battery and UC. The system consist of wind turbine coupled with PMSG. The PMSG output is rectified by uncontrolled rectifier. The rectifier is connected to dc-link through a boost converter. The battery and UC are connected to dc-link by dc-dc bidirectional converter.Due to presence of storage device and associated converter the dc-link can be controlled independently. The dump load is connected through buck converter. A 3 phase VSI used to connect the system to grid. Wind system performance is studied for two different cases. For case 1 the wind system connected to grid with battery and for case 2 the battery and UC combination is considered. For system performance the wind speed change is considered as step change, minimum wind speed (below cut in speed) is 0 m/s ,the rated wind speed and maximum wind speed is 11.5 m/s. The storage device ratings are calculated consider maximum power requirement and single units are considered for the study.

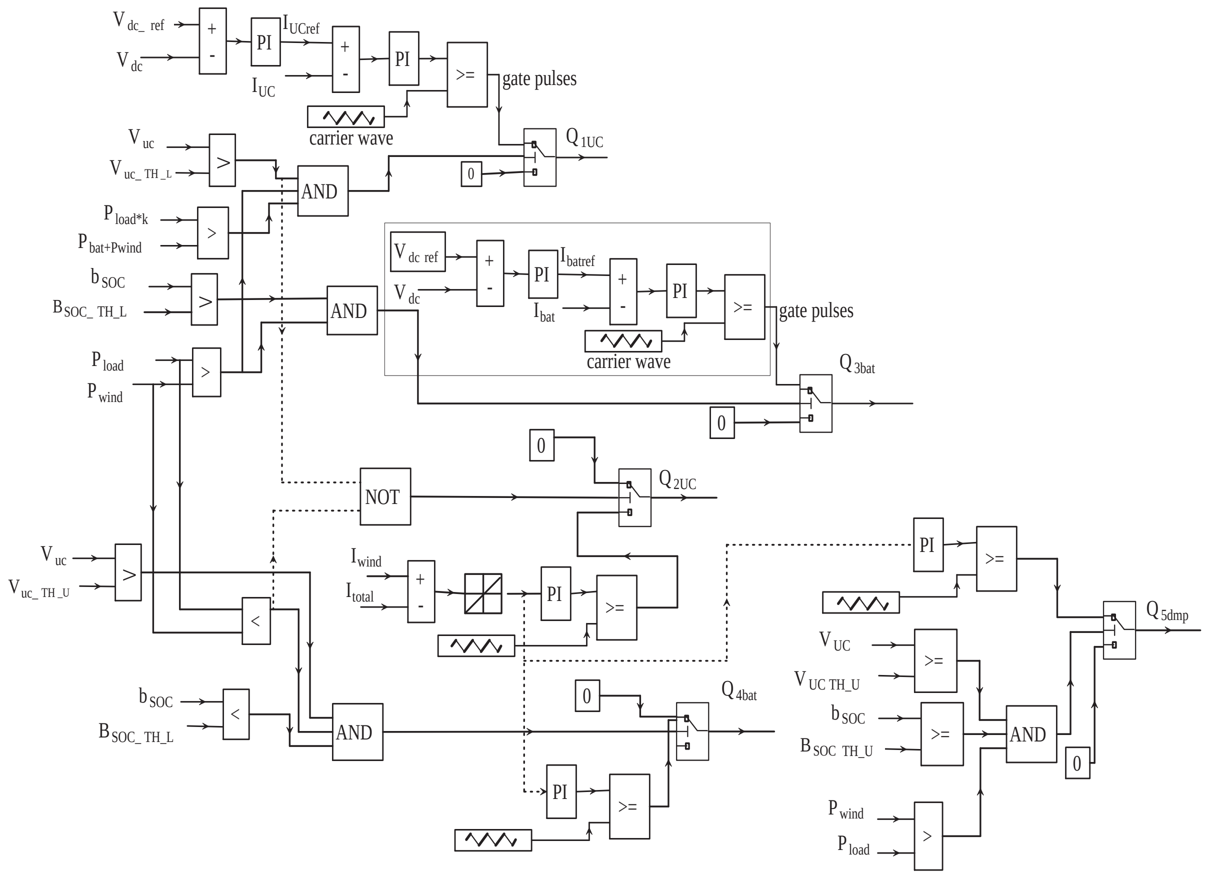
3.3 Control Schemes for Wind System with Storage

The control scheme is shown in Figure 3.2(a). The battery discharge is initiated based on the two criteria one is, the load (P_{load}) is more than wind power generated (P_{wind}) and battery state of charge (soc) is greater than the lower threshold level($B_{soc\_TH\_L}$). Once these two conditions are met, depending on error from comparing dc voltage reference and measured voltage, the battery reference current (I_{bat_ref}) is generated from outer PI controller. The error between I_{bat_ref} and battery current (I_{bat}) is used by inner PI controller to generate control signal for boost mode of operation.

The charging of battery is carried out if load is less than the wind power generated and soc of battery is less then $B_{soc\_TH\_U}$ this condition is set to whenever the wind power is excess than the load. By setting parameter $B_{soc\_TH\_U}$ the battery charging can be initiated ($B_{soc} < B_{soc\_TH\_U}$) or stopped ($B_{soc} > B_{soc\_TH\_U}$) . The dump load is utilized when the load is less the wind power generated and battery is fully charged($B_{soc} >= B_{soc\_TH\_U}$). The The difference between load current (I_{total}) and current from wind system (I_{wind}) is given to PI controller to generate the control signal to buck converter of dump load or buck mode of operation of bidirectional converter of battery.



(a)



(b)

Figure 3.2: Control schemes of wind system (a)with battery (b)with battery and UC

The control schematic for controlling the battery and UC coordinated operation is shown Figure 3.2(b). The UC discharge is initiated when the load (P_{load}) is greater than sum of wind power (P_{wind}) and battery power(P_{wind}), UC voltage and battery state of charge (soc) are above lower threshold limit ($V_{uc} > V_{uc\_TH\_L}$ & $B_{soc} > B_{soc\_TH\_L}$).Once these conditions are met, depending on error from comparing dc voltage reference and measured voltage, the UC reference current (I_{UC_ref}) is generated from outer loop PI controller. The error between I_{UC_ref} and UC current (I_{UC}) is used by inner PI controller to generate control signal for boost mode of operation. When $P_{bat} + P_{wind} < P_{load}$, battery and UC are in within the discharge level the UC instantly starts discharging to deliver required power. The battery starts discharging or increases power delivery slowly and power increases gradually.The PI parameters of UC and battery are chosen such that the UC instantly discharges required power and decreases slowly as battery gradually increases its power delivery. The UC discharges till the battery reaches the required power. For UC discharge the P_{load} is multiplied by the constant k while comparing with the sum of wind and battery power

($P_{bat} + P_{wind} < P_{load} * k$). This is to avoid the UC toggling between discharging and idle mode when battery power nearly equal to required power. The k value is taken as 0.95 or 0.9. For simulation time considered the storage devices will not go below the lower threshold limit of battery and UC ($V_{uc} < V_{uc\_TH\_L}$ & $B_{soc} < B_{soc\_TH\_L}$) as storage unit size considered for the study. Hence to verify the charging of battery and UC the upper threshold limits are used to set device in charging or idle mode. When the conditions $P_{load} < P_{wind}$ and $V_{uc} < V_{uc\_TH\_U}$ regardless of battery threshold limits the ultracapacitor starts charging as UC given the first priority. The battery charging is carried out when the conditions $B_{soc} < B_{soc\_TH\_U}$ and $V_{uc} > V_{uc\_TH\_U}$. The excess power (P_{wind} -P_{load}) is dissipated through dump load when both battery and UC are at their maximum storage limit ($B_{soc} >= B_{soc\_TH\_U}$ and $V_{uc} >= V_{uc\_TH\_U}$).

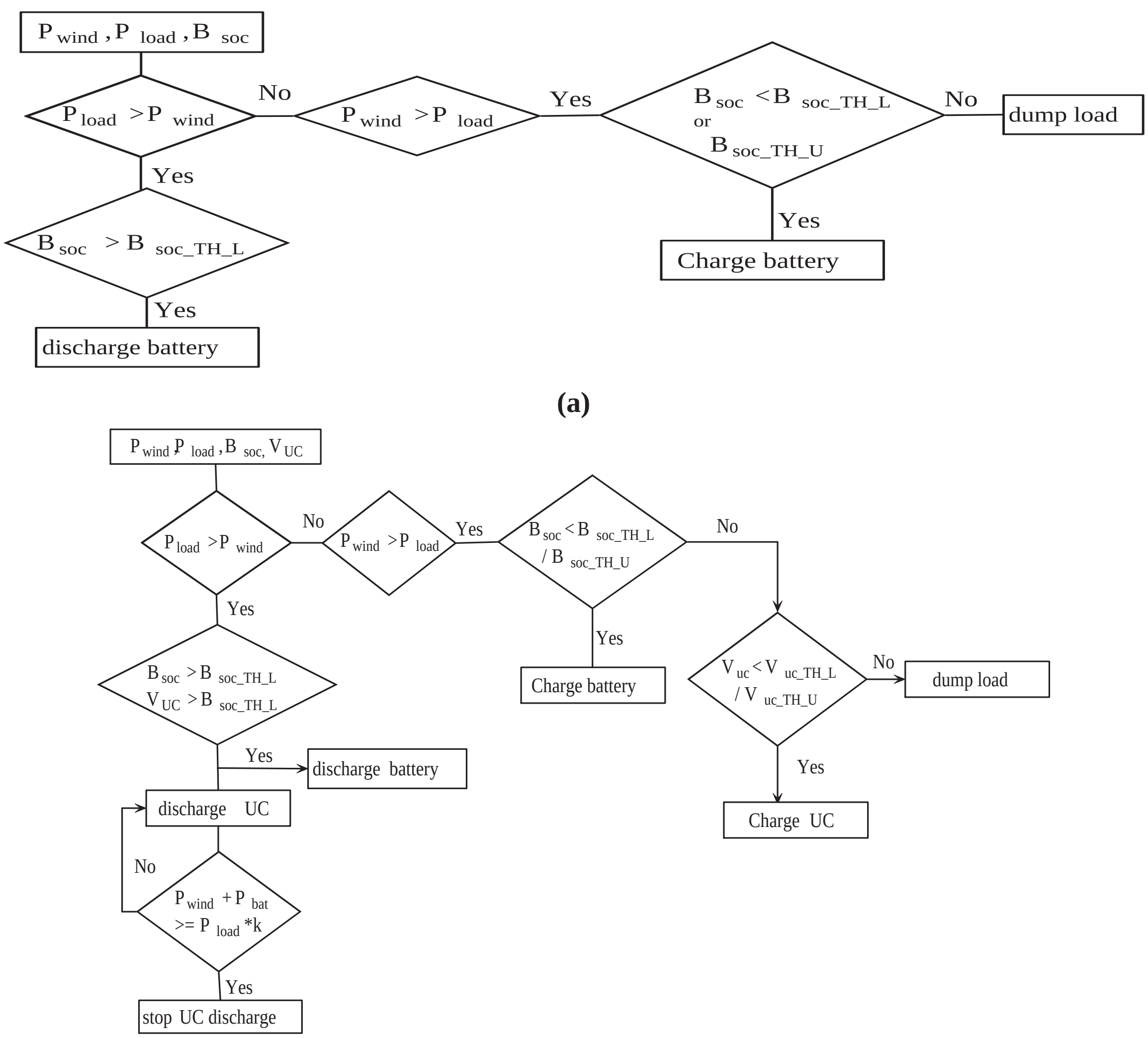


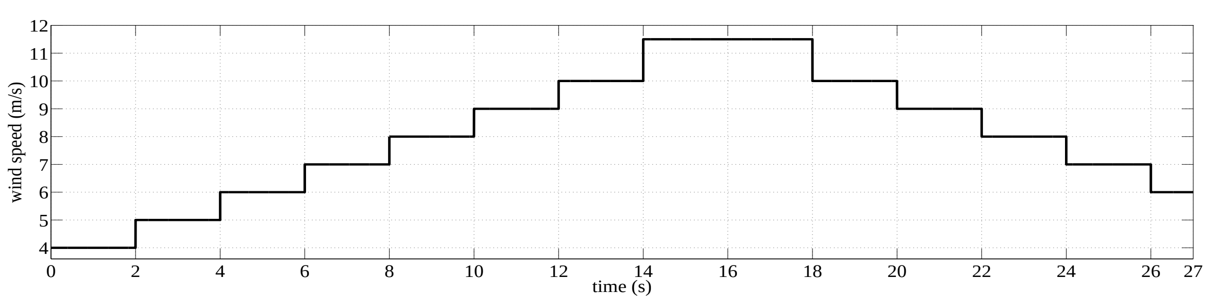
Figure 3.3: Flow charts of control schemes (a)with battery (b)with battery and UC.

The flow chart for wind system with battery control scheme implemented is shown in Figure 3.3(a). The flow chart for UC-battery coordination and control scheme is shown in Figure 3.3(b).

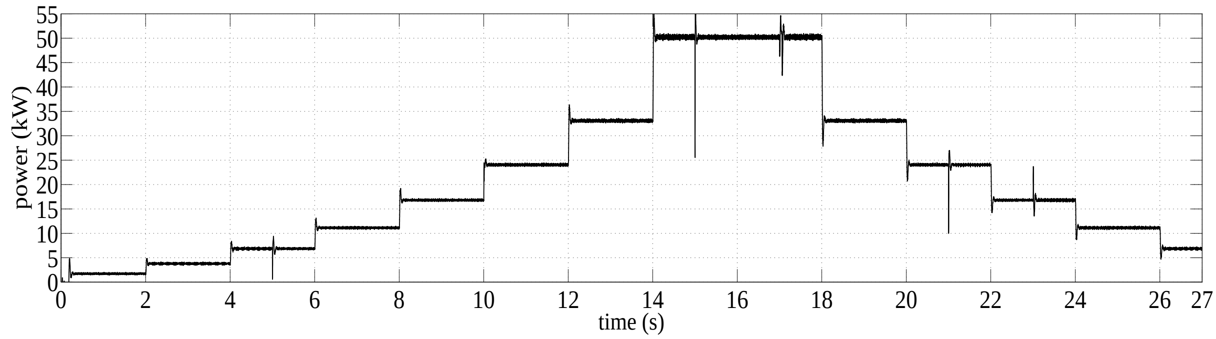
3.4 Results and Discussion

The Performance of the wind system connected to grid without storage is discussed in section 3.4.1. The performance of the system for variation in wind speed, change in load are shown through simulation results. The simulation parameters are as follows- dc-link voltage-450V, grid voltage-220V, two resistive loads of 5kW and 45kW are considered for study. The performance of the wind system with battery is presented by simulation results in section 3.4.2.The simulation parameters as follows dc-link voltage 750V, grid voltage-380V,active power-5kw and 45kW, reactive power-0.5kVAr and 4.5kVAr. The response of battery and associated controller to deliver the required power when wind power is less than the required load is shown. The charging of the battery in the low load conditions is given.The condition when no wind power and battery drained out ($B_{soc} < 20\%$) is not considered for study. It assumed that the battery power is sufficiently available. The performance of wind system with battery and ultracapacitor in grid connected mode is presented in 3.4.3 section. The coordination and control operation of battery-UC combination to supply the required load with battery protection against the abrupt discharging is given. The simulation parameters are as follows dc-link voltage 750V, grid voltage-380V,active power-5kw and 45kW, reactive power-0.5kVAr and 4.5kVAr, UC-120kW, battery-200Ah,350V.

3.4.1 Wind system without storage



(a)



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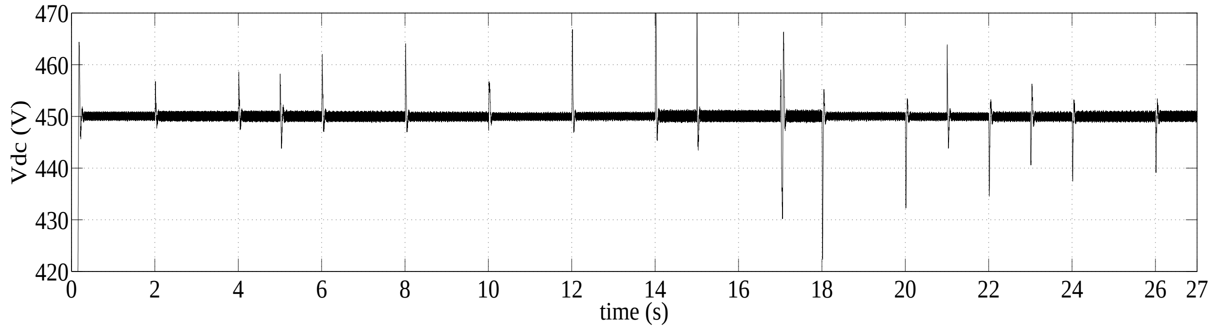
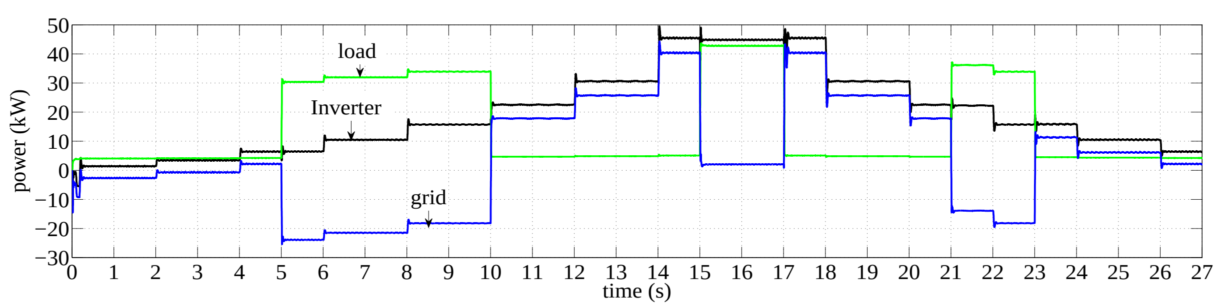


(c)

Figure 3.4: (a) wind speed (b)dc-link power (c)dc-link voltage

The wind speed is varied from 5m/s to 11.5m/s in steps of 1m/s at every 2s interval for the duration of 0-18s. The wind speed is decreased from 11.5 in steps of 1m/s at 2s interval for the 18-27s as shown in Figure 3.4(a). The Figure 3.4(b) shows the generated wind power at dc-link. As the wind speed increases the power generated from wind system at dc-link increases and decreases as wind speed decreases. The dc-link voltage is shown in Figure 3.4(c) and voltage is maintained constant. The transients can be noticed in dc-link power (Figure 3.4(b)) and voltage (Figure 3.4(c)) for change in wind speed (2,4,6...26s) or load (5, 15, 17, 21 and 23s). Any variations at inverter side or in wind speed affects both dc-link voltage and inverter output. However the transients settles down quickly.



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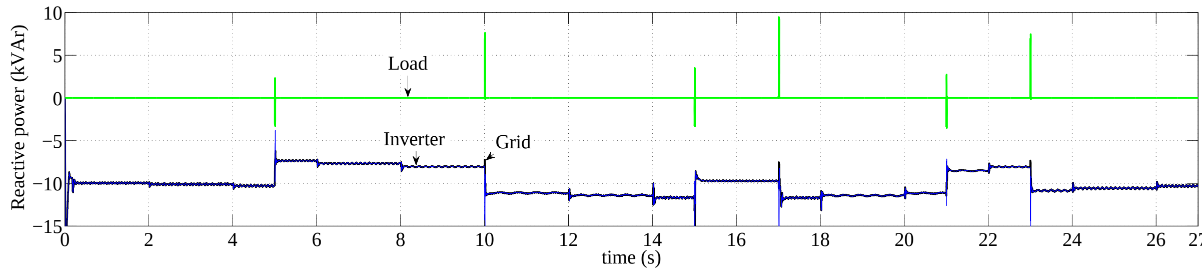

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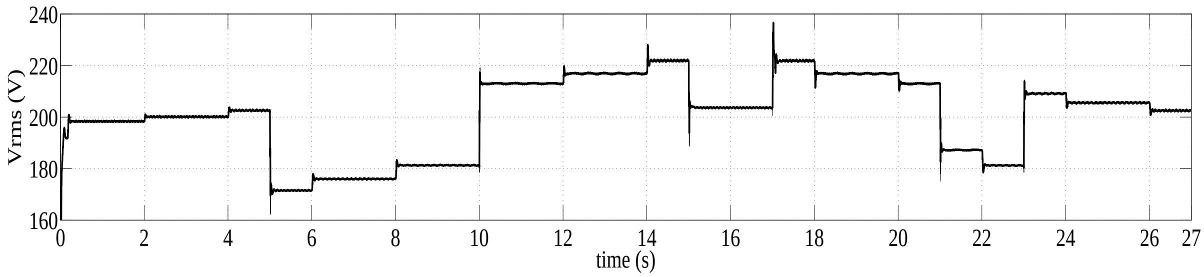

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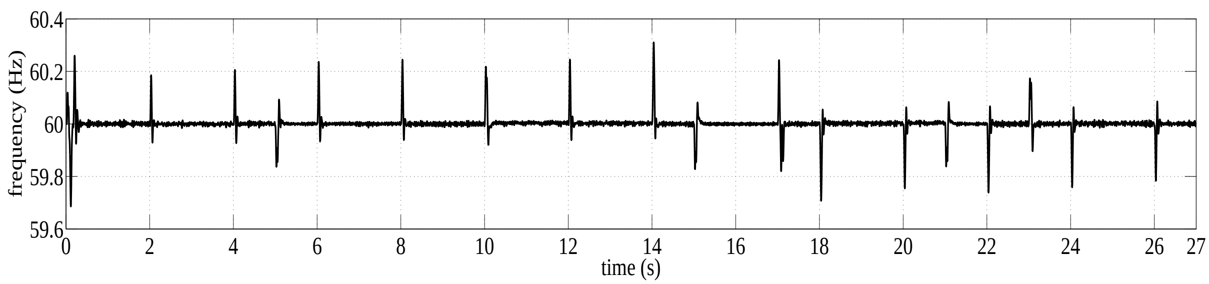


(d)

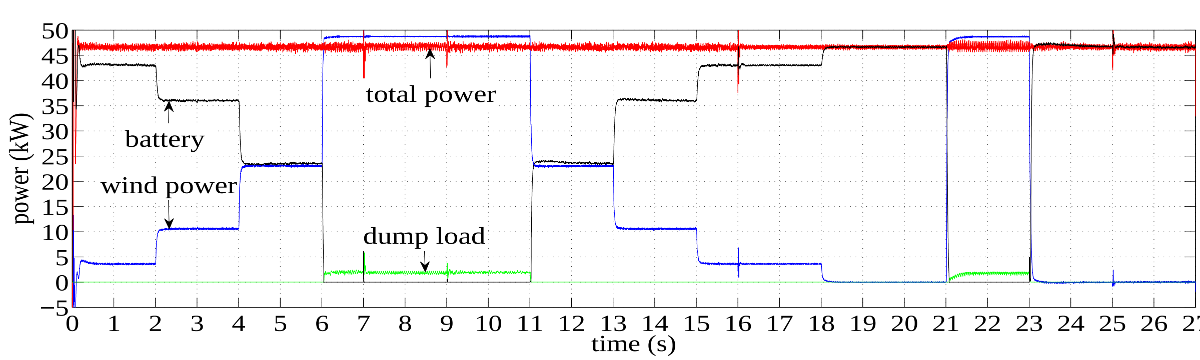
Figure 3.5: PCC parameters (a)active power (b)reactive power (c)rms voltage (d)frequency

The ac grid side parameter are shown in Figure 3.5. The Figure 3.5(a) shows the active power variations at PCC. As wind power varies the inverter power also varies. During the time 0-4s the connected load is 5kW and the wind power generated is less than the 5kW. Hence the grid supplies the deficit power. At 4s the wind power increased and load is less, the excess wind power is injected into grid. At 5s load is increased to 45kW maintained till 10s. During this time interval the wind power is less than the required load hence the deficit power is supplied by the grid. At 10s the load power is reduced to 5kW, as wind power is more than the load, excess wind power injected into the grid. At 15s again load increased to 45kW, the load sharing between inverter and grid can be seen in Figure 3.5(a). Figure 3.5(b) shows the reactive power variations at pcc. The rms voltage at PCC in shown in Figure 3.5(c). The rms voltage varies for inverter output variations and load change.Frequency of the system is shown in Figure 3.5(d)

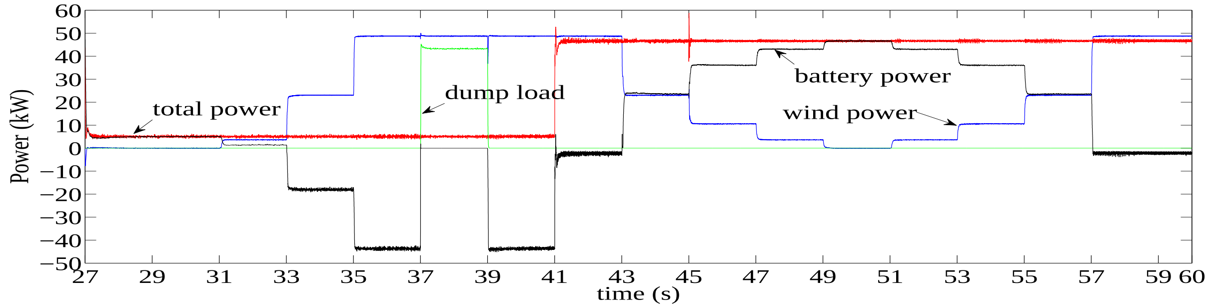
3.4.2 Wind system with battery

The dc-link power voltage and battery soc are shown in Figure 3.6. The Figure 3.6(a) shows the power variations of wind, battery and dump load. Initially inverter output is set to 45kW and wind speed to 5m/s. The wind speed is varied from 5 to 7, 9 and 11.5 m/s at time 2, 4 and 6s respectively. As wind power increases the power delivered from battery decreases. At 6s generated wind power is higher than the load hence the excess power is dissipated into dump load.As wind speed is decreased from 11s the wind power also decreases hence required deficit power is supplied by the battery.At 18s wind speed is set to 1m/s (below the cut in speed). The load requirement is met by battery alone at the time duration. At 21s the wind speed is increased from 1-11.5m/s immediately the battery stops discharging and dump load is activated due to excess wind power than the load. At 23s the wind speed is changed from 11.5 to 1m/s as the wind power generation stops the battery supplies the required load. The response is to evaluate the instant discharge ability of battery and associated controller.

The battery charging and transition between charging to discharging and between dump load is shown 3.6(b). At 27s the inverter output is set to 5kW. At 31s the wind speed is increased from 1 to 5m/s. As the wind power is less than the load the battery is supplying the deficit load.At 33s the wind speed is increased to 9m/s, the battery starts charging with excessive wind power as load is less than the generation. At 35s the wind speed is set to 11.5 m/s. The battery upper threshold is set to 75 at 37s instantly the battery stops charging and dump load is activated. At 39s the battery is set to charge again. At 41s the inverter output is increased to 45 kW while battery is charging with excess wind power. At 43s the wind speed is reduced to 9 m/s as wind power decreased the battery changes from charging to discharging mode. From the results it is observed that the battery and associated controller are capable of supplying the required load instantly. The transients can be observed in dc-link power when the loads are varied(7,9,16,25,45s) which settles down quickly.



(a)



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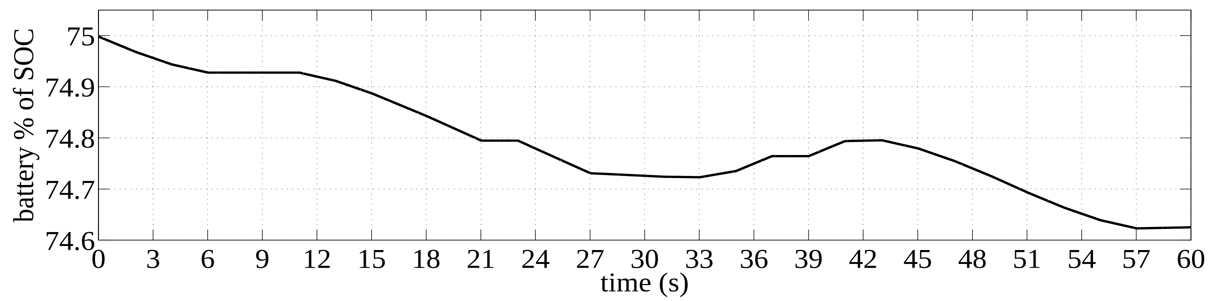

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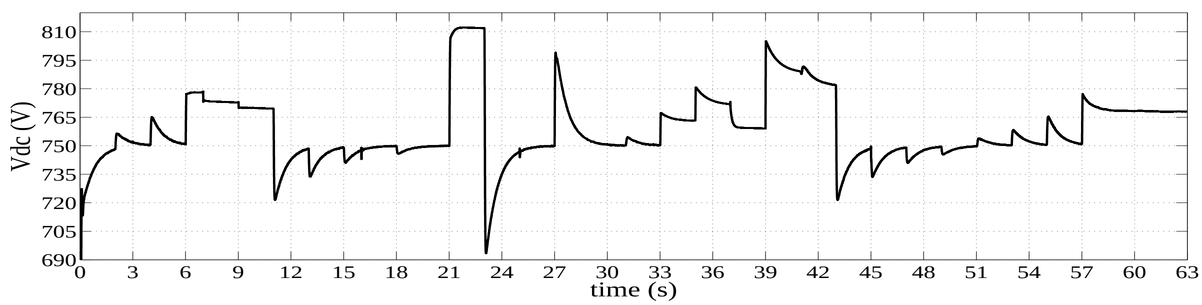
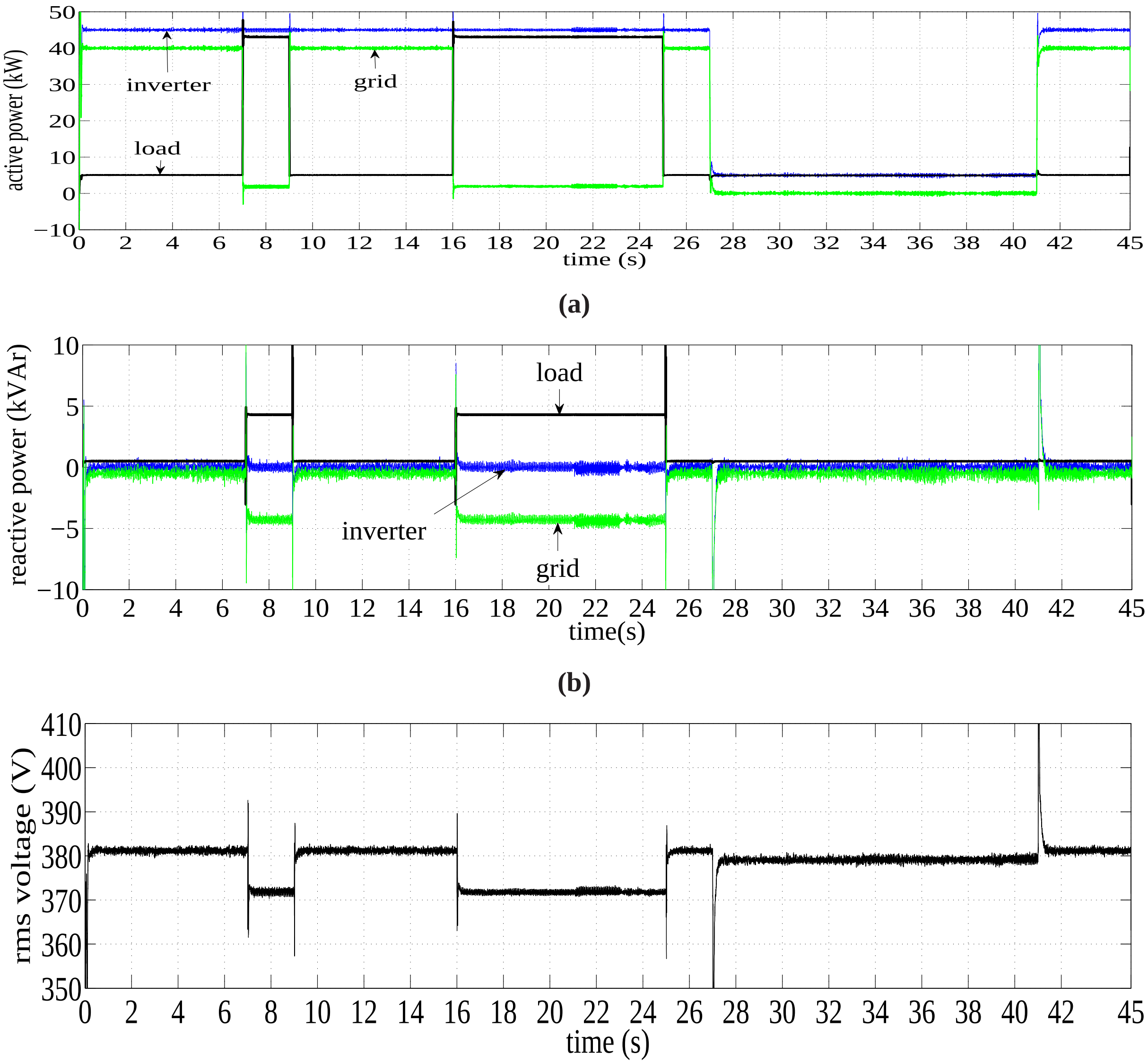


(d)

Figure 3.6: dc-link parameter with battery (a)wind and battery sharing the load (b)battery charging (c)battery state of charge (d)dc-link voltage

Figure 3.6(c) shows the dc-link voltage variations. The transients can be noticed during wind speed change and load change. The transients settle down gradually when wind power is more than the load and dump load is activated. The transients settle down fast during wind speed change, load change and for battery charging. The response of battery %soc for discharging (0-6s,11-21s,23-33s,43-57s) and charging (33-37s,39-43s,57-60s) is shown in Figure 3.6(d).

The inverter,load and grid active and reactive power with rms voltage at PCC is shown in Figure 3.7. The active power sharing between inverter, load and grid is shown in Figure3.7(a). The inverter output is varied as follows 0-27s 45kW, and from 27s 5kW. The load active power is set for 5kW for 0-7s ,11-16s and from 25s to rest of the time period.A 45kW active load is maintained for 7-9s and 16-25s time duration. The time duration when the load is 5kW the excess power from the inverter is fed to grid.



(a)

(b)

(c)

Figure 3.7: (a) active power (b)reactive power (c) rms voltage

The Figure 3.7(b) shows the reactive power variations. The inverter output reactive power is set to zero hence the reactive power requirement from the load is met by the grid.The 10% reactive power is considered for the study, for 5kW active power the 500VAr and for 45kW the 4.5kVAr is set.The transients can be observed for inverter output and load change. The rms voltage is shown in Figure 3.7(c). The dip in the voltage cab be seen for increase in the load and inverter output reduction.The transients occurred and settles down fast when load or inverter outputs were varied.

3.4.3 Wind system with battery and ultracapacitor

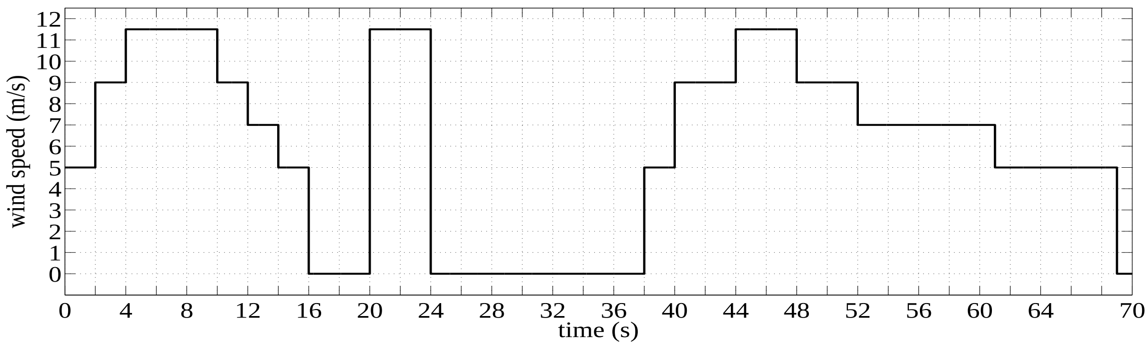
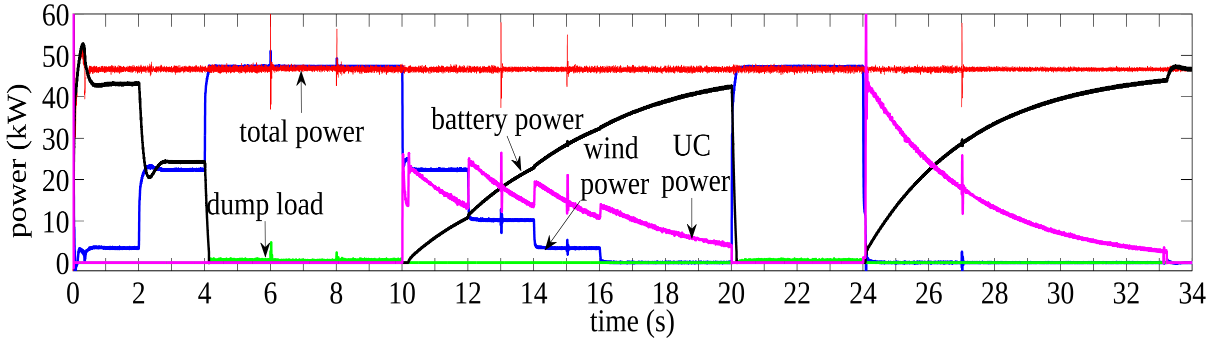


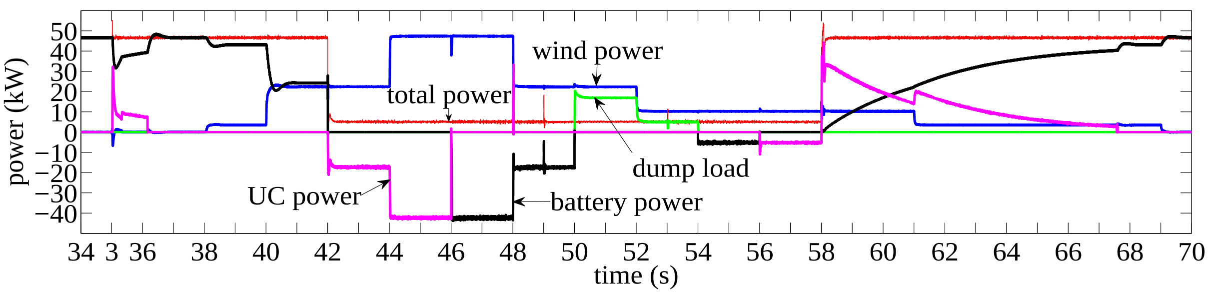
Figure 3.8: Wind speed

The wind speed pattern is shown in Figure 3.8. The dc-link parameters;dc-link power, voltage,battery soc UC terminal voltage are shown in 3.9. The power variations at dc-link is shown in Figure 3.9(a). Initially the inverter output is set to 45kW , wind speed to 5m/s, the battery is supplying the deficit load. At 2s the wind speed is increased to 9m/s as wind power is increased the power delivered by the battery has been decreased. At 4s the wind speed is set to 11.5 m/s as generated wind power increased and is higher than the required load hence the battery stops discharging and excess power is dissipated through the dump load.

At 10s the wind speed is reduced from 11.5 to 9m/s as wind power is decreased instantly the UC delivers the required power meanwhile the battery gradually starts discharging. Further the wind speed is reduced to 7, 5 and 0 at 12,14 and 16s respectively. From the figure it can be observed that as wind power decreases the UC instantly delivers power proportionally and battery power increases gradually. At 20s the wind speed changed from 0 m/s to 11.5 m/s as wind power is more than the required the battery stops discharging and excess power is delivered to dump load. At 24s the wind speed is reduced from 11.5m/s to 0 m/s as wind power becomes least instantly the UC starts discharging to supply required load meanwhile battery starts increasing gradually and reaches the required power level. The coordinated operation and control of battery and UC can be noticed.At 6,8,14,15 and 27s the transients were occurred due to change in the load at inverter side.



(a)



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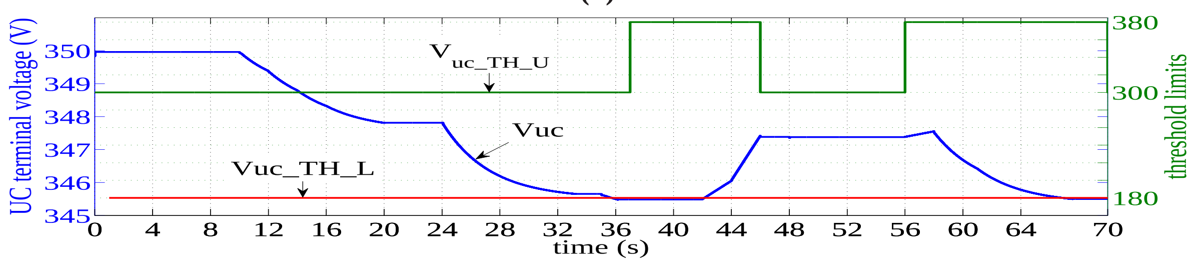

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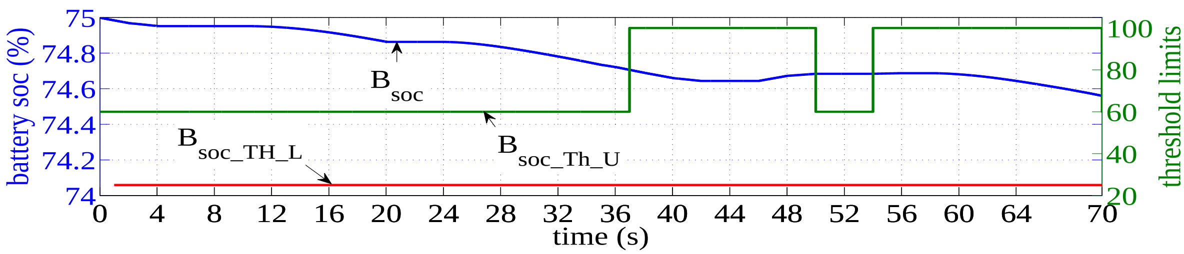

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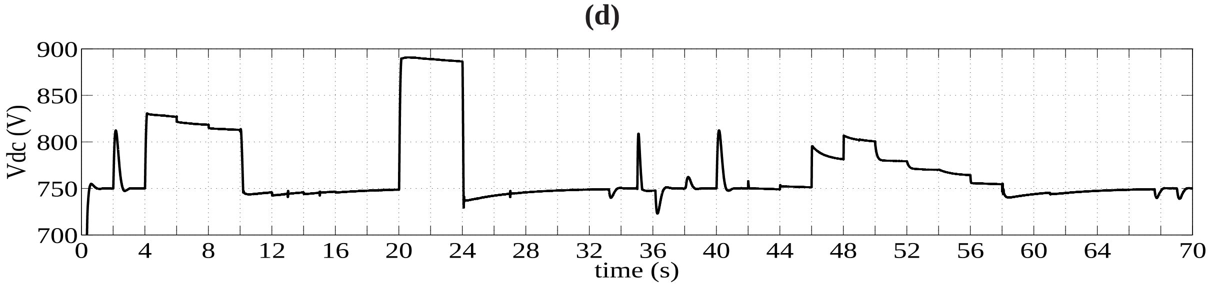


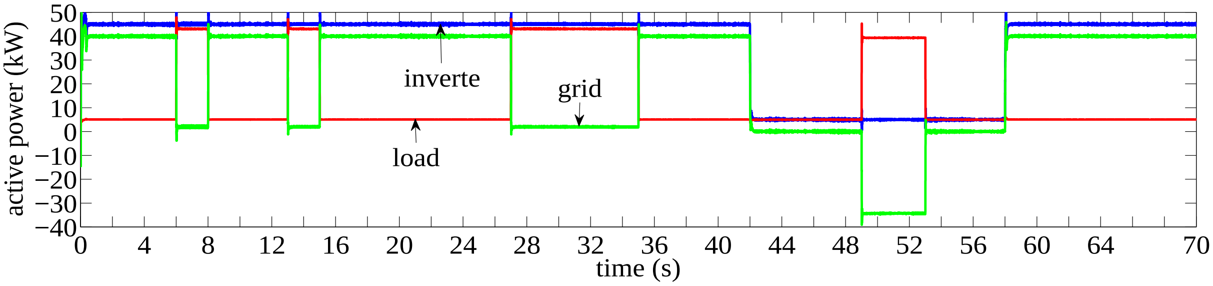
(e)

Figure 3.9: dc-link parameter when (a) battery and UC discharges (b) charging of battery and UC (c) UC terminal voltage with threshold limit (d) battery state of charge with threshold limit (e)dc-link voltage

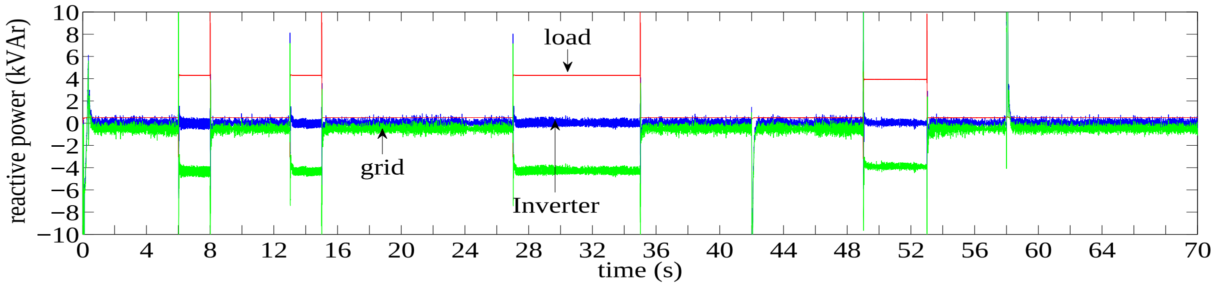
In the Figure 3.9(b) at 35s the load has been changed due to which a transients appears which will triggers the UC discharges momentarily as UC discharge condition is set on ($P_{load} > P_{bat} + P_{wind}$). However as transients settles down the UC stops discharging. At 37s the battery and UC are set to charging mode. At 38s the wind speed changed from 0 to 5m/s and at 40s it is increased to 9m/s.During the time the the load is met by both wind and battery. Even charging conditions are set for battery and UC, as excess wind power is not available the battery still discharges and UC is in idle mode. The inverter output can be set as per the requirement and it is set is set to 5kW at 42s. As load in reduced,the wind power is higher than the required load and UC and battery are set for charging mode. Hence UC starts charging as first priority is given to it. At 46s the UC charging condition reset to idle mode. As UC stops charging and wind power is excess than the load, immediately the battery starts charging.At 50s the battery also reset to idle mode hence the dump load is activated to dissipate the excess power.At 54s battery again set to charging mode. The UC starts charging at 56s as its charging is activated at that time. These conditions are set to evaluate the charging of battery/UC from varying wind power and transition between the storage devices.Which can be seen in figure for time duration 42-58s. At 58s the inverter output is set to 45kW during the time UC is in charging and battery in idle mode. Immediately the UC changes its state to discharging mode and battery also starts discharging gradually. The UC terminal voltage variation and threshold limit change are shown in Figure 3.9(c). The battery $\%$ of soc response and threshold limit set/reset are shown in Figure 3.9(d).

Figure 3.9(e) the dc-link voltage variations. The voltage transients can be noticed during the time instants when wind, load and inverter powers are varied and are settles down immediately. The voltage rise are seen during the dump load activation and during transition from UC to battery or battery to UC while charging and these transients settles down gradually.

The active and reactive power variations of inverter, load and grid with rms voltage and THD at PCC are shown in Figure 3.10. The Figure 3.10(a) shows the active power variations of inverter, load and grid. Inverter output is varies as follows 0-42s,58-70s P=45kW, from 42-58s active power P=5kW. The inverter reactive power output is set to zero. The load variations are as follows 0-6s,8-13s,15s-27s,35-49s and from 58-70s P=5kW,Q=500VAr. During the time interval 6-8s,13-15s,27-35s and 49-53s P=45kW and Q=4.5kVAr. For the time durations when the inverter active power is 45kw and load is less, the excess power is fed to grid. During time intervals when inverter power is 5kW and load is high, the required power is supplied by the grid. The Figure 3.10(b) shows reactive power sharing between inverter, load and grid. The inverter reactive power is set zero hence load reactive power demand is met by grid.



(a)



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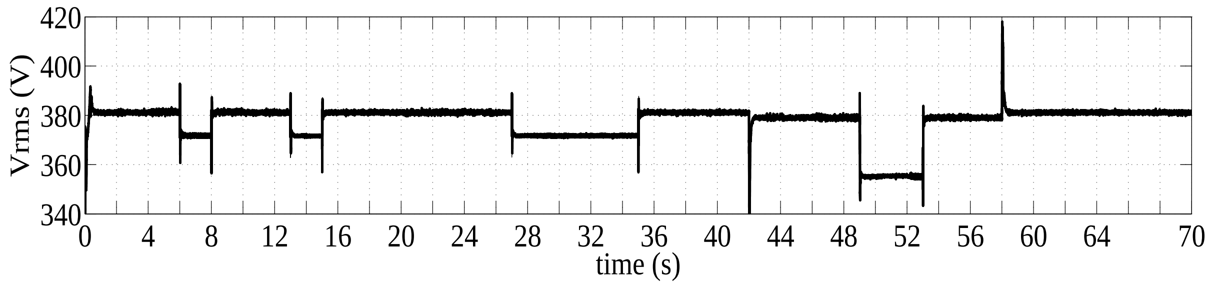

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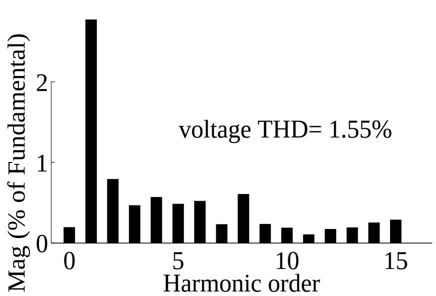

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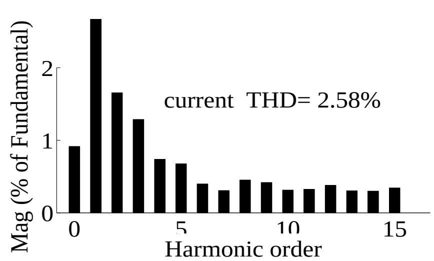


(e)

Figure 3.10: (a)active power (b) reactive power (c) rms voltage (d) % THD of voltage (e) % THD of current

The Figure 3.10(c) shows the rms voltage of PCC. The voltage dip can observed during the load increase (5 to45kW) and inverter output reduction (45 to 5kW). The rest of the time duration the voltage is at required level (380V). The inverter output voltage and current THD are shown in Figures 3.10(d) and 3.10(e). The THD's are within standard limits.

3.5 Conclusion

The performance of the wind system connected to grid without storage and with battery and battery-ultracapacitor combinations are shown through simulation results in this study. The wind system directly connected to grid without storage supplies fluctuating power to grid which is not desirable.The wind power fluctuations affects load and the grid imported/ exported power. It is the simplest method and less complex in terms of control strategies concerned. From the performance of system it is observed that the output needs to be smoothened and hence the storage system is required. The wind system performance with battery and battery-UC combination is studied.The wind system with battery effectively smoothen output power and supplies constant power. However the battery undergoes severe discharging cycles which not desirable for battery performance. The ultracapacitor-battery combination effectively smoothen wind power fluctuations along with battery instant discharging and rate of discharges is controlled by doing so the battery performance can be improved. The dump load is employed in both cases which is not efficient way of wind power utilization. The performances of control schemes employed for control and coordination of battery and UC-battery combination is satisfactory.

Chapter 4

PERFORMANCE OF WIND-SOFC BASED MICROGRID WITH UC AND ELECTROLYZER

4.1 Introduction

The different energy resources are combined together to mitigate the power fluctuation of renewable energy resources. The combinations leads to hybrid system in which energy resources support one another to supply the load. The different combinations like wind-PV, wind-PV-storage, wind-diesel-PV with storage are possible. The power fluctuations from wind systems can be effectively dealt with storage device. Batteries are commonly used, however these undergoes random and uneven discharge rates which severely affects the battery life. In order to control discharge profile the ultracapacitors are utilized. The battery-UC combination effectively delivers the load requirement within the storage capacity limitations. The dispatch capability of wind with storage is limited. A alternate solution is required to utilize wind power better. Few studies have been reported the combination of wind-diesel with battery and UC [Chad et al. 2010, Mahamadou et al. 2013] for isolated mode of operation. The combination is reliable though it is not economical and environmentally friendly due to usage of fossil fuels. The versatile combination of Wind-PV with storage has been studied extensively. Few studies presented the combined operation of wind-PV combination with different aspects [Chianget al. 2010, Rupesh and Vivek 2015, Rajan and Arul 2015] .

The wind-PV combination addresses the few drawbacks of renewable resource like power fluctuations effectively however these are limited by storage capacity and state of charge. A necessity arise for an environmental friendly energy resource which can supply power uninterrupted. This requirement can be fulfilled by the fuel cell. A fuel cell is a electrochemical device which converter hydrogen energy into electricity with no harmful effluents. Among different types fuel cell the solid oxide fuel cell is well suited for stationary power generation. The input for the fuel cell is hydrogen and it can be generated with different sources. However to meet the eco friendly requirement the renewable based hydrogen generation is preferred. The wind energy can be used to generate the hydrogen from electrolyzer. The wind based hydrogen is reported in [Rion et al. 2010].

The hydrogen generation from renewable and its storage has many benefits [Seyyed and Chan 2014]. The fuel cell requirement is hydrogen and it can be generated from renewable resources. Hence the combination of Fuel cell and renewable resources with hydrogen generation can lead to effective solution for environmental friendly power generation. The possible combination of fuel cell with PV-wind and electrolyzer has been presented in [Kaushik 2005]. The hybrid system with Wind, PV,FC and electrolyzers are presented in[Onar et al. 2006, Narender and Vivek 2007, Seul-Ki et al. 2008, Seyyed and Chan 2011]. The SOFC is well suited for constant load applications. Due to its slow dynamic response fuel cell require time to respond for sudden load variations. The transient load variations are detrimental to fuel cell life. Hence in order to mitigate load transient effect and slow dynamic response an energy storage device is required to compensate during transient period. The battery and ultracapacitors are used for such applications[Alireza et al. 2007 , Caisheng and Hashem 2007]. The UC has capability C to discharge burst of power instantly and it can be used for mitigation of SOFC slow dynamic response.The combination of renewable resources with fuel cell ,storage device and electrolyzer can lead to eco friendly reliable and sustainable power generation. The combination of wind-SOFC-UC with electrolyzer shows the significant potential for clean power generation.

In this chapter the performance of the hybrid system consisting of wind system, solid oxide fuel cell, UC and electrolyzer has been given. The SOFC response and mitigation of slow dynamic response by UC is presented. The utilization of wind to generate hydrogen and charge ultracapacitor is reported. Initially the response of SOFC-wind system without UC and electrolyzer is presented. The inverter output following the of active and reactive power references is shown. The response of SOFC,UC,wind power and electrolyzer for different wind speeds and inverter active power change at the dc-link is presented.The load variations, inverter output, grid power and voltage responses are given in this work.

4.2 Wind-SOFC based Microgrid with UC and Electrolyzer

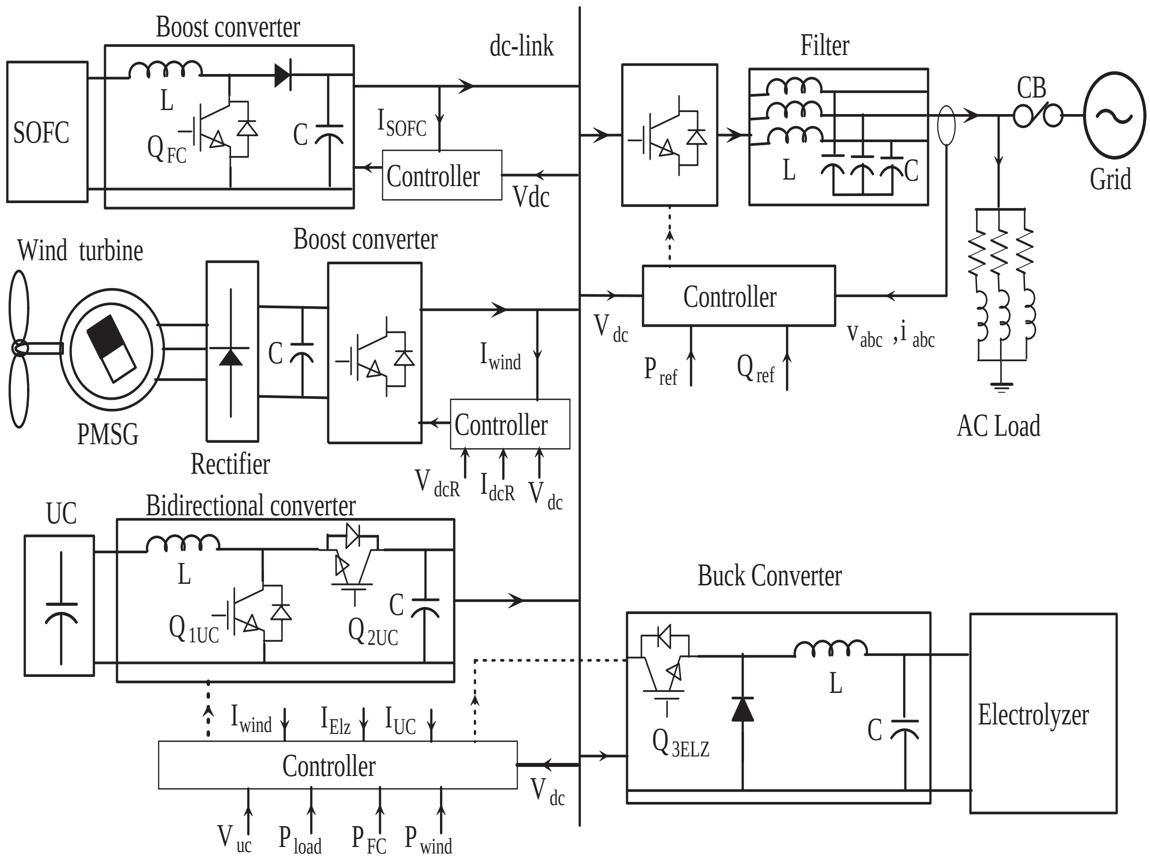
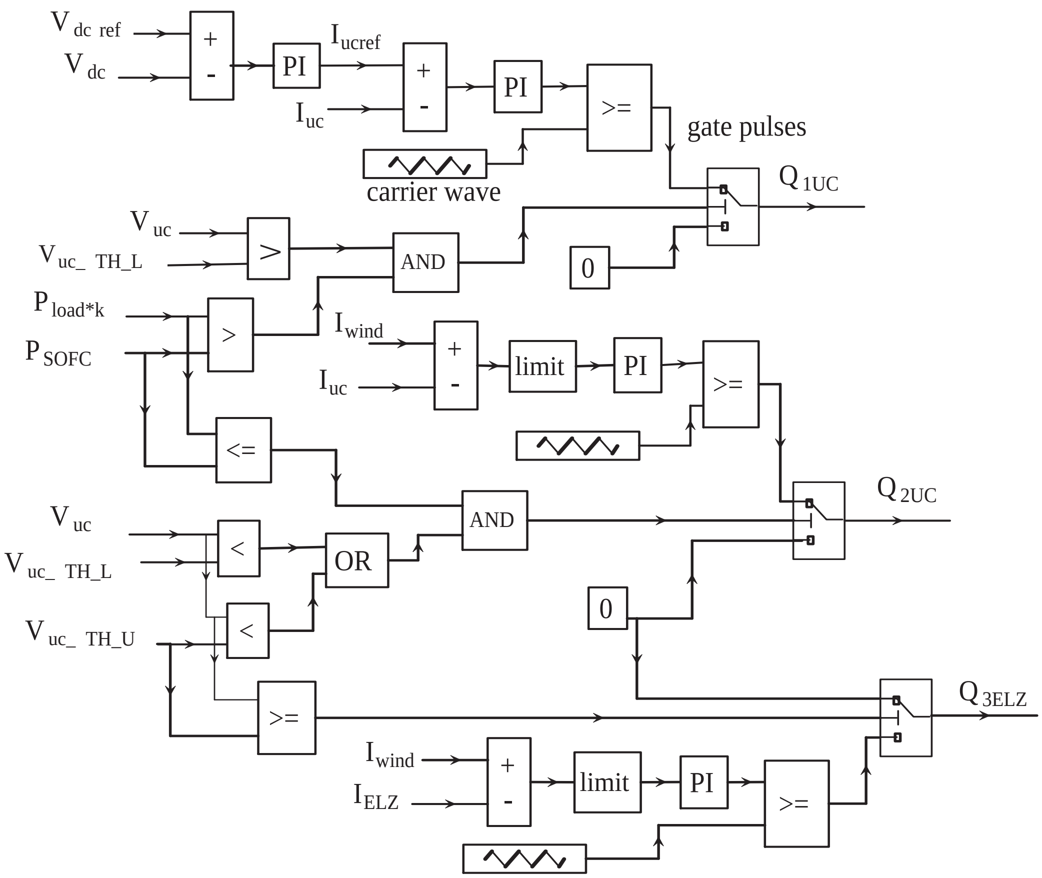
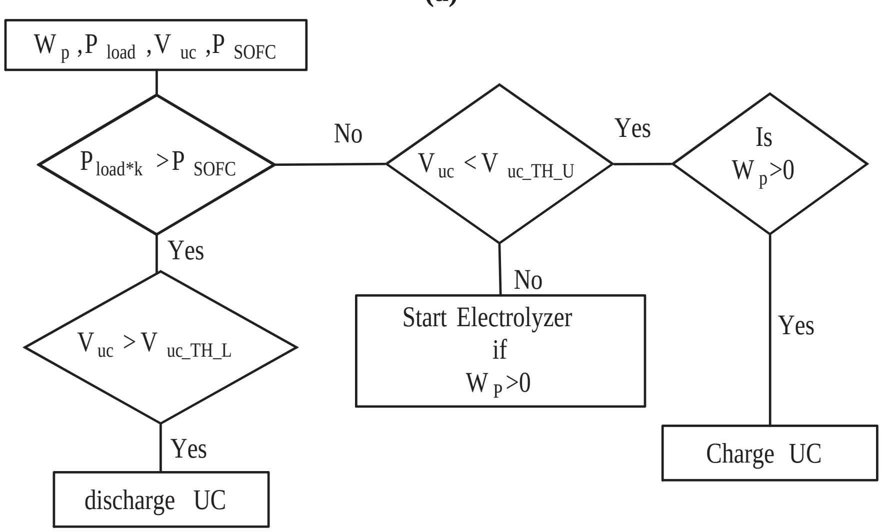


Figure 4.1: Schematic diagram of Wind-SOFC based hybrid system

The schematic block diagram of wind-SOFC based hybrid system is shown in Figure 4.1. The system consists of a wind generation system and solid oxide fuel cell as energy resources, UC as storage as well source and electrolyzer for hydrogen generation.The wind turbine is coupled with PMSG,its output is rectified by a uncontrolled rectifier. The dc output from the rectifies is then given to boost converter and it is controlled by MPPT controller.The SOFC is interfaced with dc-link through a boost converter to match the voltage requirement. The UC is connected to common dc-link through a bidirectional converter so that it can be discharge required power and charged using wind power.An electrolyzer is connected to dc-link by buck converter which will generate the hydrogen by electrolysis of water.A three phase VSI is used to connect the dc-link with grid. The wind power is continuously used by the electrolyzer or the for the ultracapacitor charging. A control schematic is employed to control the SOFC-UC coordination to mitigate the slow dynamic response of the fuel cell. The control schematic is shown in Figure 4.2(a)



(a)



(b)

Figure 4.2: (a)control schematic (b) flow chart

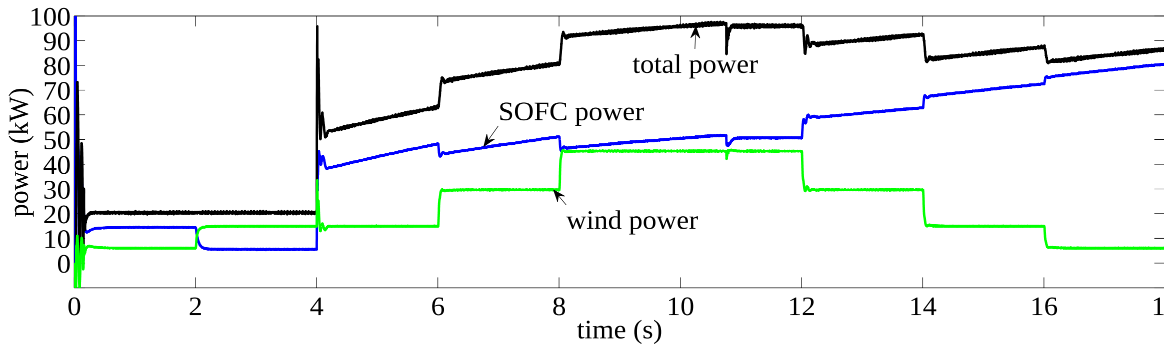
The flowchart for control scheme implemented is shown in Figure 4.2(b). The UC starts discharging when the conditions $P_{load} * k > P_{SOFC}$ and $V_{uc} > V_{uc\_TH\_L}$ are satisfied. The reference dc-link voltage and measured voltage are compared to get the UC reference current (I_{UC_ref}) from the outer PI controller. The (I_{UC_ref}) and UC current (I_{UC}) are compared and the error is given to the inner PI controller which generates control signal to boost mode of operation of UC converter. The UC instantly releases the required power and slowly decreases the power delivered as SOFC power generation increases gradually. The similar two loop control scheme has been used to control SOFC boost converter.The UC charging by wind power is carried out when $V_{uc} < V_{uc\_TH\_L}$ or $V_{uc} < V_{uc\_TH\_H}$ are set. The electrolyzer is turned on whenever the wind power is available and UC is in idle mode.

4.3 Results and Discussion

The performance of the wind-SOFC microgrid with UC and electrolyzer is presented. The different wind speeds, variations in load, change in inverter output are considered for the study. The combined and complimenting operation of SOFC-UC for inverter output change is shown. The performance of control schemes for above conditions is given. The utilization of wind power to generate the hydrogen by electrolyzer is presented. The dc-link voltage, power variations at dc-link, charging of UC are detailed. Initially the performance SOFC-wind combination without ultracapacitor and electrolyzer is presented. The inverter active and reactive power outputs following the reference power is presented along with dc-link power response for the same.

4.3.1 Wind-SOFC system without storage

The performance of the microgrid without UC and electrolyzer in shown Figures 4.3 At 2s the inverter power output is increased from 25kW to 85 kW. From the Figure 4.3(a) it can be seen that when power reference to inverter is changed, SOFC takes time to reach the required power output due to its slow dynamic response. During the time in the presence of wind system the fluctuating power output adversely affects the SOFC power delivery. Due to wind power fluctuation, the dc-link voltage is also varies and is seen in Figure 4.3(b). It can be observed from the Figure 4.3(c) that the output power of the hybrid system fluctuate due to slow dynamic response of SOFC. Hence in order to supply constant power to the grid in the presence of wind system with SOFC, the mitigation of slow dynamic response of SOFC is necessary.



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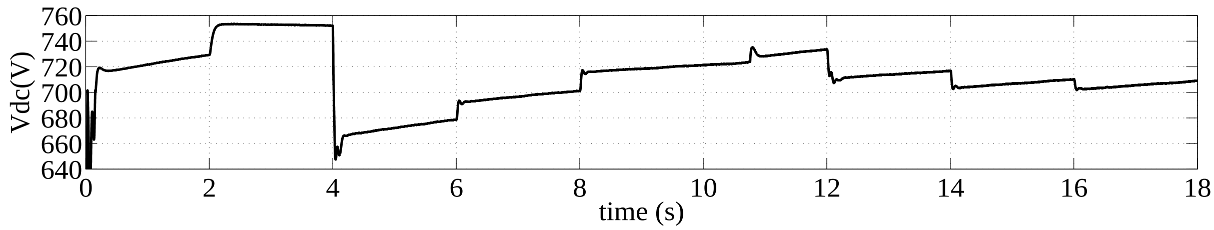

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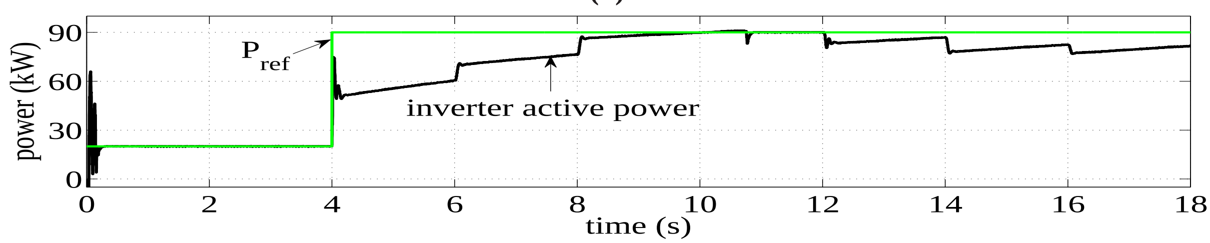
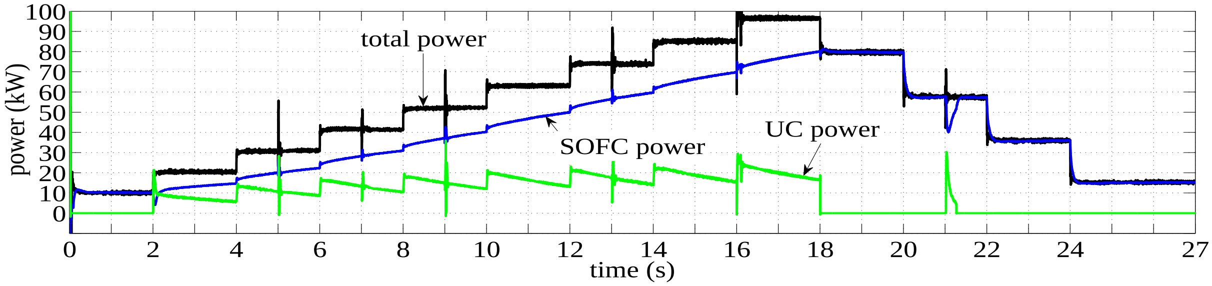


(c)

Figure 4.3: The Wind-SOFC based hybrid system response without UC and electrolyzer (a) dc-link power (b)dc-link voltage (c) inverter active power

4.3.2 Microgrid with ultracapcitor and electrolyzer

The Wind-SOFC based microgrid load following performance is shown in Figure 4.4 The inverter output power following the reference values (P_{ref}&Q_{ref}) is shown in Figure 4.4(a). The inverter active power reference (P_{ref}) is increased from 10kW in steps of 10kW every 2s from 2-16s time duration. From 18s the inverter (P_{ref}) has been decreased. The reactive power reference Q_{ref} is set to zero. From the figure it can be seen that inverter output follows the active and reactive power references. The UC delivers proportional power at every instant when inverter power increased as shown in Figure 4.4(b). The SOFC power gradually increases and UC power decreases accordingly. The large transients can be seen in dc-link and inverter power (at 5,9,13,21s) due to load change which settles down quickly.



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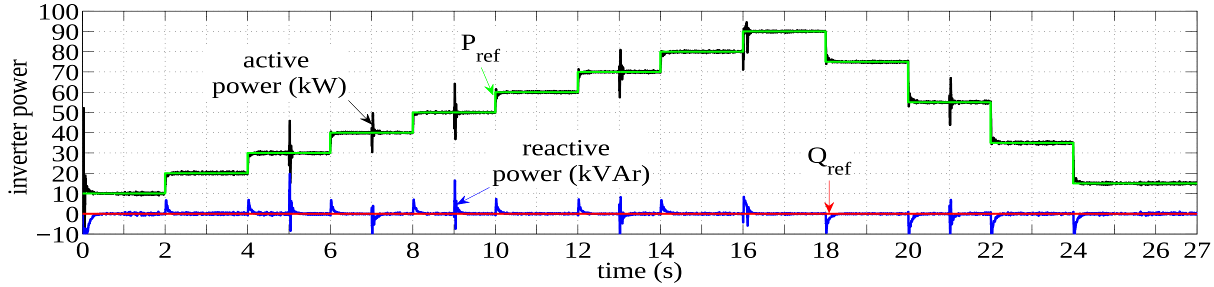


(b)

Figure 4.4: The load following performance (a)power variations at dc-link (b)inverter active and reactive power

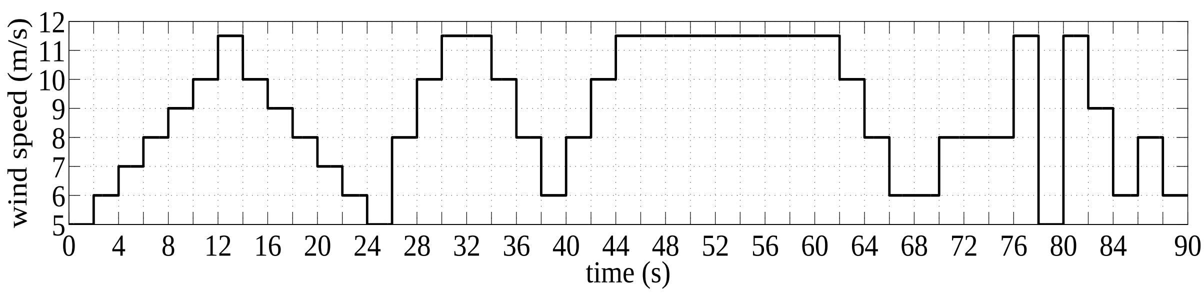


Figure 4.5: Wind speed variations

The wind speed pattern considered for the study is shown in Figure 4.5 The Figure 4.6 shows the power variation at common dc-link with UC and electrolyzer. Initially the inverter output power reference is set for 10kW. At time 2s the inverter power reference is changed to 90kW. The wind speed is varied from 5m/s to 11.5 m/s in the time interval 0 to 12s and decreased from 11.5 m/s to 5 m/s during the time period 14 to 24s in step of 1m/s. The fuel cell takes time to reach the required power level due to slow dynamic response, during the time UC supplies the deficit power instantly as seen in Figure 4.6(a) Also it can be observed that the power consumption of the electrolyzer varies according to the wind power generation which minimizes the frequent variation in fuel cell power.

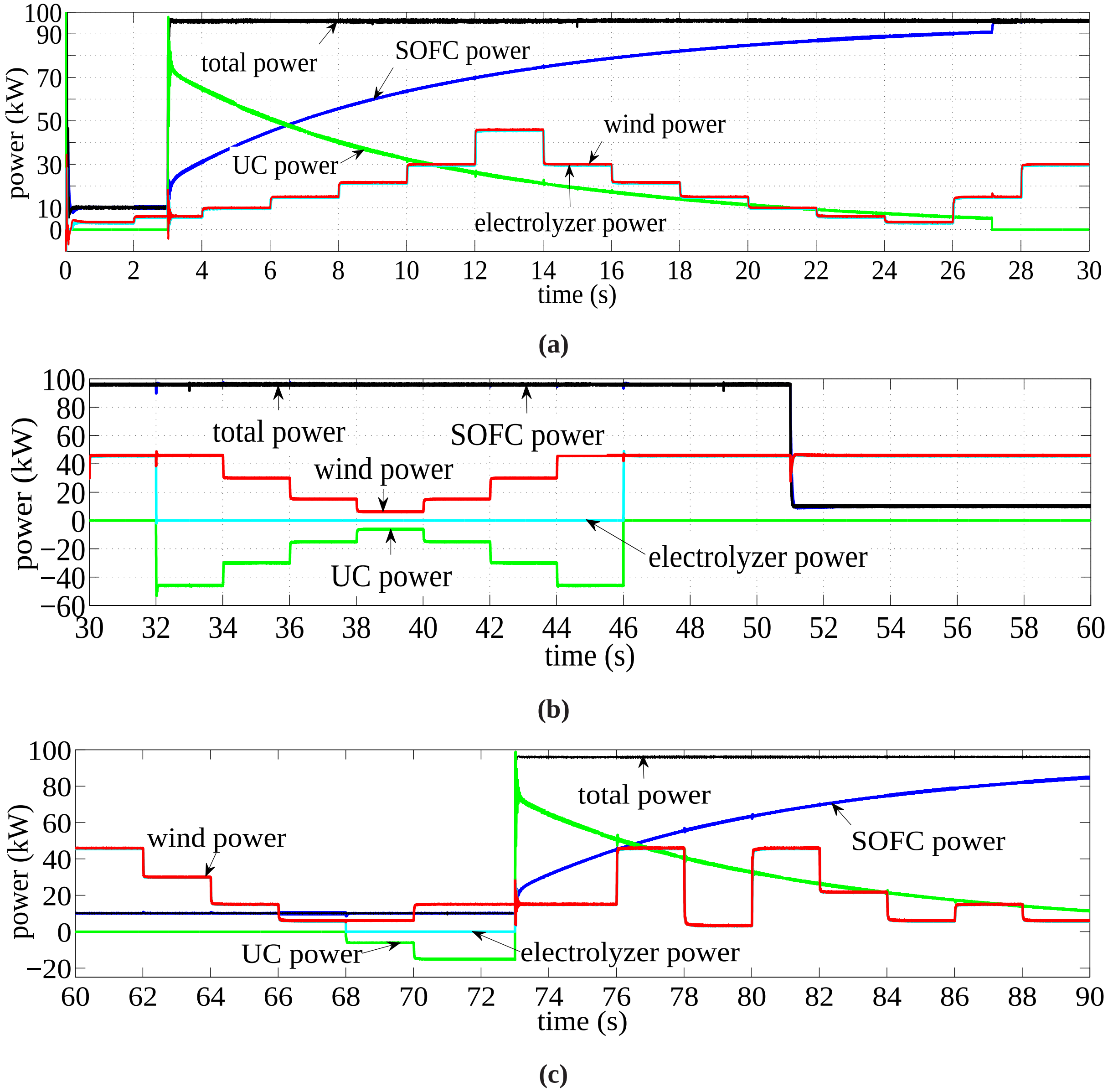


Figure 4.6: dc-link power variations when (a) load increased (b)UC charging by wind power (c)UC transition from charging to discharging mode.

The wind speed is increased from 5m/s to 11.5m/s in the time duration 26 to 30s. At 32s the UC is set to charging mode by changing the $V_{uc\_TH\_U}$. From 34s the wind speed varied in steps of 2m/s at every 2s. As wind speed varied, the power generated by wind system varies, accordingly the UC power consumption varies. The buck converter controller is able to track the wind power variations and charges UC as seen Figure 4.6(b), the electrolyzer stops consuming power at 32s as UC charging starts. The Figures 4.6(a)and (b) shows the quick response of controllers in supplying the instant power by UC and tracking the wind power generation and effective utilization by UC or electrolyzer. At 46s the UC set to idle mode while wind speed is at rated value. From 46s to 62s the wind speed is kept at 11.5m/s in order see the dc-link power response for variations in the load change while inverter output is decreased to 10kW at 51s. At 68s the UC set to charging mode again and it follows the wind power. At 73s UC changes its mode from charging to discharging when the inverter output is increased to 90kW.

The UC terminal voltage response and dc-link voltage variations are shown in Figure 4.7. The Figure 4.7(a) shows the ultracapacitor terminal voltage variations along with threshold limit.Initially the V_{uc} is set to 360V and $V_{uc\_TH\_U}$ to 300V. From 3s the UC starts discharging as inverter output is increased, terminal voltage of UC keep decreasing and stops at 27s.At 32s the $V_{uc\_TH\_U}$ is set 380 as the $V_{uc} < V_{uc\_TH\_U}$ the UC starts charging. The UC charges for time duration 32-46s as the UC is reset to idle mode at 46s by changing the $V_{uc\_TH\_U}$ to 300V. At 68s the UC is set to charging mode again and keep charging until the inverter output is changed at 73s. When inverter output is increased the controller changes UC charging mode to discharging instantly.

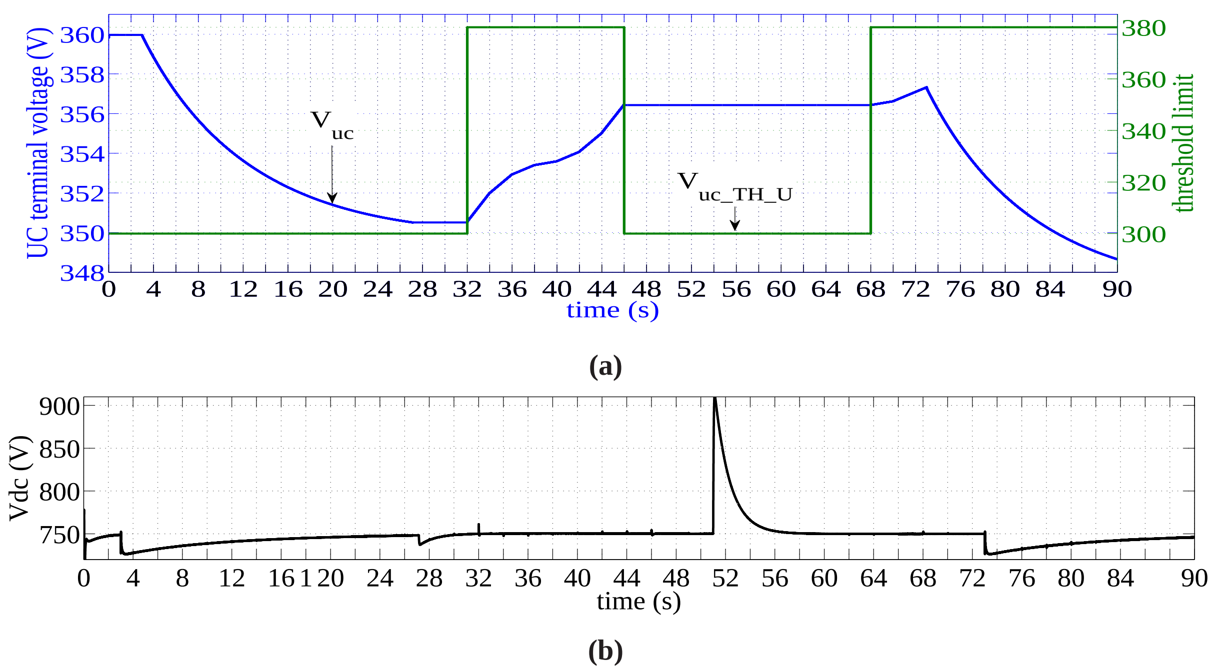
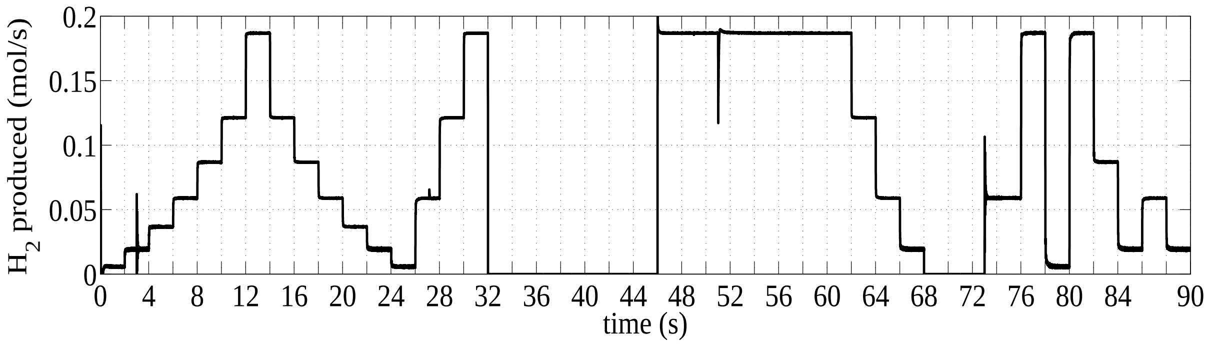


Figure 4.7: (a)UC terminal voltage (b) dc-link voltage

The dc-link voltage response is shown in Figure 4.7(b). The voltage is maintained constant at all time except for inverter output change. At 51s the inverter output reduced 10kW, during time instant the dc-link voltage rises and settle down to nominal value. When the inverter output increased from 10kW to 90kW at 3 and 73s the voltage dip can be observed eventually the dc-link voltage reaches to nominal. Small transient are occurred when ever the UC changes to charging/discharging or load is changed.



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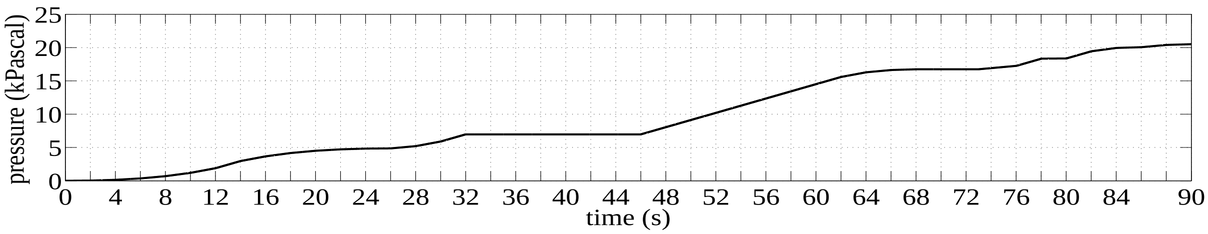
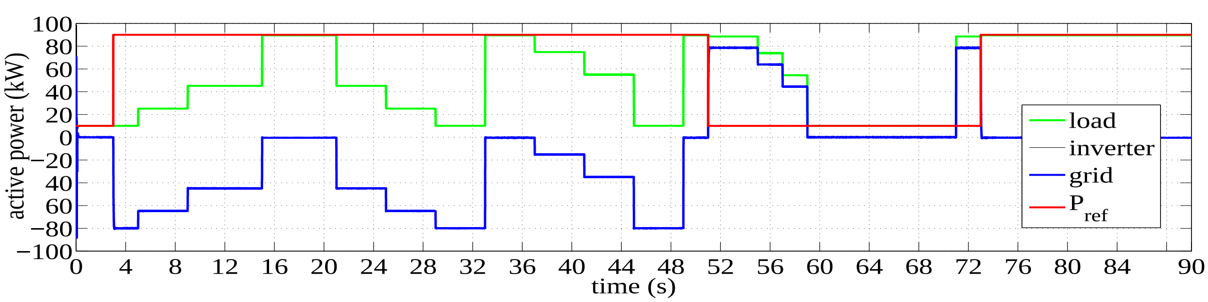


(b)

Figure 4.8: (a)hydrogen produced (b)storage tank pressure

The hydrogen generation from electrolyzer and pressure variations of storage tank is shown in Figure 4.8. The hydrogen produced from electrolyzer is shown in Figure 4.8(a) and pressure variation is shown in Figure 4.8(b). As wind power varies the hydrogen production also varies. Whenever the wind power is used to charge the UC the electrolyzer stops (32-46s and 68-73s). The pressure of hydrogen storage tank increases as hydrogen quantity increases.



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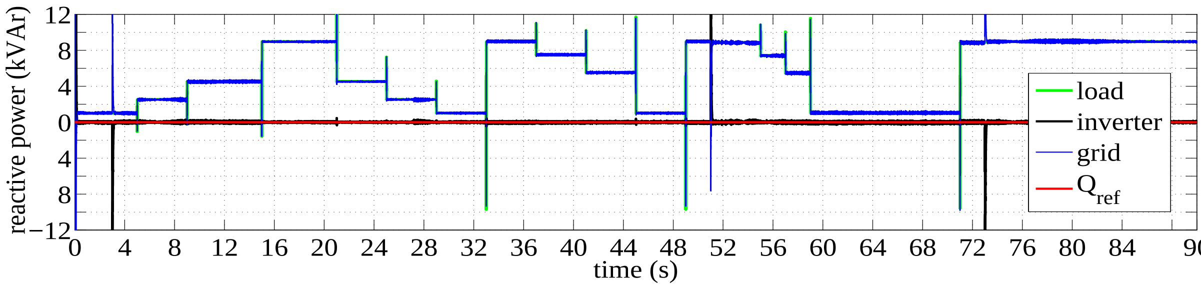

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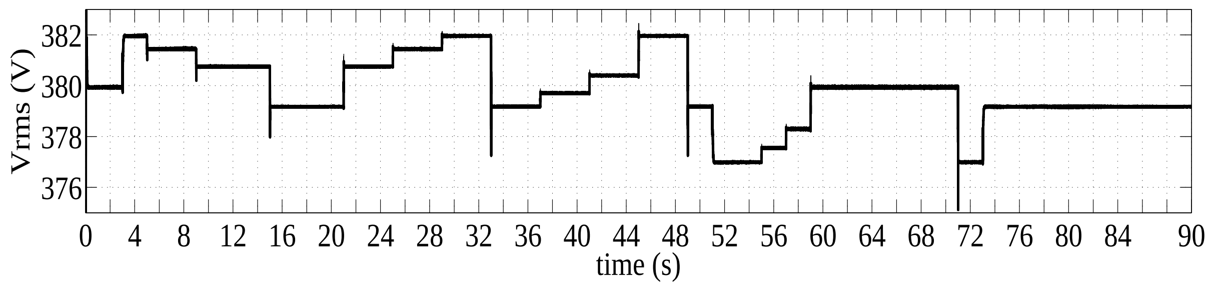
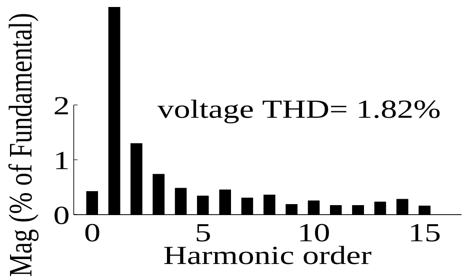


(c)

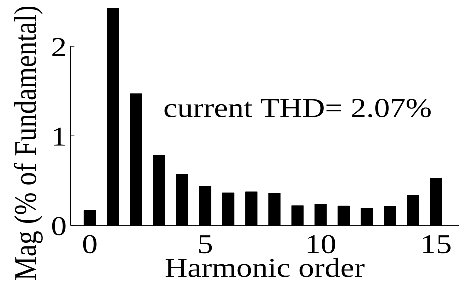
Figure 4.9: At PCC (a)active power (b)reactive power (c)rms voltage

The active and reactive of inverter, load and grid along with rms voltage response at PCC is shown in Figure 4.9. Figure 4.9(a) show the active power sharing between inverter, grid and load at common coupling point. Initially the connected load is 10kW and it is increased/decreased in steps of 25kw, 45kW and 90kW as shown in figure. The inverter output is set 10kw for the time duration 0-3s and 51-73s.The inverter output in maintained at 90kW during 3-51s and 73-90s. When inverter and load are equal (0-3s,15-21s,33-37s,49-51s and 73-90s) the grid power is zero. When inverter output is higher than the load (3-13s,21-33s and 37-49s)the excess power is fed to grid. When inverter power is less than the load power (51-59s) the deficit power is supplied by the grid. The reactive power response is shown in 4.9(b). The load reactive is considers are 1,2.5 4.5 and 9kVAr and it is met by the grid as inverter reactive power is set to zero. The Figure shows the reactive power variation of inverter, load and grid. The transients are seen during the change in inverter output at 3, 51 and 73s also for change in load.

Figure 4.9(c) shows the rms voltage at point of common coupling. The voltage remains constant during change in wind speed and switching of UC or electrolyzer. The inverter voltage is constant for any changes at dc-link voltage. The voltage rise can be seen when inverter output is more than the load and dip in voltage when the load in more than the inverter output. However the voltage is maintained well within the rated value.



(a)



(b)

Figure 4.10: % THD of (a)voltage (b)current

Figures 4.10 show the total harmonic distortion of inverter voltage and current at point of common coupling. The voltage and current THD are 1.82% and 2.07% respectively as shown in Figures 4.10(a) and 4.10(b) which are within the permissible limit of the standard.

4.4 Conclusion

The performance of Wind-SOFC base microgrid with electrolyzer and ultracapacitor is presented in this chapter. The control schemes are employed to control power electronic converter works satisfactorily in mitigating the slow dynamic response of SOFC by using ultracapacitor. The UC effectively performance and releases required power instantly when the load has been increased. The controller associated with electrolyzer converter is able to track the wind power variations and used by the electrolyzer to generate hydrogen. The wind power fluctuations are effectively suppressed by electrolyzer and also used for charging of UC. The common dc-link facilitates the integration of all devices into one single point and by which the wind power can be used by electrolyzer or the UC with minimum conversion stages. The system do not employ any dump load hence wind power is used efficiently. The system is dispatchable, reliable and efficient.

Chapter 5

PERFORMANCE STUDY OF MICROGRID WITH DC LOAD

5.1 Introduction

The combination of DG systems effectively mitigate the power fluctuations with energy storage systems. The fuel cell and renewable sources with hydrogen generation gives promising results in achieving green power generation which is reliable and sustainable.The effective utilization is limited if they are operated only in grid connected or isolated mode. To exploit maximum benefits it can be operated in both grid connected mode as well islanded mode. The part of grid which is supplied by the DG efficiently regardless of grid availability forms the microgrid [Chris et al. 2008]. The microgrid provides the more flexibility in control and operation and able to provide reliable, sustainable and quality power. The microgrid operation control and management strategies are discussed in [San Martin et al. 2010, Eduardo et al. 2014].

The dc load are increasing nowdays. The dc loads are supplied with many conversion stages. The industries like data-centers, communication and commercial building required dc power [Daniel and Ambra 2007, Daniel et al. 2008]. The appliances like LED lighting, BLDC motors, electric vehicles are based on dc power. The dc system has many advantages like reduced conversion stages, reduced losses and less cost.The fuel cell,rectified output of wind system and battery outputs are in dc form. Hence using power in dc form can be more advantageous [David et al. 2013, Jackson et al. 2013]. In order to supply new coming loads based on dc power, the microgrid may have flexibility is supplying both existing ac load and dc loads as well. The different ac-dc microgrid structures with DG system and storage are presented in [Hiroaki et al. 2010, Lie and Dong 2011, Xiong et al. 2011, Poh et al. 2013]

In this chapter the performance of ac/dc microgrid is presented. The SOFC and wind system with PMSG are considered as energy resources. The ultracapacitor and battery are considered for storage system along with electrolyzer to generate hydrogen. All the energy resources, storage devices, electrolyzer and dc loads are connected to common dc-link. The both ac and dc loads are considered. The dc load of 48V and 380V are considered for study. The ac loads are fed by 3-phase VSI which also interface with grid.The performances is studied for the both grid connected and islanded mode.The SOFC considered as main source in its absence the minimum loads are supplied by the battery. The UC is used to mitigate the slow dynamic response of SOFC as well control discharge rate of battery. The wind power is used charge ultracapacitor,battery and to generate hydrogen. In case of the wind power unavailability and UC goes below lower limit, battery power is used to charge the UC. For the wind power utilization, two cases are considered one is when wind power is used to supply the load with SOFC in grid connected mode. In second case the wind power is used charge the energy storage device or for the electrolyzer and SOFC supplies load.The performance is studied for islanded mode of operation.The ac/dc microgrid schematic block diagram is shown in Figure 5.1.

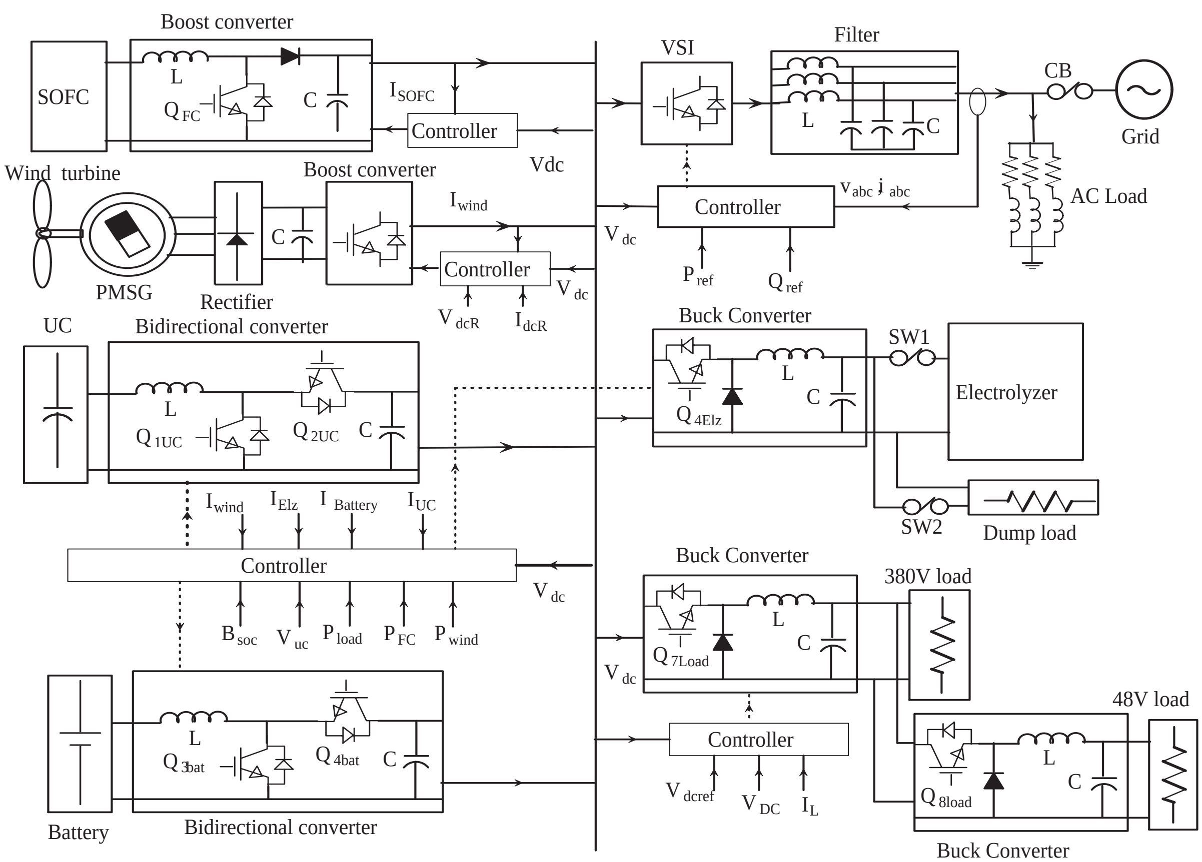
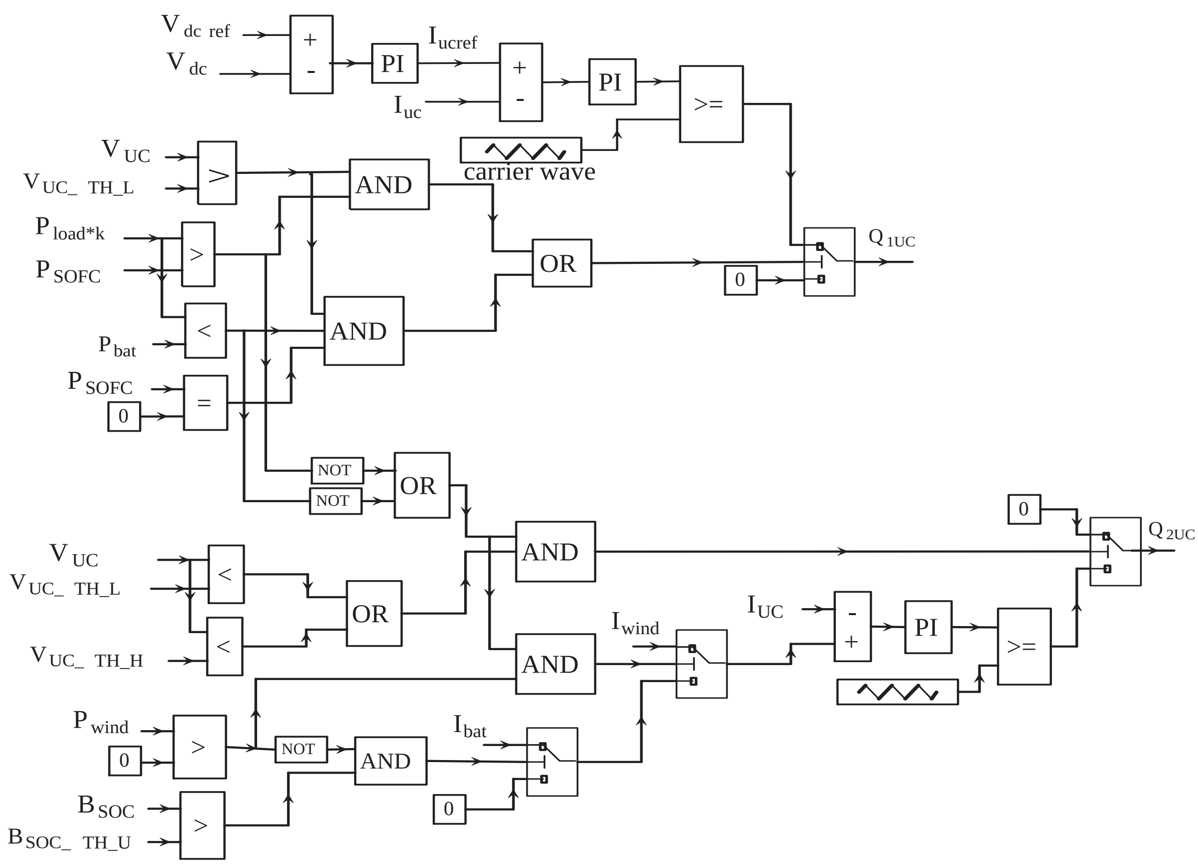


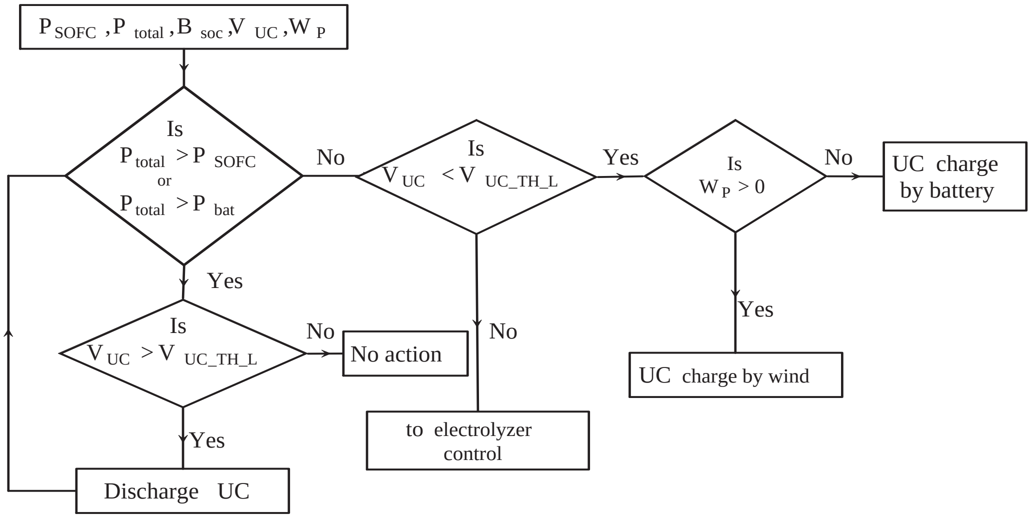
Figure 5.1: Block diagram of ac/dc microgrid.

5.2 The Microgrid Control Schemes

The control schemes are employed to control and coordinate the different energy resources, storage devices and load. The UC has to discharges when the load has been increased. The battery discharges when the fuel cell is disconnected which serves the minimum load and in case UC needs to be charged using battery. The wind power is used by electrolyzer, battery and UC or dissipated by dump load. The control has to provide fast and smooth transition between these devices for effective wind power usage and maintaining the dc-link voltage within limits. A simple islanding detection scheme has been adapted in this work. In grid connected mode the the microgrid uses both dc and ac load, a proportional power reference for inverter output need to be set by which total load (dc and ac combined) do not exceeds the rated capacity. In islanded mode a proper load control scheme is necessary to balance the dc and ac load within the capacity.However in this study the explicitly the load control is not considered as it may comprise many combinations. The resynchronization is not considered specifically.The load variations are considered are minimum load and maximum load in case of islanded operation.



(a)



(b)

Figure 5.2: (a)Control scheme of ultracapacitor (b)Flow chart

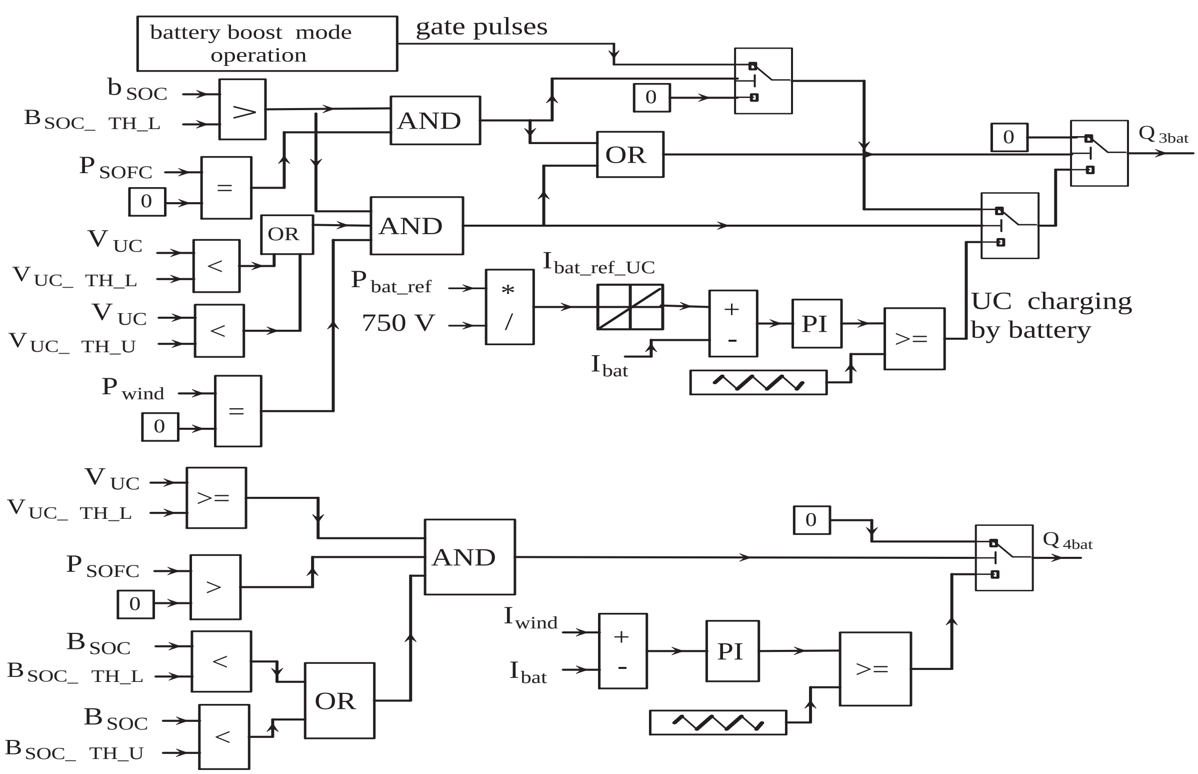
The ultracapacitor control scheme is shown shown Figure 5.2(a). The UC will discharge under following conditions;(a) when the sudden load is applied as SOFC gradually increases the power (b) when the SOFC is disconnected the battery has to supply the critical load and battery discharge rate need to be controlled and (c) when the SOFC is reconnected while battery stops discharging. For third condition without UC action, the SOFC can gradually increases power while the battery decreases the power delivery. However in our study the ultracapacitor discharging condition is considered. When the conditions $P_{load} > P_{SOFC}$ (for load sharing the $P_{load} > P_{wind}$+P_{SOFC}) and $V_{uc} > V_{UC\_TH\_L}$ are met uc starts discharging instantly. The V_{dc_ref} and V_{dc} are compared and error is given to outer PI controller to generate the reference current (I_{UC_ref}). The error between reference current and UC current (I_{UC}) is used to generate the control signal. The control signal is used to generate gate pulses for boost mode of operation of UC bidirectional converter. Ultracapacitor instantly discharges when SOFC is disconnected and battery also starts discharging slowly. The UC discharging is initiated instantly when the SOFC reconnected and battery stops discharging(for load sharing case the battery discharge mode is not considered).

The UC charging is carried out when the $V_{uc} < V_{uc\_TH\_L}$, $P_{load} >= P_{SOFC}$ and $V_{uc\_TH\_U}$ are set to charging mode. The UC can be charged using wind power when the above condition is met (in case of load sharing the ultracapacitor charging is initiated when $P_{wind} > P_{load}$). In case the UC is below the lower threshold value $V_{uc\_TH\_L}$ and wind power is not available, at this condition if the battery soc is well within the $B_{soc} < B_{soc\_TH\_L}$, the battery power is utilized for charging of the UC.The flow chart for ultracapacitor control scheme is shown in Figure 5.2(b).

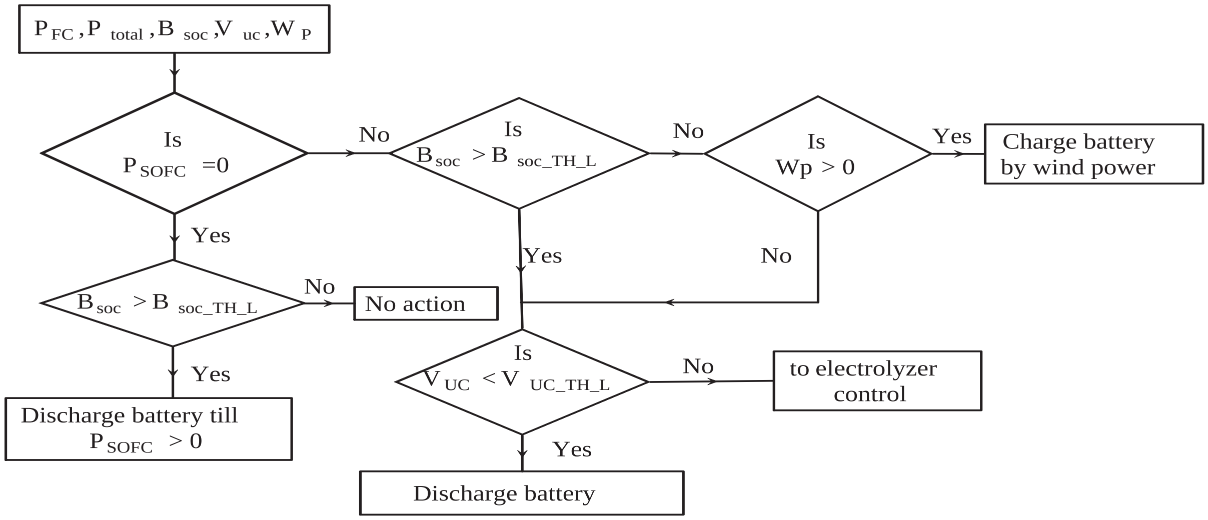
5.2.1 Battery control scheme

Battery control schematic is shown if Figure 5.3(a). The battery is discharged under two conditions. The first condition is when the SOFC is disconnected. The error between V_{dc_ref} and V_{dc} is used to generated I_{bat_ref} from outer PI controller. The battery current I_{bat} and I_{bat_ref} is compared and error given to inner PI controller to generated control signal which then used generate gate pulses. The PI values are selected such that the battery power gradually increases.

For second condition when the UC charge is below the lower threshold limit $V_{uc\_TH\_L}$ and wind power is zero. To control the quantity of power delivered from battery depending upon battery SOC and battery capacity the battery power reference need to be set. The $I_{bat\_ref\_uc}$ is calculated from the battery power reference P_{bat_ref} and V_{dc}. The reference current is passed through the rate limiter which controls the rising or falling rate of reference current. The reference battery current is compared with battery current I_{bat} and error is given to PI controller to generate control signal.



(a)

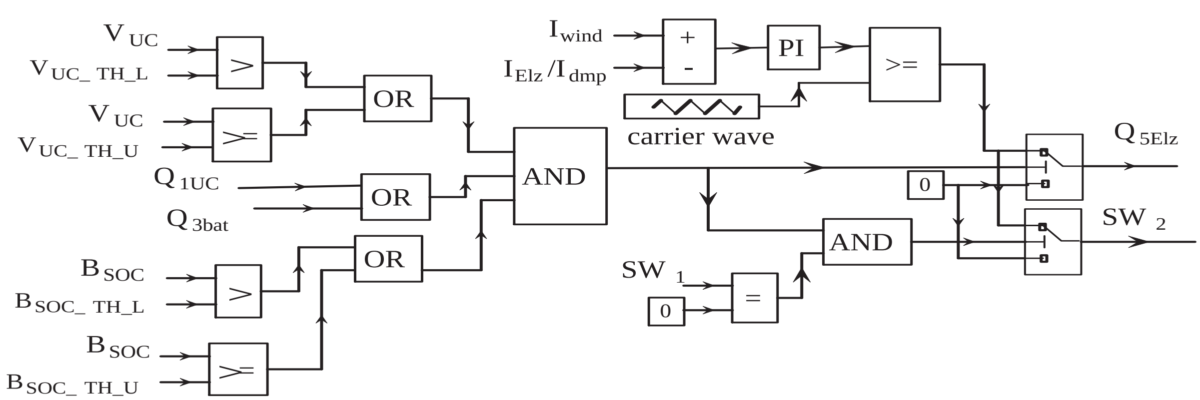


(b)

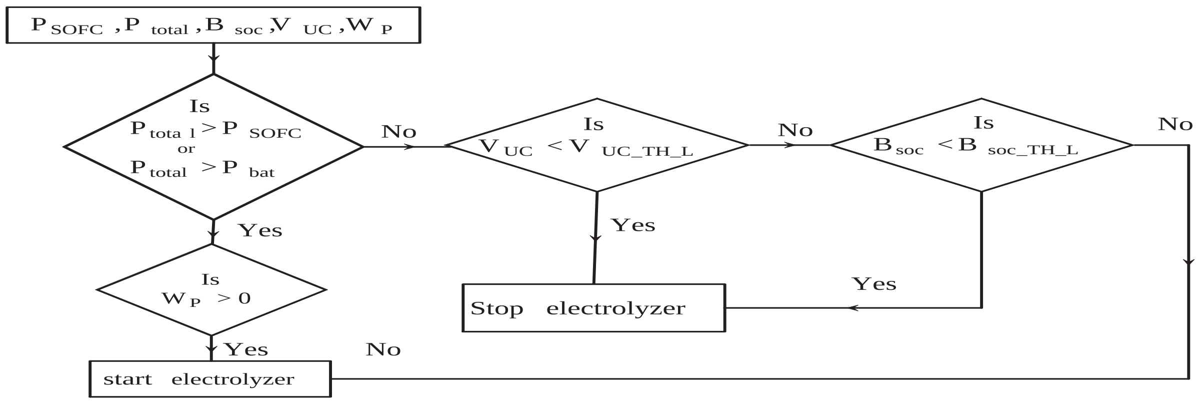
Figure 5.3: (a) Battery control scheme (b) Flow chart

The charging of the battery is carried when the $B_{soc\_TH\_L}$ below the lower threshold limit or the $B_{soc\_TH\_U}$ is set for charging mode, UC is in idle mode or discharging. The wind current I_{wind} is compared with I_{bat} and error is given to PI controller. The controller generates the control signal for buck mode of operation of bidirectional converter.The flow chart for the battery control scheme is shown Figure 5.3(b)

5.2.2 Dump load and electrolyzer control scheme



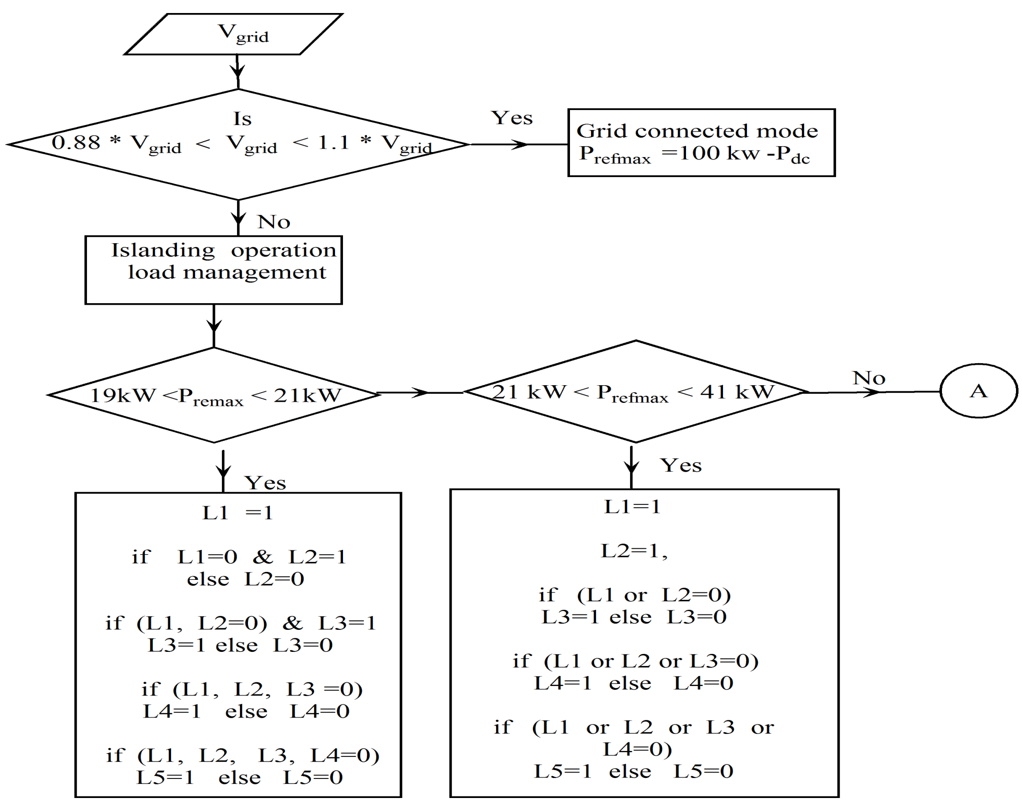
(a)

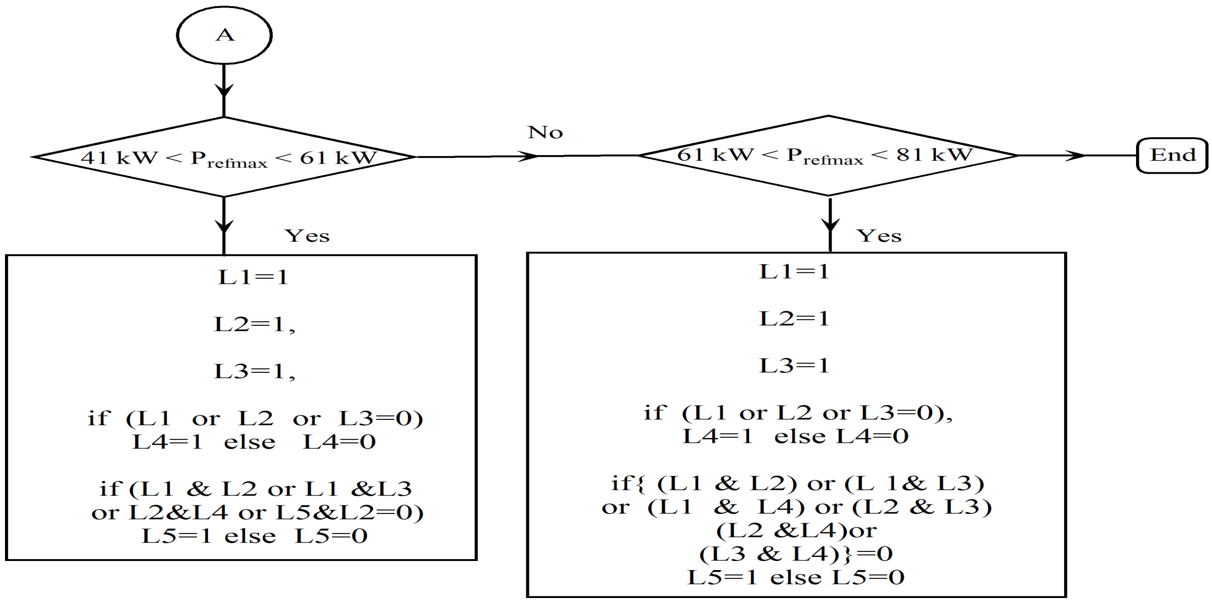


(b)

Figure 5.4: (a)Electrolyzer control scheme(b)Flow chart

The electrolyzer and dump load control scheme is shown in Figure 5.4. The electrolyzer is activated when the battery and UC are within charged condition $B_{soc} >= B_{soc\_TH\_U}$ and $V_{uc} >= V_{UC\_TH\_U}$. In case the electrolyzer is disconnected while the battery and UC are charged condition to maintain the power balance the dump load is activated to dissipate the wind power.





(a)

Figure 5.5: Microgrid islanding detection and load control scheme.

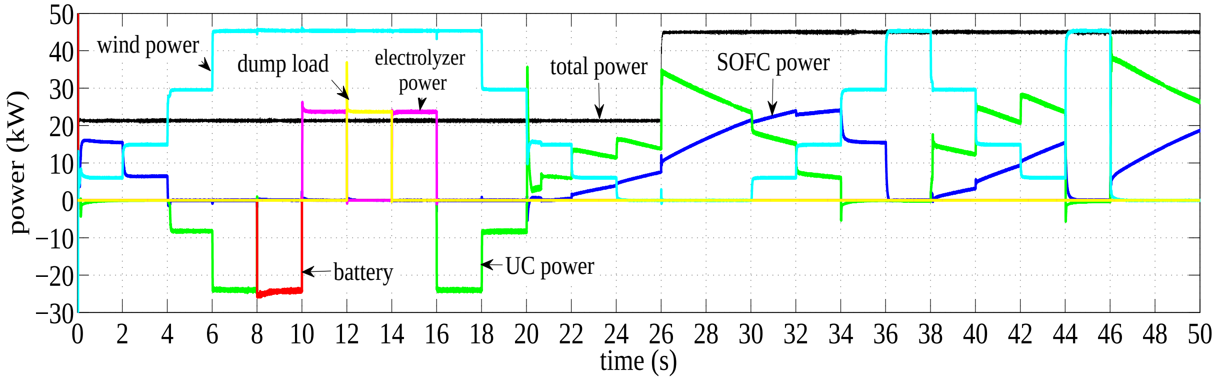
A islanding detection is adapted for system where the voltage and frequency are used to detect the loss of grid [Gaonkar et al. 2008]. The load management scheme is shown in Figure 5.5. Depending on the dc load connected, the inverter output reference can be set (P_{refmax}=100kW-P_{dc}). When the SOFC is disconnected the minimum load (20kW)is supplied by the battery and all other loads are disconnected. In case of islanding operation the ac loads are managed depending on the how much dc load is connected. A priority based load management can be used. Depending on how much power is available to ac load. The load shedding algorithm is not considered explicitly in the study. The control schemes for load sharing by SOFC and wind is not discussed separately. The conditions for UC ,battery and electrolyzer control remains same with few modifications.

5.3 Results and Discussion

The microgrid performance study is presented in this section. The two scenarios are considered. For case one the wind and SOFC share the load in grid connected mode is presented. The UC, battery, SOFC and electrolyzer power variations are presented using simulations results. The dc load voltage and power response (48V and 380V) is given. The inverter power output and load change are studied. The different load levels i.e the load is less than wind power, load is almost equal to wind power and load more than than the wind power considered.

In the second scenario the SOFC supplies connected load and wind power is used to charge the battery/UC or to generate hydrogen in islanded mode of operation. The battery supplies the minimum (20kW together ac and dc) when the SOFC is disconnected. The UC performance for the mitigation of slow dynamic response and controlling the battery discharge rate is presented.

5.3.1 Microgrid performance in grid connected mode



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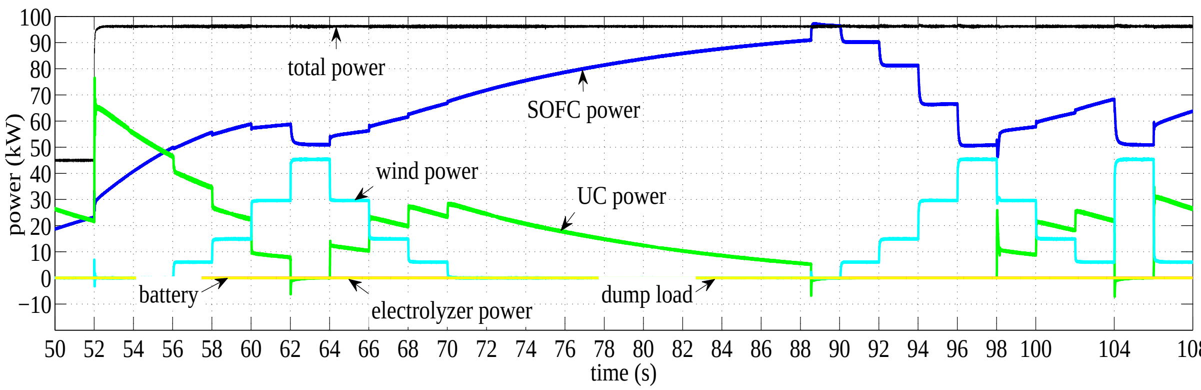
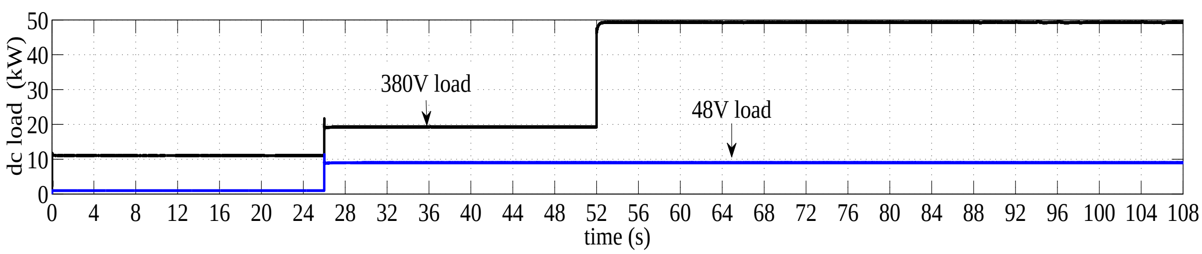


(b)

Figure 5.6: (a) dc-link power when the load is less than or equal to wind power (b)dc-link power when load is more than the wind power.

The dc–link power response is shown is Figure 5.6. The performance system when load is less than or equal to wind power is shown Figure 5.6(a). Initially the load is kept at 20kW (10kW ac and 10kW dc) The wind speed is varied from 6-11m/s and maintained till 18s. The total load is shared by the wind and SOFC, as wind power increases the SOFC power delivery decreases. When wind is higher than the load (from 4s) the excess wind power utilized by UC, battery,electrolyzer or by the dump load(4-18s). At 18s the wind power decreased at this instant the UC is charging, as load is less than wind power UC continued to charge. At 20s the wind power further reduced which is less than the load hence UC starts discharging instantly and SOFC gradually increases its power.At 45s the load is increased to 45kW (20kW dc 25kW ac). The wind speed is varied (increased from 0-11.5m/s and decreased to 0m/s in steps) as wind power is varied the SOFC, wind and UC share the load as UC releases the required power proportionally. From 26 to 50s as wind power varies the SOFC undergoes fluctuations which varies from zero to load requirement.

The system response when the load is higher than the wind power is shown in Figure 5.6(b). At 52s the load power increased to 95kW (50kW dc and 45kW ac) at this time the UC is discharging as load is increased the UC compensate the required power and SOFC continued to increase the power and UC decreases accordingly. From 52- 108s the wind power varied as the SOFC power also varies accordingly. However any increases in SOFC power takes place gradually. In this case the SOFC fluctuate between maximum to half of the maximum load as wind supplies the rest of the load. The load sharing sets the SOFC into fluctuations which is not desirable.



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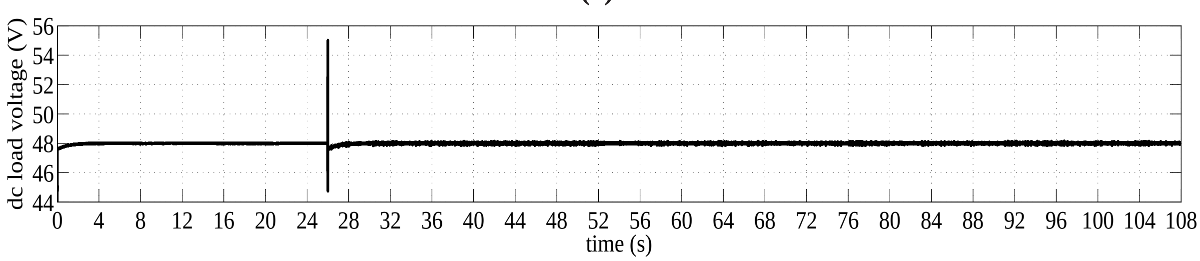

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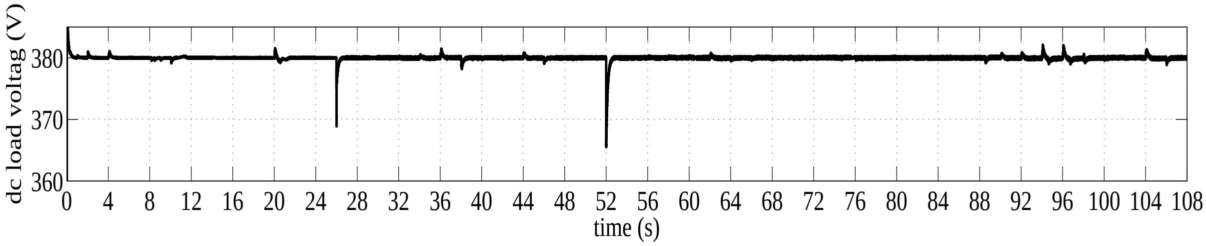
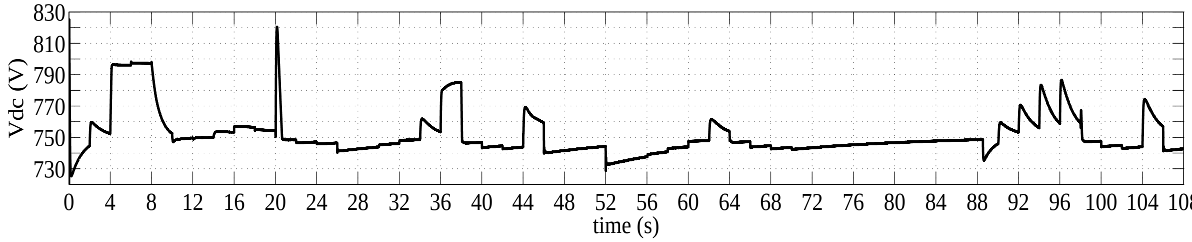


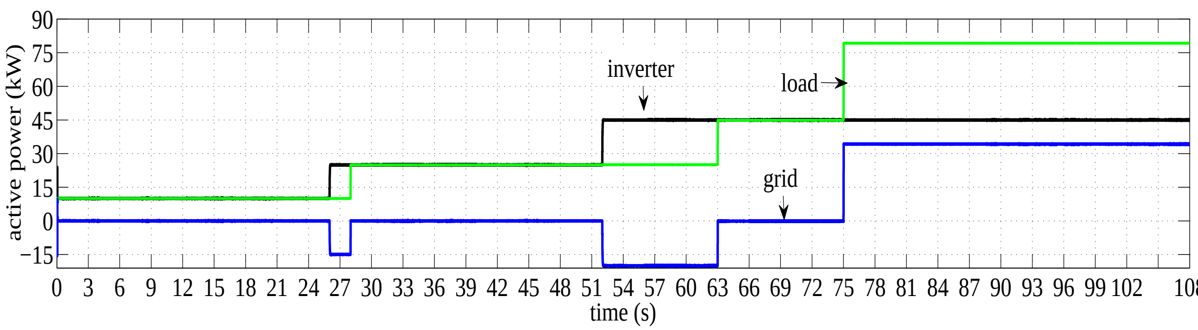
(c)



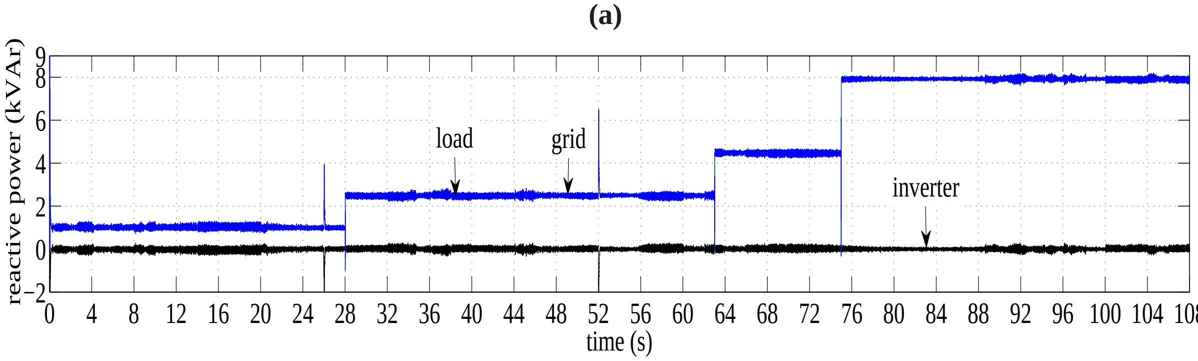
(d)

Figure 5.7: (a) dc load (48V and 380V) (b)48V dc load voltage (c)380V dc load voltage (d)dc-link voltage.

The dc load, load voltage and dc-link voltage response is shown in Figure 5.8 The dc load variations is shown 5.8(a). The dc load voltage 48V and 380V are shown in figure 5.8(b) and 5.8(c) respectively. The transients can be observed when there is load change, however these settle down quickly. A momentary dip in voltage can be seen in 380V load voltage when the load in increased. The dc-link voltage is shown i Figure 5.7(d) The voltage rise can be seen wind power is more than load. The transients can seen whenever the UC discharges or wind power varies.



(a)



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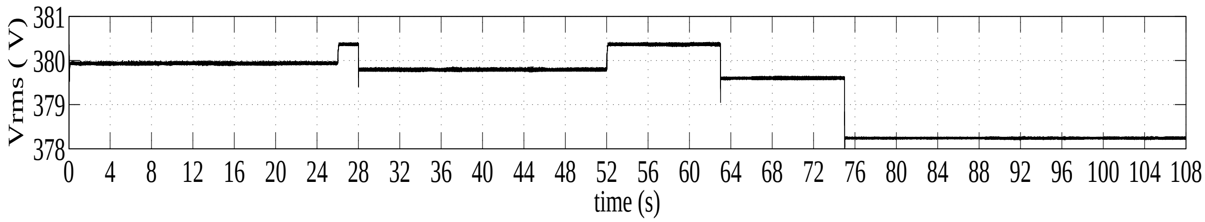


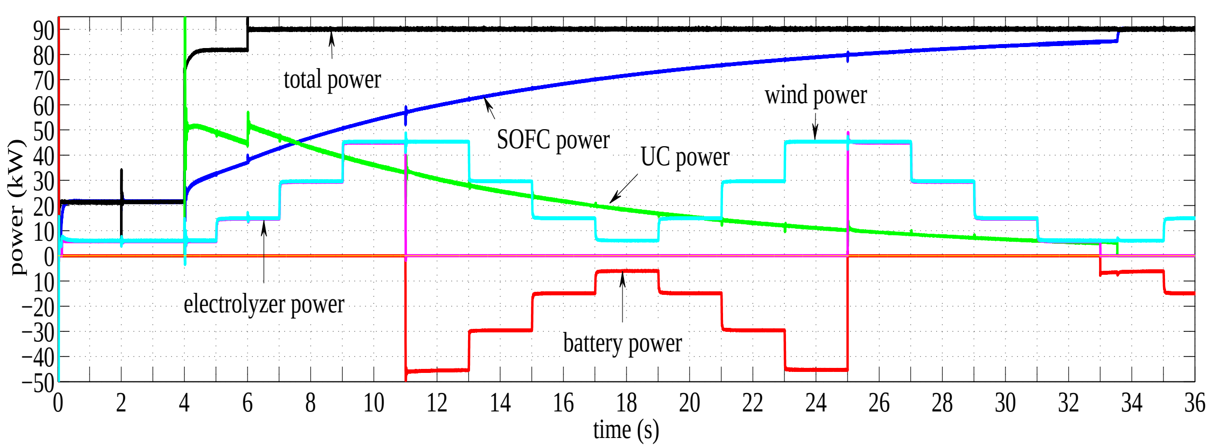
(c)

Figure 5.8: (a)active (b) reactive power (c) V_{rms} at PCC of microgrid

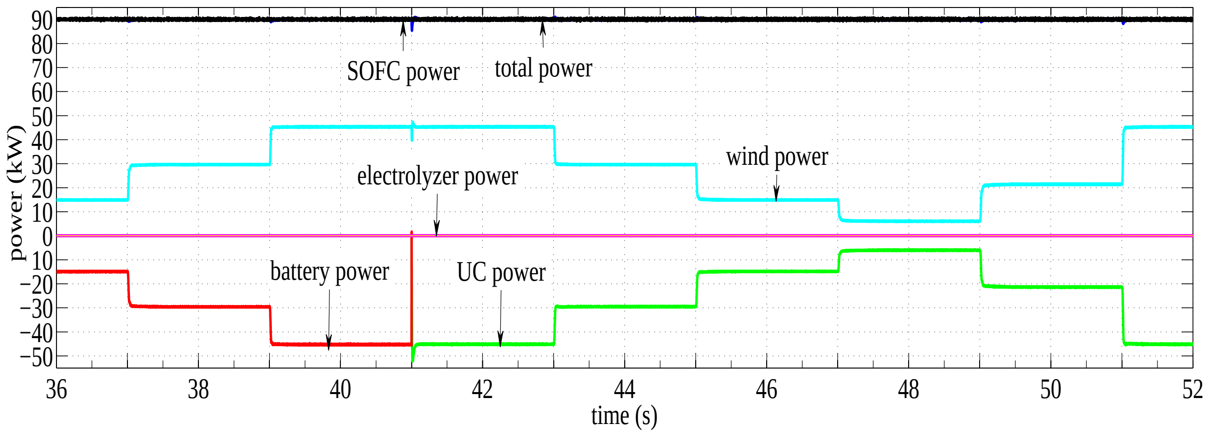
The active and reactive power sharing between the inverter, grid and load with rms voltage at PCC is shown in 5.8. The inverter, grid and load active power variations is shown in Figure 5.8(a). The reactive power variations is shown in Figure 5.8(b). The inverter reactive power is set to zero in grid connected mode hence the load reactive power is compensated by grid. The rms voltage at PCC is shown in Figure 5.8(c).The voltage is maintain constant for all conditions except small dip in voltage can be seen when the load is increased.

5.3.2 The microgrid performance in islanded mode.

In this section the microgrid operation in islanded mode is given. Initially the microgrid is connected to main grid. At 2s the grid voltage is set zero to indicate the loss of grid. A programmable three phase voltage source is used for this purpose.



(a)

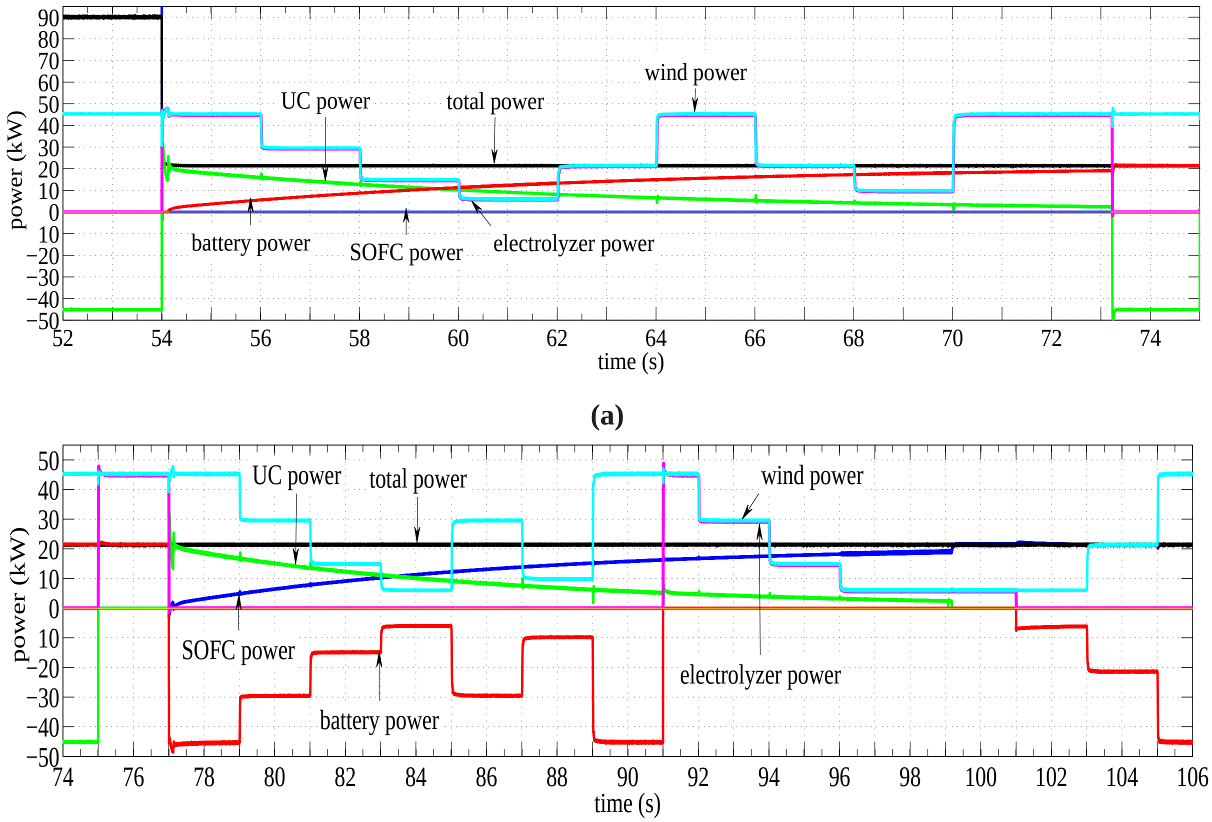


(b)

Figure 5.9: The dc-link power variations (a)UC discharge and battery charging (b)UC charging, transition between storage devices and electrolyzer

The dc-link response for dc load increase is shown in Figure 5.9(a). Initially the the wind speed is at 6m/s and electrolyzer in on. At 2s the grid is disconnected and inverter starts supplying load in islanded mode. At 4s 380V dc load is increased to 70kW. Immediately the UC starts discharging to supplying the required load as SOFC gradually increases the power delivery. At 6s the 48V dc load increase to 1kW to 10kW instantly the UC responds to load change increases the UC power delivered. The wind speed is varied from 5s.The wind speed from from 6 to 11.5m/s (increase/decrease) for every 2s. As the wind power varies the electrolyzer power also varies. At 11s the battery is set to charging mode, the battery starts charging with varying wind power.At 25s the battery is set to idle mode immediately electrolyzer starts consuming the wind power.

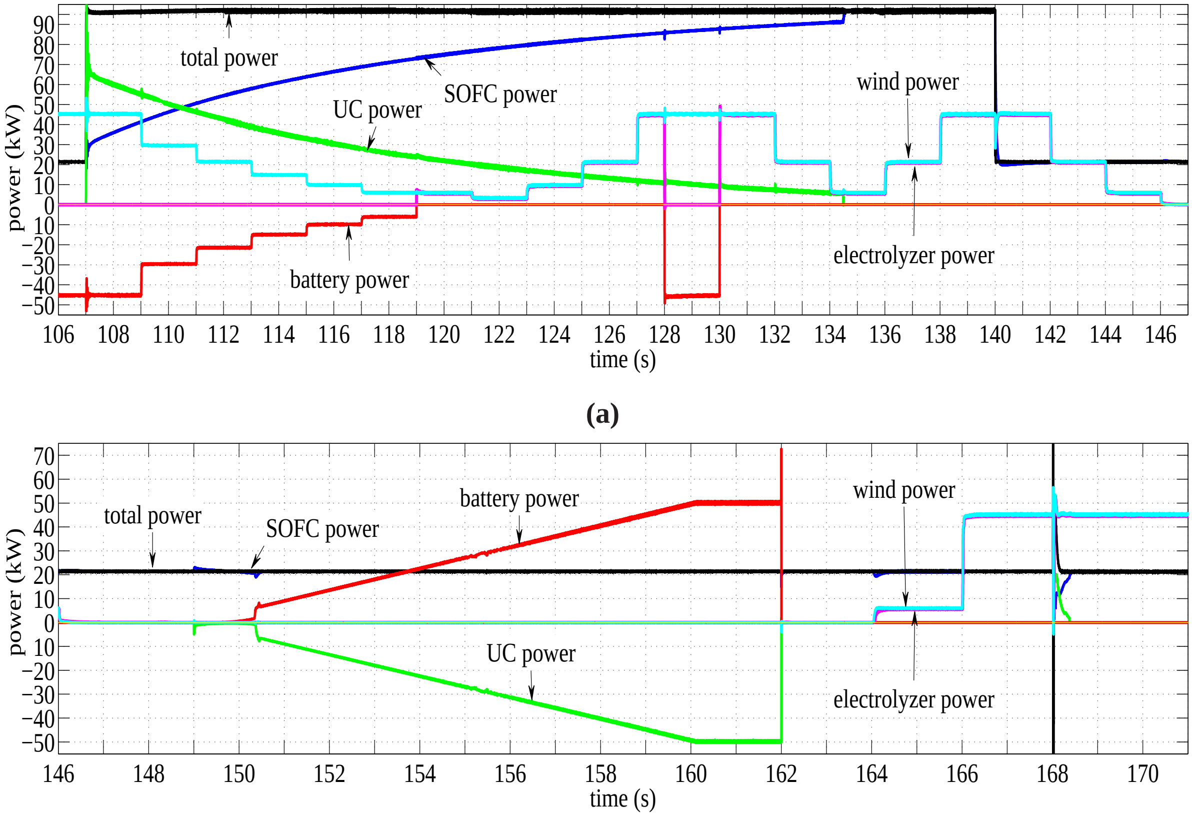
At 11s and 25s wind power is at maximum and its utilization is interchanged between electrolyzer and battery, the transients can be observed in dc-link and settles down fast. However at 33s when wind power is minimum (6m/s) the battery is set to charging mode and the transients are not significant. Around 33.4 the UC stops discharges as SOFC reached the required power level. The Figure 5.9(b) shows the transition of battery charging to UC charging. At 41s the UC set to charging, as first priority is given to UC it starts charging and battery enters to idle mode. As the wind varies UC power consumptions varies.



(b)

Figure 5.10: (a)Battery supplying load (b)SOFC reconnected.

From 51s the wind power reaches to maximum(11.5 m/s), UC is charging, battery is also in charging mode.The Figure 5.10(a) shows the UC, battery and electrolyzer response to SOFC disconnection. At 54s the SOFC disconnected, instantly the UC takes transition from charging to discharging mode, battery starts discharging slowly and gradually increases the power and electrolyzer starts consuming the wind power.At 72.2s the battery reaches the load requirement and UC stops discharging and starts charging using the wind power as it its charging mode is in set mode.The electrolyzer becomes idle. At 75s the UC stops charging and electrolyzer becomes active.At 77s the SOFC is reconnected to dc-link hence the UC Starts discharging and battery changes its discharging mode to charging. (In the study the SOFC start up case is not considered.)As SOFC power increase the UC decreases and stops at around 99s. The wind is keep varying according the battery charging varies.At 91s the battery is set to idle mode hence as UC is still discharging the electrolyzer starts generating hydrogen.At 101s the wind power is at minimum the battery is set to charging mode again.



(a)

(b)

Figure 5.11: The dc-link power response when(a)ac load is increased (b) UC charging by battery power

The system response for increase in ac load is shown Figure 5.11(a).At 107s the ac load is increased from 10kW to 80kW. Immediately the UC starts discharging, transients can be seen in battery power battery as it is in charging, however transients settles down fast. The SOFC power gradually increase accordingly UC power decreases. At 119s the battery is set idle mode when the wind power is minimum. The wind speed kept varying (between 6m/s to 11.5 m/s) at every 2s. At time 128s & 130s the battery set to charging and idle mode during which the transients can be observed in dc-link. Around 134.3s the UC stops discharging as SOFC reached the load demand. The ac load is decreased to 10 kW at 140s and wind speed decreased to minimum at 146s. At 149s the battery is initiated to charge the UC as wind power is zero. The UC starts charging gradually from battery. Battery power increases slowly as shown in Figure 5.11(b). At 162s the UC set to idle mode hence the both battery and UC enters to idle mode.From 164s the wind start increasing and reaches to maximum value by 166s. At 168s the microgrid is reconnected to grid hence large transients can be observed at that time.

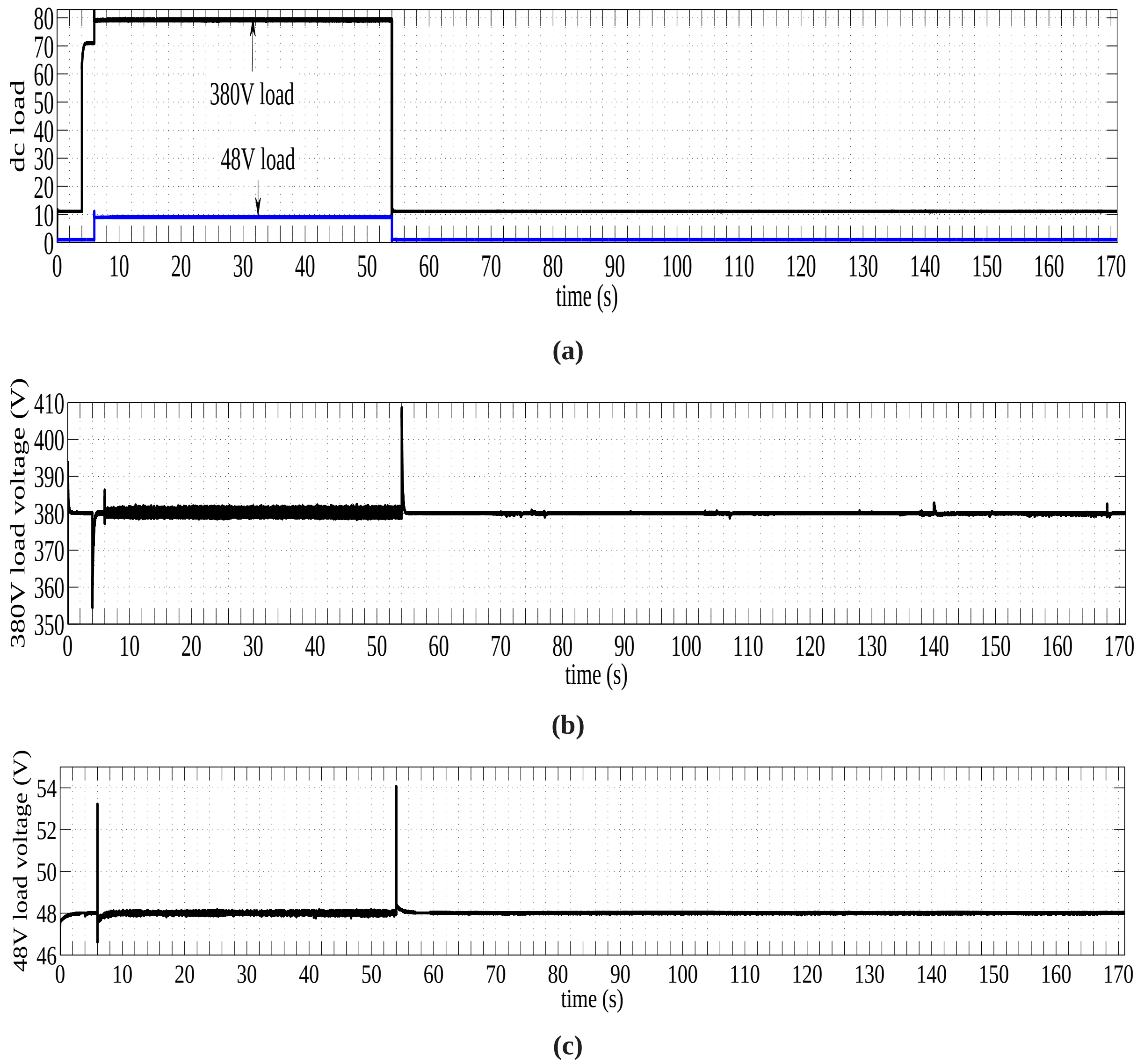
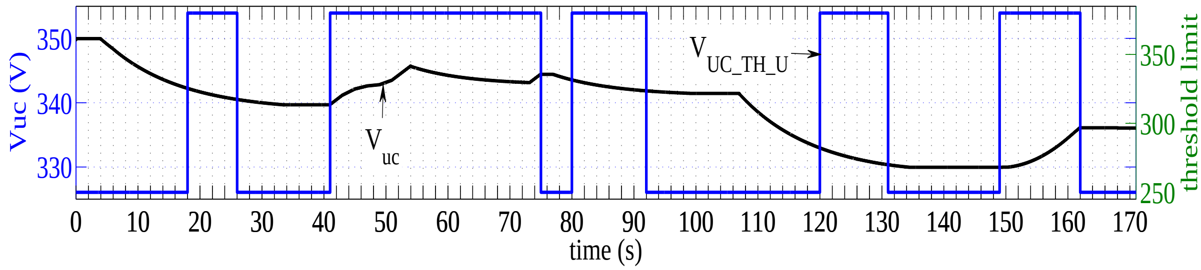


Figure 5.12: dc-load and voltage variations.(a) 48V and 380V load variations (b)380V load voltage (c)48V load voltage.

The Figure 5.12 shows the dc load and voltage response. The 380V load is increased at 4s and 48V load is increased at 6s the response of the load change is shown in Figure 5.12(a). The load change effects are seen in the load voltage responses. When the load (380V) is increased dip in the voltage can be seen in Figure 5.12(b).At 6s transient occurs and settle down fast. However the voltage is maintained at 380V.At 54s the both 380 and 48 V loads are set to minimum (10 kW and 1kW respectively), rise in both load voltages can be observed. The 48V load voltage is shown in Figure 5.12(c)



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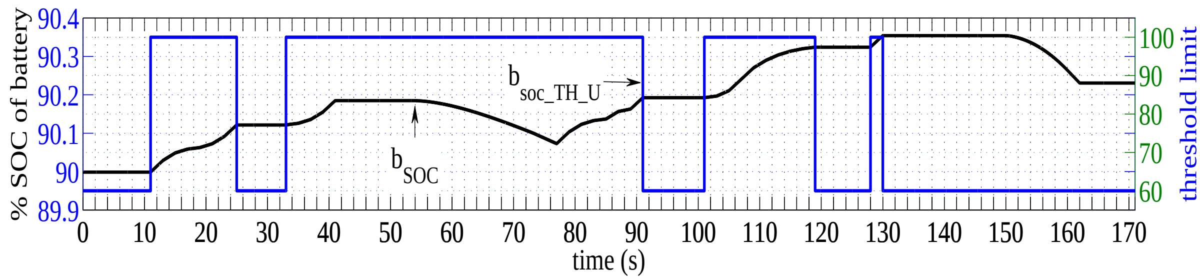

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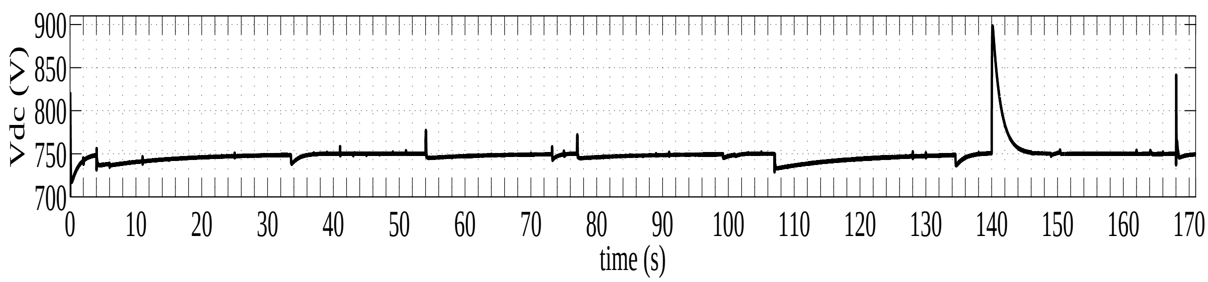
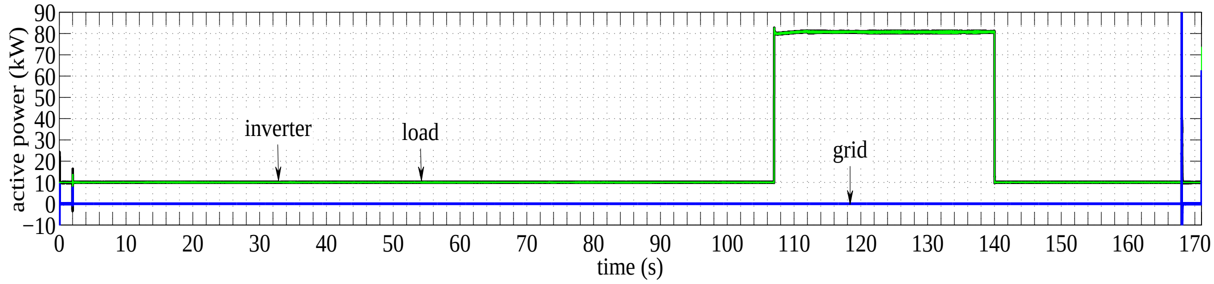


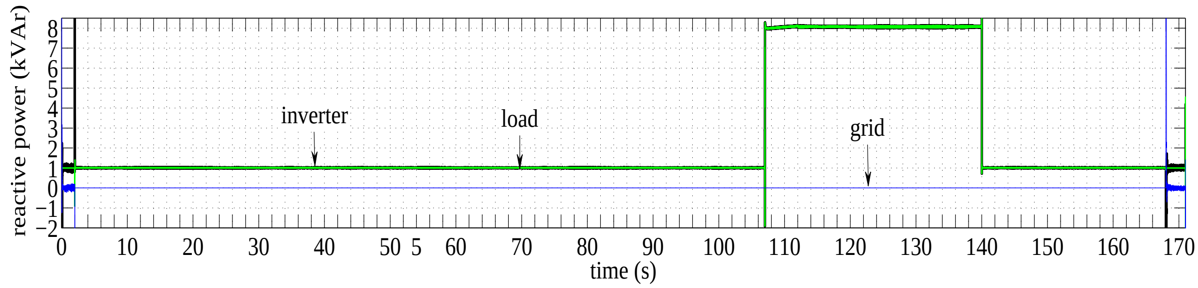
(c)

Figure 5.13: (a) UC terminal voltage (b)battery state of charge (c)dc-link voltage variations.

The ultracapacitor terminal voltage response is shown in Figure 5.13(a). As the UC discharges the terminal voltage decreases (4-33s,54-72.3s,77-99.2s,107-134.3s). The threshold limit used to control charging mode is also shown in the figure. The controller able manage properly when UC is set to charging mode when it is discharging. The UC keep discharging even when the $V_{UC\_TH\_U}$ is set to charging mode (18-26s ,54-72.3s,..).The Figure 5.13(b) shows the battery state of charge along with upper threshold limit.When battery charges the SOC increases (11-25s,33-41,77-91,101-119s and 128-130s) and decreases when battery discharges(54-77s and 150-162s). As control schemes responds properly the battery discharges even when the it set to charging mode by setting the $B_{SOC\_U\_TH}$ is set to 100. The dc-link voltage is shown in Figure 5.13(c).The transients are occurred when the load in changed, dip in the voltage can be observed when the load is increased and spike in the voltage when the load in reduced. A large spike can be observed when the ac load in reduced to minimum(140s) and when the system in reconnected to grid (168s).



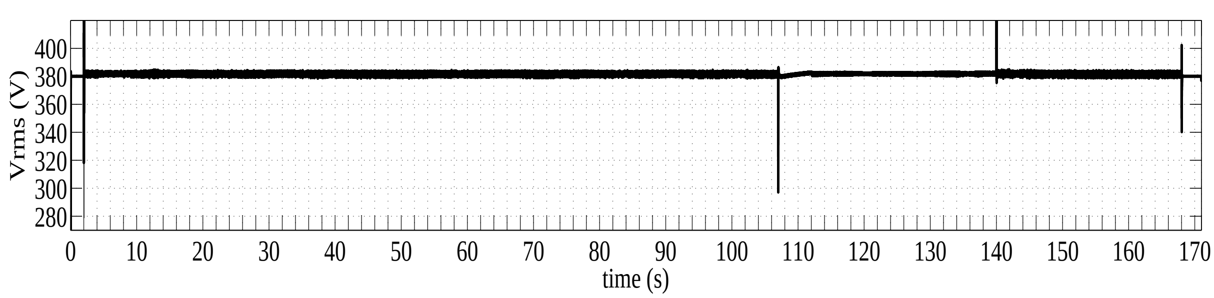
(a)



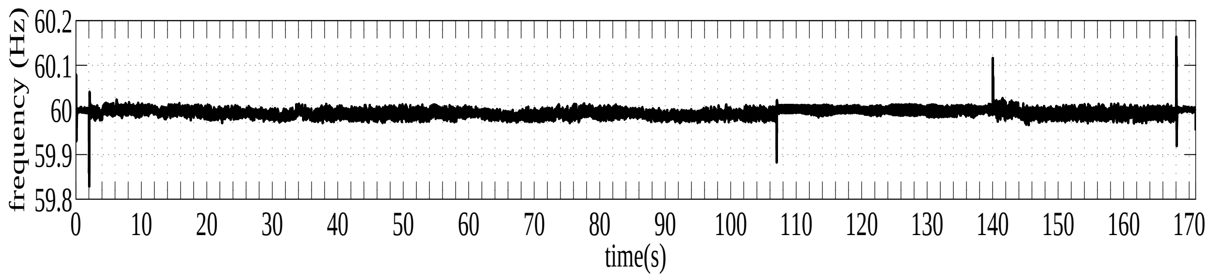
(b)

Figure 5.14: Inverter (a)active power (b)reactive power

The active power response of inverter, load and grid is shown in Figure 5.14(a). Initially inverter supplies required load and grid active power is zero. At 2s the variations in active power can be seen in figure as system switches to islanding mode. At 107s the load active is increased to 80 kW and inverter efficiently supplies the load demand. The load is decreased to minimum (10kW) at 140s. The large variation occurred at 168s when the system is reconnected to grid. Similarly the reactive response is shown in Figure 5.14(b). Inverter effectively delivers the load reactive power demand. The variations can be seen when when system disconnected (2s) or reconnected (168s) to grid.



(a)



(b)

Figure 5.15: Inverter (a) rms voltage (b)frequency

The rms voltage of inverter is shown in Figure 5.15(a).The voltage variation occurred when the microgrid switches between grid connected to islanded(2s and 168s). A momentary dip in voltage can be observed when the ac load is increased (104s) and rise at 140 when load is reduced.However the inverter output voltage is maintained at 380V.The frequency response of inverter is shown in Figure 5.15(b). The frequency is maintained constant except for the instant when the system switches between grid to islanded mode (2s and 168s) and when load is varied (104s and 140s). The variations are small and settles to nominal value quickly.The wind speed variations is shown in Figure 5.16

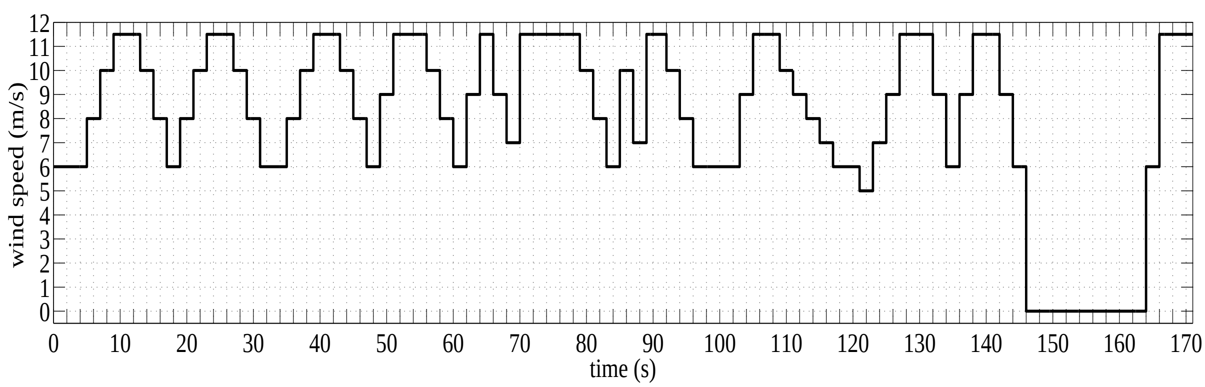
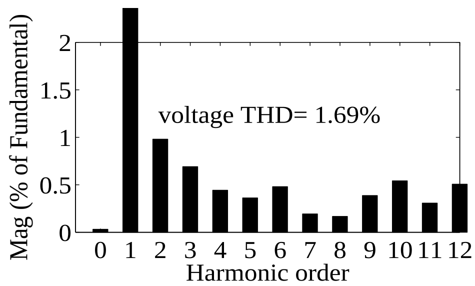
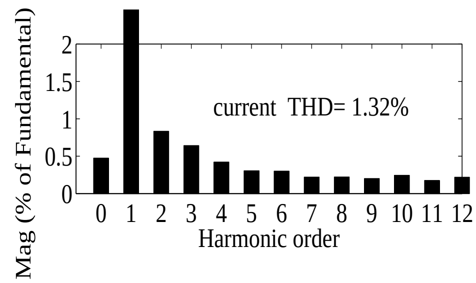


Figure 5.16: wind speed variations

The inverter %THD is shown in Figure 5.17.The voltage %THD of the inverter is 1.69% and is shown in Figure 5.17(a) and is current %THD is 1.32% shown in Figure 5.17(b). The voltage and current THD values within permissible limits



(a)



(b)

Figure 5.17: THD of inverter output (a)% THD of voltage (b)% THD of current.

5.4 Conclusion

The performance of the microgrid is presented in this chapter. The microgrid is operated in both grid connected and islanded mode. The performance analysis of microgrid in grid connected mode while SOFC and wind share the load is given. The SOFC performance is affected due to change in wind speed as SOFC power varies frequently.The storage devices charging is limited. Storage devices can be changed when the load is less than the wind power generated. The SOFC power variation is drastic when load is less than or equal to wind power. In grid connected mode ac loads can be supplied regardless of connected dc load. However the inverter output need to limited to rated value of SOFC considering the dc load. The performance of controller employed for control and coordination of energy resources, storage devices and load is satisfactory. The microgrid operation in islanded mode is presented in this chapter. The wind power is utilized by the battery, UC and electrolyzer as per condition and SOFC alone caters load effectively. The wind power fluctuations are effectively mitigated using electrolyzer and storage while slow dynamic response of SOFC and battery discharge is controlled by UC effectively. The battery is able to supply the minimum load when the SOFC is disconnected from dc-link. UC charging is carried out by using battery power when wind power is zero.

Chapter 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusions

The Fuel cell and renewable based DG system has significant importance and potential to supply reliable and sustainable power and enhancing distribution system performance. The microgrid is upcoming and adaptive technology which serves the customer requirement well. The microgrids compliances with grid interfacing requirement.Hence the presented microgrid system effectively aids in supplying reliable, sustainable, green and cost effective power. The present traditional power system structure do no adapt to new microgrid technology easily without posing many challenges.An extensive research, analysis, understanding and to draw effective solutions is crucial. To utilize microgrid to maximum and to work along with existing system the proper operation, control and management is essential. In this thesis the wind and SOFC based microgrid is presented along with battery,UC and electrolyzer. The microgrid consists both ac and dc loads and operated in both grid and islanded mode. The control strategies are employed to operate, control, coordinated and manage the resources and storage devices appropriately. The UC is used for mitigation of slow dynamic response of SOFC and battery discharge rate control. The battery has been utilized for minimum load supply. The electrolyzer uses the wind power to generate the hydrogen for later use by SOFC. The study conducted by author is presented in the following section.

- The dynamic model of microgrid based on SOFC and wind system has been implemented.The battery, UC and electrolyzer are considered from energy storage.The dynamic model of each components are employed to implement the microgrid system.

The interfacing converters and control scheme are presented. The UC considered for mitigation of slow dynamic of SOFC, load transients and battery control. The ac and dc load are considered and microgrid operated in both grid connected and islanded mode. The wind system uses the PMSG with diode rectifier and boost converter combination. It reduces the controller complexities and reduced switches and switching losses. A single VSI is used to supply the ac loads and dc loads are connected to dc-link with appropriate converter.Hence the conversion stages and losses can be reduced.The microgrid is suitable for study of different conditions, behavior of different component for different situations. The system can be used for wind range of wind speed and loads.

- The wind system performance with storage and without storage is presented. The instant discharge of battery for varying wind is given. The battery instant discharge is effectively controlled by the UC. The control scheme of UC and battery combined operation and coordination is effective.

- The performance of wind-SOFC system long with UC and electrolyzer is studied. The SOFC slow response and its effect on load is presented. The load following capability of SOFC-UC is given. The combination effectively supply the load demand with varying wind power. The slow dynamic response of SOFC is mitigated using ultracapacitor. The wind power is utilized for charging of UC and to generate hydrogen. The wind power fluctuations effectively suppressed using UC or electrolyzer. The hydrogen generated from wind power can be used for SOFC hence system leads to environmental friendly.

- A effective configuration of microgrid is given. The SOFC-wind based system with battery, UC and electrolyzer combination fulfills many requirements successfully. The combined supply of ac and dc loads is well suited for future power supply. The UC serves the short term duration storage and instant power requirement.The battery is considered for the minimum critical load supply in case of SOFC failure.The battery also fulfills the medium time duration storage requirement. The electrolyzer to generate hydrogen from wind power suffices the long term storage requirement, sustainability and mitigation of wind power fluctuations. The UC very effectively mitigates the slow dynamic response of SOFC and discharge rate of the battery. A UC suffices the two requirement.

- The system performance for SOFC-wind sharing the load and its adverse affect of SOFC power fluctuations is studied. The UC successfully mitigates fluctuations.The storage of wind power in the UC, battery or in form of hydrogen is limited when such combination is used.

- The ac and dc loads are used. The management of ac and dc loads is properly carried out.The load control and and supplying minimum load during SOFC out of service is effective. The inverter output set by taking into account the dc and is properly managed.A priority based load control scheme can be effectively employed.
- The dc-link voltage, dc load voltage and inverter voltage and frequency is is maintained at nominal values for both grid connected and islanded mode.The total harmonic distortion is well within the standard limit.
- The simulation results shown the combination of SOFC-wind with UC,battery and electrolyzer can lead to reliable and sustainable microgrid.

6.2 Scope for Future Work

The presented research work can extended to:

- The accurate electrolyzer models can be used. The compressor and motor dynamics and power consumption by auxiliary system can be considered for study.The control scheme and study of the system with using generated hydrogen by fuel cell can be added advantage.
- The realistic wind speed variations can be used to evaluate the microgridsystem performance.
- The detailed dc load models like electric vehicle, battery, motors and lighting loads can be used study the for system performance.
- The protection aspect, better islanding detection technique and smooth resynchronization methods can be considered.
- The PV system can be integrated to presented microgrid. The MTG also can be a better option with fuel cell along with temperature dynamics. The CHP applications can be explored.
- The advance and soft computing technique like fuzzy, neural or other combination can implemented for controllers.

LIST OF PUBLICATIONS

International Journals

1. Santhosha, K.A. and Gaonkar, D.N "Performance Analysis of a Variable-speed Wind and Fuel Cell-based Hybrid Distributed Generation System in Grid-connected Mode of Operation" **Journal of Electric Power Components and Systems (Taylor and Francis)** (Published online)

2. Santhosha, K.A. and Gaonkar, D.N " Performance Analysis of Wind and SOFC Based Hybrid power generation system with Ultracapacitor in Grid Connected mode" **International Journal of Distributed Energy Resources and Smart Grid** (Under review)

International Conferences

1. Santhosha, K.A., Gaonkar, D.N. and Nayak, S.K. . "Performance Study of Grid Connected Fuel Cell Based Distributed Generation System with Ultracapacitor," Proc. IEEE PES Innovative Smart Grid Technologies - Middle East (ISGT Middle East), pp.1-4, December. 2011, Jeddah, Saudi Arabia

2. Santhosha, K.A. and Gaonkar, D.N. " Performance Analysis of Variable Speed Wind Energy Conversion System in Grid Connected Mode." Proc. IEEE Fifth Power India Conference (PINCOF-12), Murthal India December 2012 (short listed for submitting to IEEE Transaction on Industrial Application.)

3. Santhosha, K.A. and Gaonkar, D.N. " Modeling and Simulation Study of Fuel Cell and Wind Energy Based Hybrid Distributed Generation System." Proc. IEEE Fifteenth International Middle East Power Systems Conference Alexandria, Egypt, December 2012 (MEPCON'12)

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Appendix

Wind turbine parameters

Rated power	55kW
Radius	7.5 m
Wind speed range	6-12m/s
Turbine speed	28.9479.3 RPM
C_{p_max}	0.4412
Inertia	Kilo Volt
λ	5.66

PMSG parameters

Rated power	55-kW
Voltage and frequency	250-V, 26-Hz
R_s	0.04Ω
Ld=Lq	8.5 mH
No of poles (P)	40
Flux/pole	1.8Wb
Inertia	1.5$kg - m^2$

Converter control parameters

PI controller	
K_p	0.01
K_i	0.1

SOFC parameters

Rated power	100kW
Absolute temperature (T)	1273 K
Universal gas constant (R)	8314 J/(kmol K)
Faradays constant (F)	96487 C/mol
Ideal standard potential (E_0)	1.18 V
Number of cells in series in the stack (N_0)	400
Constant (K_r)	0.996×10^{-6}
Maximum fuel utilization (U_{max})	0.9
Minimum fuel utilization (U_{min})	0.8
Optimal fuel utilization (U_{min})	0.85
Valve molar constant for hydrogen ((K_{H_2})	8.43 $\times 10_{-4}$kmol/(s atom)
Valve molar constant for water (K_{H_2O})	2.81 $\times 10_{-4}$kmol/(s atom)
Valve molar constant for oxygen (K_{O_2})	2.52 $\times 10_{-4}$kmol/(s atom)
Response time for hydrogen flow (τ_{H_2})	26.1s
Response time for water flow (τ_{H_2O})	78.3s
Response time for oxygen flow (τ_{O_2})	2.91s
Ohmic loss (r)	0.126Ω
Electrical response time (T_e)	0.8s
Ratio of hydrogen to oxygen (r_{H_O})	1

SOFC converter control parameters

PI controller	
Voltage loop	K_p=1.5,K_i 1.2
Current loop	K_p=0.02,K_i10

Electrolyzer parameters

Rated power	50kW
n	270
T	800C
U_0	1.21 V
r_1	8.05$\times 10^{-5} \Omega m^2$
r_2	-2.5$\times 10^{-7} \Omega m^2 C$
U_1	0.185 V
t_1	1.002 $A^{-1} m^2 C$
t_2	8.424 $A^{-1} m^2 C$
t_3	247.3 $A^{-1} m^2 C$

Electrolyzer converter control parameters

PI controller	
K_p	0.1
K_i	1

Ultracapacitor parameters

Rated power	120kW
Capacitance	180F
No. of UC in series	5
No of UC in parallel	10(BMOD0094 P075 B02,94F, 75 V, ESR=13m)

UC converter control parameters

PI controller	
Voltage loop	K_p=11,K_i 0.00001
Current loop	K_p=0.001,K_i0.01

Battery parameters

Rated power	200VA
Voltage	350 V

Battery converter control parameters

PI controller	
PI controller	
Voltage loop	K_p=1,K_i 1.2
Current loop	K_p=0.01,K_i10

dc load and control parameters

380V	10kW and 60kW
PI	K_p=0.001,K_i 0.08
380V	1kW and 9kW
PI	K_p=0.1,K_i 0.1

Grid and Inverter parameters

Grid parameters	380V,60Hz
Filter	0.2mH,9μF
dc-link voltage r	750V
Grid connected mode	
d axis	
Inverter voltage loop controller	K_p=0.001,K_i 0.1
Inverter current loop controller	K_p=1,K_i 500
q axis	
Inverter voltage loop controller	K_p=0.001,K_i 0.1
Inverter current loop controller	K_p=9,K_i 0.001
Islanded mode	
d axis	
Inverter voltage loop controller	K_p=0.01,K_i 500
Inverter current loop controller	K_p=0.15,K_i 1
q axis	
Inverter voltage loop controller	K_p=1,K_i 100
Inverter current loop controller	K_p=1K_i 1