

Investigating the Performance of Hybrid Wind-Microturbine Generation System in Stand-Alone Environment

*Dissertation Submitted in partial fulfillment of the requirement for the award
of the degree of*

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Submitted By

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled "**Investigating the Performance of Hybrid Wind-Microturbine Generation System in stand-alone environment**" in partial fulfillment of requirement for the award of the master degree in Power Systems submitted in the Electrical and Instrumentation Engineering Department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Mrs. Suman Bhullar**, (Assistant Professor EIED, Thapar University, Patiala).

The matter presented in this dissertation has not been submitted for the award of any other degree of this or any other university.


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ABSTRACT

The energy demands increment, perishing resources of fossil fuels and growing pollution levels lead to the electricity generation using renewable energy sources such as wind, solar, geothermal, tidal etc. Further, these sources remarkably reduce pollution levels and climate changes. However, with renewable resources energy availability is affected by natural causes. Conventional sources like diesel, natural gas, etc. shall be incorporated with the renewable energy sources to ensure the continuity in supply. In the proposed work, a hybrid generation system is presented which constitutes interfacing of micro-turbine generation system and the renewable energy system (wind power). A simulation model of the hybrid generation system is designed and its various characteristics are observed. From the developed model, it is observed that the Microturbine generation system acts as a backup generation system for wind energy conversion system and also supplies reactive power for asynchronous generator starting.

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1.1 Overview

The excessive consumption of fossil fuels for the increasing energy demands is the main cause of the ill impact on our atmosphere. Due to this reason, the world energy scenario is shifting towards the renewable resources of energy. These resources are seen as the replacement of the conventional resources of energy such as diesel, natural gas etc. Main reason for diverting towards the renewable resources is the dwindling sources of conventional energy resources. But, renewable resources have one disadvantage that it depends on the natural factors which are out of human control. As in case of Wind Energy conversion plant, power is supplied until there is sufficient Wind speed available to operate the Wind Turbine. So, to improve the reliability of the system renewable resources have to be clubbed with the conventional resources. For the above purpose, a Hybrid Generation System is presented in this work which constitutes Wind as renewable source and Microturbine generation as the conventional source of energy.

In distant and inaccessible areas, it may not be an economically feasible option to supply electric power from the grid. If utility has to distribute centrally generated power to these areas that comes with high cost of transmission and higher transmission losses. After the deregulation of electricity market, installation of hybrid systems as isolated units (acting as distributed generation (DG) sources) has become possible. The positive impact of DG's on the power system with which they are connected has been well acknowledged in the literature. There are various forms of DG's such as small hydro induction generators, reciprocating engines, fuel cells, wind turbines, micro-turbines and diesel fired turbines. This technology proved to be an environment friendly, efficient and reliable power source. An appropriate modelling is required for studying the operation and impact of these DG's, constituting hybrid generation system on power system.

A hybrid generation system generally comprises renewable sources such as Wind Power, Solar Power etc. and conventional sources of energy like diesel, natural gas etc. to form an equivalent of a miniature grid. But, there are two important issues related to such type of

composition first the high emission rate from conventional techniques and secondly high capital for energy from renewable resources. For Wind Energy Conversion System, the renewable energy source in this dissertation, there is zero emission but it has comparatively higher cost. On the other hand with the modern micro-turbines generating system considered in hybrid generation system, cost of energy is relatively low and it has low emissions.

With the help of Power Electronics Interface, a hybrid system could be made to operate either in grid connected mode or isolated mode. The main reason for using Power Electronics Interface is that to maintain the system parameters i.e. voltage and frequency within desired limits. Inverter is used to control the voltage level and power angle, it is also the main block of Power Electronics Interface.

The proposed Hybrid Generation System comprises a Microturbine using a conventional source of energy and Wind Energy Conversion System as the renewable source of energy. A storage unit is added to improve the overall efficiency of the hybrid system.

Electricity generation using Wind Energy is one of the best sources of renewable energy. There have been vast advances in the Wind Turbine technology. These advances have increased the efficiency of the Wind Generation systems and have made it economically more viable.

On the other side, Microturbine System the other component of the Hybrid Generation System tries to counterbalance the high installation cost of wind energy system. Microturbine has become the key component in the distributed generation due to their low installation cost and high reliability. Microturbines have low emission levels and are able to run on various fuels like propane, natural gas etc.

1.2. Literature Review

Rowen (1983) presented a mathematical model of heavy duty gas turbine for dynamic power studies and could be used to analyze system connected to it. He was among the first ones to present such a model for gas turbines. The proposed model has a single shaft design in terms of p.u. values. The system was able to control the speed, acceleration and fuel. The developed model was appropriate to work in both isolated and parallel operation conditions.

Hannett et. al. (1993) mentioned the comparison of the models resulting from testing programs and typical models. They observed that the response of the system with simulation of

typical model was more efficient than that of actual system. A computer simulation model of a governor turbine on the Alaskan Rail belt combustion turbine units was made by using data obtained from field test program.

De Mello *et. al.* (1994) explained the combined cycle plants as the important ingredient of power system. With the introduction of generation mix, it was necessary to model these types of plants to improve system dynamic performance. The modelling requirements were presented in this study for a combined cycle plant including controls that played an important role in these types of plants.

Zhu *et. al.* (2001) developed a simplified split shaft Microturbine model with slow dynamics. In addition, solid oxide fuel cell (SOFC) system was incorporated by using appropriate control systems and parameters for a particular time frame. The results showed the system's capability to provide the load following service in distribution system.

Hajagos *et. al.* (2001) presented a test model of the Gas Turbine with the help of transfer function blocks. The model was tested for various control functions such as fuel system control, speed control and acceleration control.

Muljadi *et. al.* (2001) explained variable speed Wind Turbine operation using pitch controlled strategy. In the considered system, the control was such that it could generate maximum energy while minimizing loads. In the high wind speed, turbine was controlled to protect the structure and to maintain the aerodynamic power produced by the wind. Whereas, at low to medium wind speeds the generator and the power converter were controlled in such a way, so that maximum energy could be extracted from the wind.

Hinai *et. al.* (2002) presented a dynamic model of a Microturbine as distributed generator. The designed model was appropriate for transient analysis and simulation with unbalanced three-phase power system. The suggested system has four parts i.e. a Gas Turbine engine, a permanent magnet generator, a three phase bridge rectifier (AC to DC) and a power inverter (DC to AC). The simulation model was built with the dynamics of each part and their interconnections.

Gillie *et. al.* (2003) presented a hybrid generation system referred as a virtual power plant. The system consisted of a Gas Turbine driven synchronous generator and a Wind Farm

whose outputs were combined before connecting to the grid. In this study, a dynamic model for induction generator and the synchronous generator were developed. For the dynamic model of Wind Turbine, an appropriate scale was chosen to represent the output of Wind Farm.

Cano et. al. (2003) explained the ability of Micro-Grid to control the local bus voltage and the base power flow within the context of already existing grid. Due to this, the power demand from the main grid feeder was reduced.

Park et. al. (2004) suggested a hybrid generation system comprising photovoltaic and wind power supporting each other. Due to the dependence of the system on weather conditions, backup power to the system was supplied by storing energy in a spiral spring, which operated a small generator.

Valenciaga et. al. (2005) developed a comprehensive supervisor control for a hybrid generation system comprising photovoltaic and wind generation systems, battery bank and AC load. The primary objective of the supervisor control was to satisfy the load power demand and secondly, to maintain the state of charge of the battery bank to extend the life of batteries and to prevent blackouts.

Stott et. al. (2006) described the advantage of using a variable speed generator to produce considerable saving over the life-time of the unit in a Hybrid Wind-Diesel Generation system. The performed simulations proved that some additional load control might be required to maintain power quality. The system results showed that the joining of DC link did not interfere with the control of rotational speed of Wind Turbine.

Colson et. al. (2007) simulated a Hybrid Wind-Microturbine generation system. In the proposed system power management of both the generation systems i.e. Microturbine generation and Wind Energy Conversion System was done using Power Electronics Interface to reduce operational cost. The system runs under variable wind speeds and variable load condition.

Kim et. al. (2008) presented a scheme of versatile power transfer of a grid-connected hybrid generation system applying power control strategies. To operate the said system in proposed modes of operation, supervisory control for individual components was used for regulating power generation.

Goel et. al. (2009) suggested a Wind-Hydro Hybrid Generation for isolated system. The proposed system employed permanent magnet synchronous generator (PMSG) driven by hydro turbine and another PMSG driven by Wind turbine (variable speed) supplying a three phase load. This system used two back to back connected PWM controlled IGBT voltage source converters with battery at D.C link. The proposed system controlled the frequency and the magnitude of the load voltage as it had the capability of bidirectional flow of active and reactive power.

Choe et. al. (2010) presented a Hybrid Generation system using various power sharing algorithms i.e. two converter and two inverter, two converter and one inverter, one converter and one inverter of fuel cell and photovoltaic system. In addition, relative studies were performed considering output current, efficiency, maximum power point tracking, system size, D.C link voltage variation and cost.

Karim et. al. (2010) presented a Wind-Diesel-Hydrogen based power system. The system had a dynamic response of generation and consumer levels. In the proposed system, hydrogen storage medium was used instead of conventional battery system as it had some limitations. The loads were divided into primary and secondary as per the given priority which reduced the transient effect, due to sudden change in load or wind speed.

Mahalakshmi et.al. (2011) proposed a small scale hybrid generation system based on fuel cell and solar photovoltaic for the purpose of continuous supply to the load. For the maximum power tracking a simple control technique with a switched mode dc-dc converter is used.

Sebastian et. al. (2011) modeled a wind-diesel hybrid generation system having main components as Wind Turbine Generator, Diesel Generator, Consumer load, Ni-MH battery as energy storage system and a dump load. In this system, Ni-MH battery was best choice for energy storage system due to its high power capability, resistance to abuse, absence of harmful substances and low maintenance. The simulation results of the system showed outstanding improvement in system dynamics with the use of energy storage system.

Jayalakshmi et al. (2011) presented a Hybrid Generation system which has a PI controller based frequency regulation and was self governing for sudden changes in wind speed and load demand. The system comprises of fuel cell, Microturbine generator, wind energy conversion system, an aqua electrolyzer and a energy storage device such as battery.

Li et al. (2012) proposed a hybrid model comprising Wind, Photovoltaic and battery; it operates according to the status of the energy storage. The system operated as per the forecast of photovoltaic power and wind power output. The main focus of the system was on the day ahead optimization scheduling of generation.

Nayak et al. (2013) suggested a hybrid generation system based on Microturbine and fuel cell. In this study, various works related to the hybrid Microturbine and fuel cell generation system has been discussed.

Pirhaghshenasvali et al. (2014) proposed a practical hybrid generation system for stand-alone application in Iran. The author considered Photovoltaic System, Wind-Turbine Generators, Battery Banks and Diesel Generators as power sources. In this study, the optimal sizes of the units were obtained using particle swarm optimization.

1.3 Objective of the Work: The objective of the dissertation is to develop a standalone hybrid generation system that can make maximum use of the renewable energy and also maintain the continuity of supply to the user.

1.4 Organisation of Dissertation: This dissertation consists of five chapters:

The first chapter includes an introduction, Literature review, Objective of the work, organization of the dissertation.

The second chapter is based on a illustration of the various components of the hybrid generation system.

The third chapter focuses on the simulation modelling of the hybrid generation system.

The fourth chapter discusses the simulation results obtained from the designed model.

The fifth chapter includes Conclusion and Future Scope.

HYBRID WIND-MICROTURBINE GENERATION SYSTEM

Since 1990's, there is a significant development in the field of Wind Power and in the last few years it has noteworthy improvement. The most promising aspect of Wind Power is that it is almost pollution free. Renewable energy has a total installed capacity of 29989.21 MW (2013, Dec) of which Wind Power has a share of 20149.50 MW. About 6% of India's total installed capacity comes from Wind Power and fulfils the 1.6% of country's power. Indian government has decided to add 18.5 GW of renewable energy to generation share of the country, of which 11 GW is Wind Energy.

These advancements in the field of Wind Energy lead us to the design of a Hybrid Generation System comprising Wind Energy conversion system and Microturbine generation system. The major concern is to present the concept of Hybrid Generation system for increasing the usage of Wind Energy and further improving its reliability and efficiency.

While using distributed generation source like Wind (considered renewable energy source in the system) there are two main problems for electric power generation. First is the unpredictable nature of the wind which disturbs the continuity of supply and hence raises the requirement of standby supply system. Second problem with the wind generation is that the use of asynchronous or induction generator as an electric generator. While these machines has an advantage that they can be driven on variable speeds that is well suited for random wind speeds, but has a disadvantage that they require reactive power support from utility or network to which they are connected. So, the continuity of supply depends on successful incorporation of renewable sources with conventional sources of energy.

When we have not sufficient Wind Energy to meet the requirement, then we need backup supply system and in this dissertation, Microturbine generation system is used. Thus, in a Hybrid Generation system both the systems i.e. Wind Energy conversion system and Microturbine generation system complement each other. Such system act as virtual grid and could be operated either in isolated (stand-alone) mode or grid connected mode. While using hybrid systems, we require Power Electronics interface to keep their voltage and frequency within prescribed limits

as these values are affected by factors like input wind and varying load conditions. A hybrid Wind-Microturbine generation system is shown in fig. 2.1.

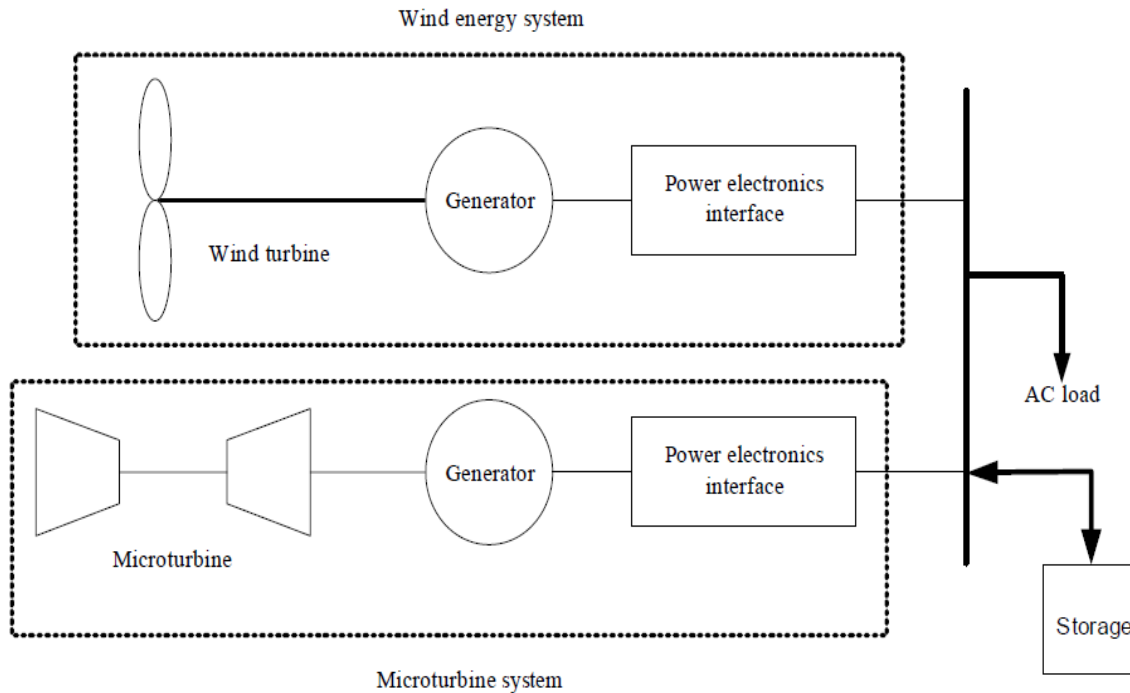


Figure 2.1 A Hybrid Wind-Microturbine Generation System

There are four main components of Hybrid generation system listed below:

1. Wind Energy Conversion System
2. Microturbine generation System
3. Power Electronics Interface
4. Energy Storage System

Energy Storage System such as battery is connected to increase the overall efficiency. However, in this dissertation emphasis of the proposed system is on the interfacing of Microturbine Generation system and Wind Energy Conversion system. So, the energy storage system is exempted from the system.

2.1 Wind Energy Conversion System

Electricity generation using wind energy is a complex system in which knowledge from the wide array of fields such as mechanical, electrical, civil and aerodynamic engineering come

together. The main components of the Wind Energy Conversion System are rotor blades, rotor, nacelle (which transfers mechanical power to generator) and generator as shown in figure 2.2. A typical Wind Energy Conversion System with functional construction is shown in figure 2.2.

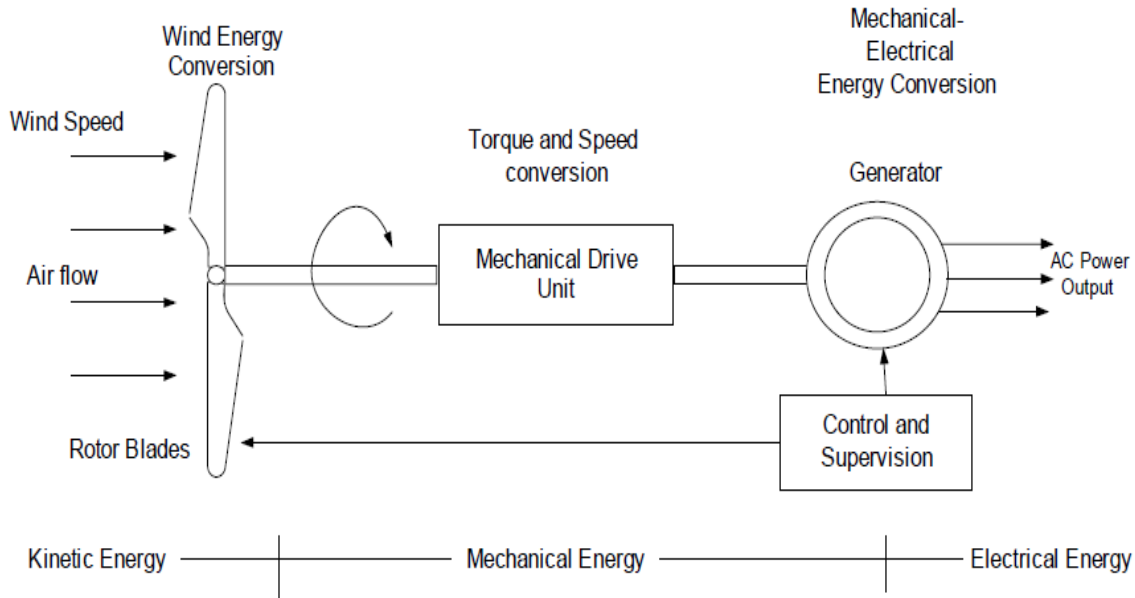


Figure 2.2 Power conversion in a wind energy conversion system.

The Wind Turbine confines the kinetic energy of wind with the help of two or more rotor blades and the rotor is mechanically coupled to the electrical generator. In the mechanical assembly the main component is the gearbox, which converts slower rotational speeds of Wind Turbine to the higher for the electrical generator. The electricity generation from this system is maintained as per specifications using suitable supervising techniques and controls. Protection of the overall system can also be achieved with the help of these control techniques.

There are two distinct designs available for wind turbine; first is the horizontal axis configuration and second is the vertical axis configuration. The vertical axis machine is also known as Darrieus rotor named after its inventor and has the shape resembling an egg beater. However, in most of the modern wind turbine models horizontal axis design is used [39].

As mentioned above, a Wind Energy Conversion System is a complex system which converts wind energy to mechanical energy and then to electrical energy. The Wind Turbine output power or torque is dependent on various parameters such as wind speed, type and size of the turbine, etc. To design a dynamic model of Wind Turbine, behavior of the turbine under

these parameters should be realized considering its region of operation. With the study of Wind Turbine behaviour, desired operational characteristics can be achieved using suitable control techniques.

2.1.1 Inputs and Outputs of a Wind Turbine

1. Energy given to the wind turbine is decided by the wind speed that is independent input quantity.
2. Turbine's rotor geometry and arrangement give rise to specific input quantities of the machine.
3. Rotor blade pitch angle, Turbine speed, and Rotor blade tilt that come up from the transmission system of the wind energy conversion system.
4. By varying the above three inputs, turbine output quantities i.e. power or drive torque can be controlled.

2.1.2 Power Extraction from the Air Stream [39]

With the understanding of input and output variables of the wind turbine, it is possible to relate these two values by deriving an expression. The derivation of the relation between the wind speed and power is as follows:

The kinetic energy of air having mass m moving with speed V is given by:

$$\text{kinetic energy} = \frac{1}{2} \cdot m \cdot V^2 \dots\dots\dots (2.1)$$

The power in moving air flow is the flow rate of kinetic energy per second.

$$\text{Power} = \frac{1}{2} \cdot (\text{mass flow rate per second}) \cdot V^2 \dots\dots\dots (2.2)$$

The actual power extracted by the rotor blades is the difference between the upstream and the downstream wind powers. Therefore, equation (2.2) results in:

$$P = \frac{1}{2} \cdot (\text{mass flow rate per second}) \cdot (V^2 - V_0^2) \dots\dots\dots (2.3)$$

Where:

P is the mechanical power extracted by the rotor in watts.

V is the upstream wind velocity at the entrance of the rotor blades in m/s.

V_0 is the downstream wind velocity at the exit of the rotor blades in m/s.

Let ρ be the air density in (kg/m^3) and A is the area swept by the rotor blades in (m^2); then the mass flow rate of air through the rotating blades is given by multiplying the air density with the average velocity.

$$\text{mass flow rate} = \rho \cdot A \cdot \frac{V+V_0}{2} \dots\dots\dots (2.4)$$

From eq. (2.3) and (2.4), the mechanical power extracted by the rotor is given by:

$$P = \frac{1}{2} \cdot \left[\rho \cdot A \cdot \frac{(V+V_0)}{2} \right] \cdot (V^2 - V_0^2) \dots\dots\dots (2.5)$$

After algebraic rearrangement of the terms, we have:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \cdot C_p \dots\dots\dots (2.6)$$

Where,

$C_p = \frac{(1+\frac{V_0}{V})(1-\frac{V_0^2}{V^2})}{2}$ is the fraction of the upstream wind power, which is captured by the rotor blades and has a theoretical maximum value of 0.59. It is also referred as the power coefficient of the rotor or the rotor efficiency. In practical designs, the maximum achievable C_p is between 0.4 and 0.5 for high-speed two blade turbines and between 0.2 and 0.4 for slow speed turbines with more blades [39].

From eq. (2.6), we see that the wind speed, wind flow conditions of the rotor and the effective area of the rotor blades determines the operating conditions and power absorption of the turbine. Thus, by changing the flow conditions and by varying the effective area at the rotor system the output power of the turbine can be varied, which forms the base for the control of wind energy conversion system.

2.1.3 Tip Speed Ratio

The tip speed ratio (TSR) is defined as the linear speed at the tip of the blade to the free stream wind speed. It is denoted by λ [39].

$$TSR = \lambda = \frac{\omega R}{V} \dots\dots\dots (2.7)$$

Where:

R is the rotor blade radius in meters.

ω is the rotor angular speed in rad/sec.

TSR is related to the operating point of wind turbine for extracting maximum wind power. At a particular *TSR*, the maximum rotor efficiency C_p is achieved. This value is specific to the aerodynamic design of the turbine. To keep the *TSR* constant at the optimum levels at all times, the rotor must turn at low speed at low wind speed and at high speed at high wind speed. The larger the value of *TSR*, wind turbine will rotate faster at a given wind speed. Turbines with high speed are preferred for efficient electricity generation. From equation (2.7), for a particular value of wind speed V , turbines with large blade radius R result in low rotational speed ω , and vice versa. Wind turbines with high tip speed are preferred for operation over a wide range of wind speeds.

2.1.4 Operating Schemes of a typical Wind Turbine

There are basically two types of wind energy conversion systems; one is *Constant Speed or Fixed Speed Wind Turbines* which operate approximately at constant speed predetermined according to the generator design, and second is *Variable Speed Wind Turbines*.

The control scheme of the various components of the Wind Turbine is decided by the operating strategy of the system. For example, as a part of the control strategy of the whole system, power output of the turbine at high wind speeds can be controlled using pitch angle control or it is possible to capture maximum energy using rotor torque control. But when using a fixed speed stall regulated turbines, there is no option for control input. These turbines are designed with fixed pitch angle of turbine blades to operate at a specific wind speed with optimal tip speed ratio. The problem with these turbines is that when wind speed increases, it increases the angle of attack and in turn exposing large area of blade to wind. Due to which turbines shifts to stall region, resulting reduced rotor efficiency and limits output power. This stall regulated concept can be varied by operating the turbine at two separate constant operating speeds. This can be achieved by either changing the gear ratio or changing the number of poles of the electrical generator. The main advantage of stall control method is that it is simple. But it has some significant disadvantages, for example, wind turbine with stall regulated method is unable to capture wind energy for wind speeds other than its design.

Pitch regulation in Fixed-speed pitch regulated turbines is used for start-up. After start up it is only used to limit the power above the rated wind speed of the turbine. For the purpose of optimization of power output, generator torque control is used in variable speed Wind Turbines.

There is a 20-30% increase in the energy capture with variable speed turbines as compared to fixed-speed operation.

Characteristic curve for variable speed and constant speed wind turbine are shown in the Figure 2.3 [25].

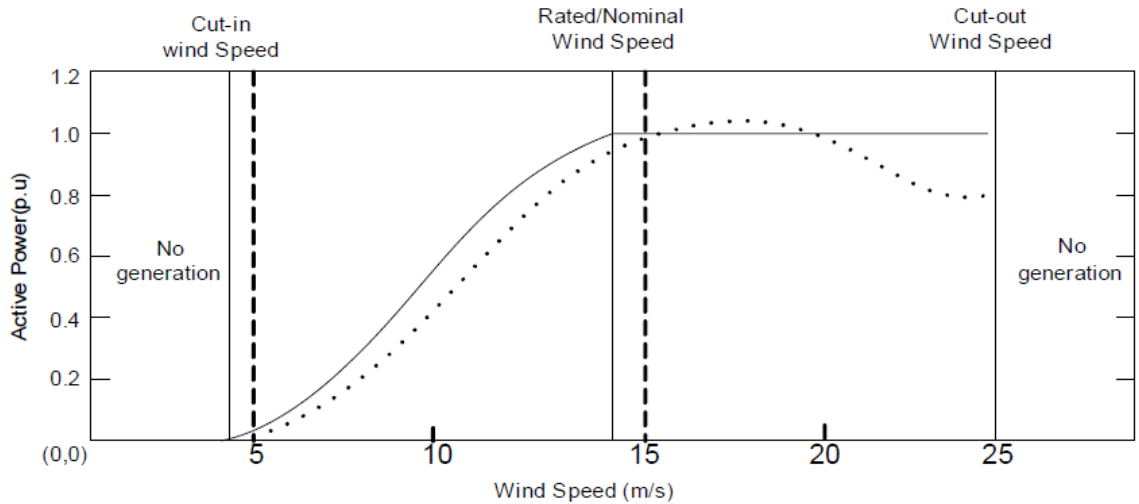


Figure 2.3 Characteristic curves for variable speed pitch controlled (solid) and constant speed stall controlled (dotted) wind turbine.

The output power of a constant speed stall controlled Wind Turbine increases a bit higher than the rated limit, but decreases after sometime until cut-in speed of the turbine is reached. This type of feature ensures that the generator is not overloaded even if the wind speed exceeds its nominal values, thus providing an element of passive power output regulation. On the other hand, with variable speed operation even if the energy captured from wind is more, but the variable speed control adds to the cost of overall system. So a balance has to be maintained between energy increase and cost increase while designing a variable speed system.

2.1.5 Variable Speed Wind Turbine System

A typical pitch regulated Variable Speed Wind Turbine is shown in figure 2.4. There are many parameters characterizing a variable speed wind turbine that are related [25]. Some of them are listed below:

1. The turbine nominal rotor speed, rotor diameter and power coefficient curve determines the nominal wind speed of a wind turbine for a given nominal power.

2. The parameters of the pitch angle controller are determined by the rated power and the allowable amount of rotor over speeding.
3. Turbine cut-in speed is determined by the rotor inertia.

There are two methods of affecting the turbine operation using variable speed pitch controlled wind turbines, namely blade pitch change and speed change. In other words, the control schemes used for the operation of variable speed wind turbine are:

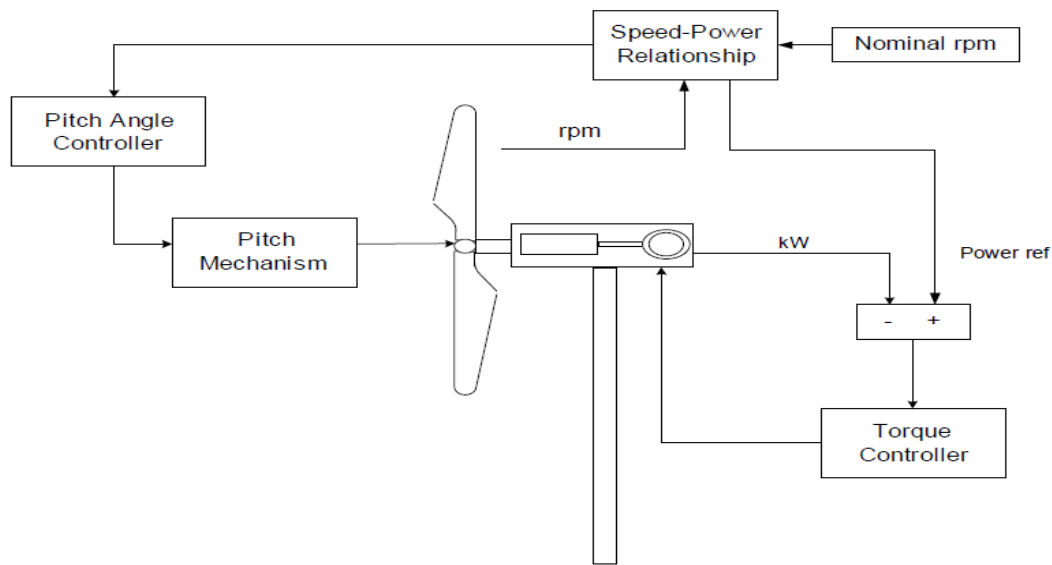


Figure 2.4 Typical variable speed pitch regulated wind turbine.

1. Power optimization scheme: This scheme is used to optimize the energy capture ensuring the optimum tip speed ratio, when the wind speed is below the rated limit. For this, constant wind speed has to be maintained corresponding to optimum tip speed ratio. If electrical load is controlled to change the speed, it results in generator overloading for wind speeds above nominal values. To overcome such problems, other methods of speed control such as generator torque control can be used.
2. Power limitation scheme: This method is used to limit the output power to the rated power when wind speed is above the rated value. It is done by reducing aerodynamic efficiency by varying the blade pitch angle. Thus, limiting the wind turbine power to the acceptable levels.

The above two strategies with their respective regions are mentioned in the figure 2.5.

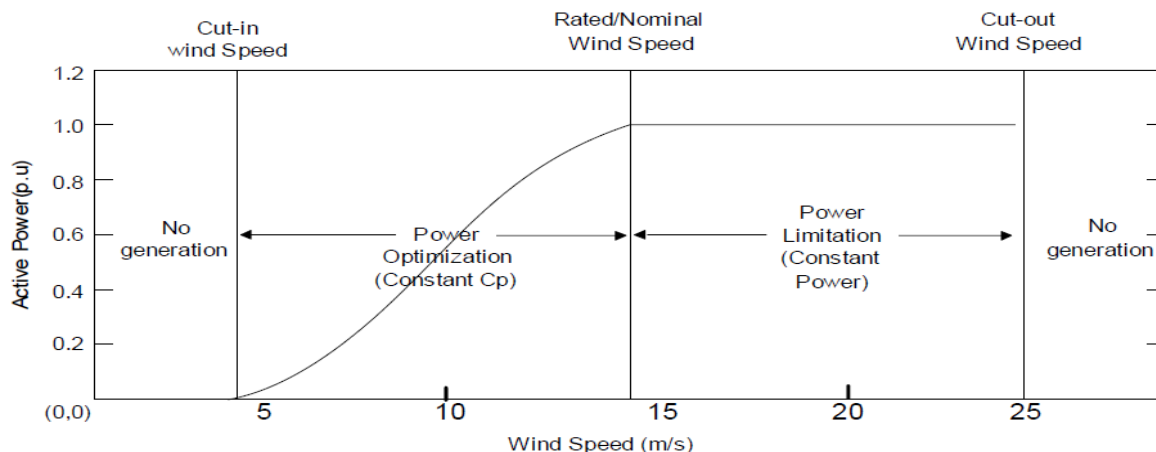


Figure 2.5 Power optimization strategies of variable speed pitch control wind turbine.

Table 2.1 Comparison between the Variable Speed and Fixed Speed operations [39]

	Constant Speed	Variable Speed
Advantages	Simple and robust	Less mechanical stress
	Inexpensive electrical system	Higher energy capture
	Electrically efficient	Aerodynamically efficient
	Fewer parts, hence high reliability	Low transient torque
	No frequency conversion, hence, no current harmonics	Mechanical damping system not needed, the electrical system could provide the damping
	Lower capital cost	No synchronization problems. Stiff electrical controls can reduce voltage sags
Disadvantages	Aerodynamically less Efficient	Electrically less efficient
	Mechanical stress	Expensive
	Noisy	Sometimes, involves complex control strategies

2.1.6 Pitch Angle Controller

Pitch angle controller controls the torque exerted on the turbine shaft by controlling wind flow around wind turbine blade. The pitch angle is kept constant at its optimum value for wind speeds less than the rated wind speed. It should be noted that due to the size of the rotor blades the pitch angle changes at a finite rate, which may have quite low values. The maximum rate with which the pitch angle can change is in the order of 3 to 10 degrees/second. With the pitch angle controller a slight over speeding of the rotor above its nominal value can be allowed without causing problems for the wind turbine structure.

2.2 Microturbine Generation System

While using a hybrid generation system having a renewable energy source, the system must contain a backup generation that should maintain the continuity of supply at the time, when there is insufficient supply from renewable source. In the proposed model, Microturbine is used as the backup generation system. As compared to the conventional gas turbines, the popularity of Microturbine generation systems is growing up in distributed generation because of its higher efficiency (with recuperator), faster response and smaller size. They are capable of running on variety of fuels at both higher and lower pressure levels.

In 1950's the automotive industry started development works on small, stationary and automotive gas turbines; which resulted in Microturbine technology. As a result, Microturbines are able to combine the low cost of automotive turbochargers with the reliability of commercial aircraft generators.

Micro-turbines can be defined as the small gas turbines which creates high energy gas stream that runs electrical generator by burning liquid or gaseous fuels [28]. Microturbine generation have the advantage of quick response time and are very useful to grid during requirement peak power supply. Microturbine generation have also the advantages of supplying power to remote areas and in Combined heat and power applications, where exhaust gases from the Microturbine are used to supply thermal energy needs for a commercial/residential load. Generation capacity has a range 30-400 kW where as conventional gas turbines range from 500 kW- 300 MW [33]. In micro-turbines the variety of fuels can be burned at high and low pressure levels. Generally the electrical efficiency of Microturbine Generation systems is marginally

lower than reciprocating generators. The overall efficiency of Microturbine ranges from 15 to 17% without a recuperator where as it increases to 33- 37% with the effective recuperator having efficiency of 85%. However micro-turbines are simpler in installation, higher reliability, lower level of maintenance requirements, lower emissions, reduced noise and vibrations. This makes design of Microturbine Generation System simpler and efficient. The emissions from micro turbine are up to 8 times lower than the diesel generator [22].

2.2.1 Types of Micro-turbines

There are two available types of Micro-turbines systems, single shaft models and two shaft models. In single shaft Microturbine design, both the generator and the compressor are turned by the single expansion of the turbine. As a result of this design, micro-turbines operate at high speeds (some of them exceeding 100,000 rpm) and the frequency of generated electrical power is very high (in kHz). On the other hand in two shaft design, the compressor is driven using a turbine on one shaft and a separate shaft is used to operate conventional generator (connected via a gear box), generating power at frequency of 50 Hz[30]. While using a single shaft design, a Power Electronics Interface is required between the Microturbine generation system and the AC load because of the high frequency generation. There is no such requirement for interfacing with two shaft design. In the proposed model single shaft design is used.

2.2.2 Basic component and processes in Microturbine Generation System

Microturbine generation system has the following basic components:

1. Compressor
2. Turbine
3. Recuperator
4. High Speed Generator
5. Power Electronics Interfacing

The schematic diagram of a single shaft based Microturbine generation System is shown in the figure 2.6.

The operating principle of Micro-turbines is based on the thermodynamic cycle known as Brayton cycle. In this cycle, the radial or centrifugal compressors are used to compress the inlet air. The mixture of this compressed air with fuel is burned in combustor. After that in the turbine

section, the hot combustion gases are expanded resulting in the production of rotating mechanical torque driving the compressor and generator, assembled on the same shaft (single shaft design).

To increase the overall efficiency, recuperator is added in typical Microturbine systems. Recuperator is a kind of air to gas heat exchanger. It preheats the compressed air being supplied to the combustion chamber by using the heat energy from the turbine hot exhaust gas thereby reducing the fuel required for the combustion process.

Permanent magnet synchronous generator is usually employed with single shaft design of high speed generator. For the general use of power from this generator, the high frequency output in the order of kHz is converted to 50 Hz. This process of power conditioning includes rectifying high frequency AC output to DC and then inverting DC to 50 Hz supply. In a single shaft design, power Electronics interfacing is a very critical component and is usually designed to handle voltage spikes and transients.

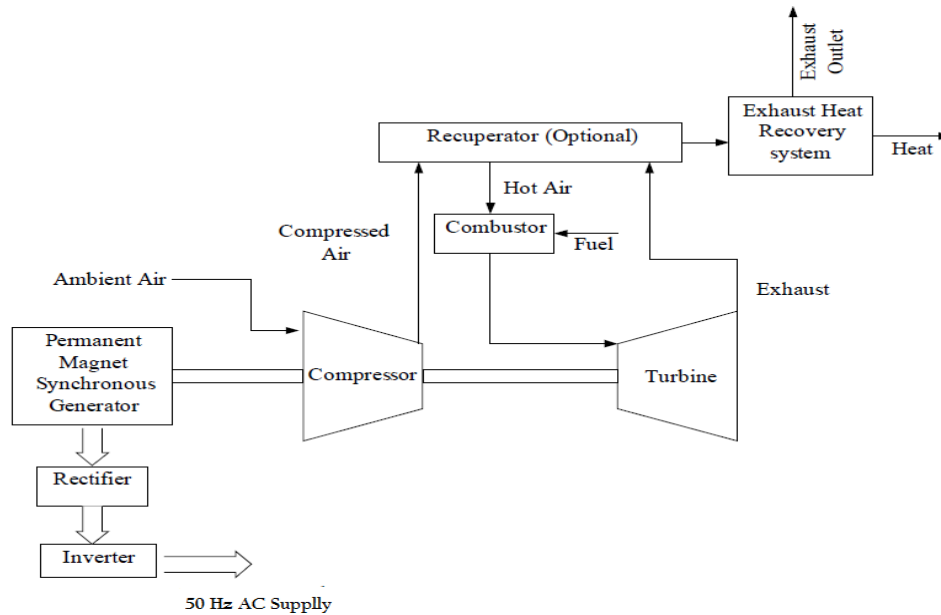


Figure 2.6 Single shaft based Microturbine Generation System.

2.2.3 Permanent magnet synchronous generator

Electrical power is generated with Microturbine with the help of a high speed generator. These high speed generators are driven directly by turbo-compressor shaft. With the use of single shaft design, small gas turbines are particularly benefited due to the elimination of the gearbox

which reduces shaft speed to the speed of conventional machines. The resulting machine with this scheme is compact, reliable and more efficient. The shaft speed of the machine is above 30,000 rpm and may exceed 100,000 rpm. For these high speed machines, high energy permanent magnets such as Samarium-Cobalt or Neodymium-Iron-Boron (NdFe) have proved to be very suitable.

In permanent magnet synchronous machine, permanent magnet is used instead of DC field winding. The advantages of this are higher power density, more robust construction of rotor, elimination of field copper loss, and lower rotor inertia. But it has the disadvantage that the convenience of field flux control is lost and there is a possible chance of demagnetization. The efficiency of the machine is higher than the induction machine, but its cost is higher than induction machine.

(A) Region of operation of Permanent Magnet Synchronous Machine

Permanent magnet is generally designed to operate in the demagnetization segment of the B-H curve shown in figure 2.7 [38].

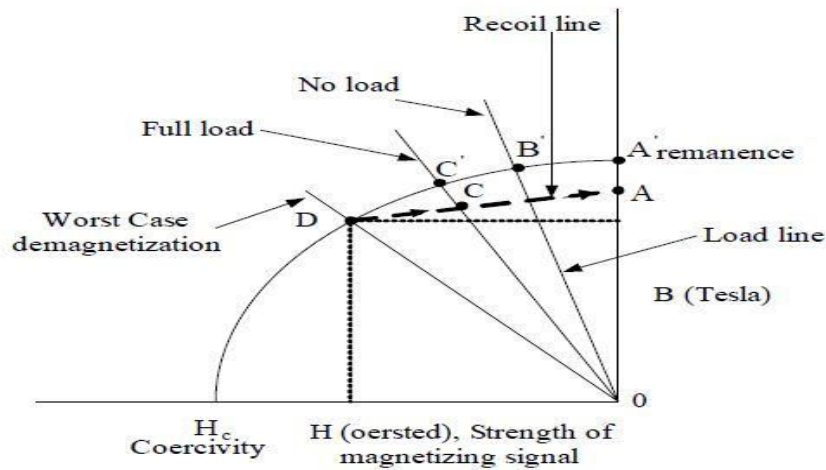


Figure 2.7 Operating points of permanent magnet machine on B-H curve.

Initially maximum flux density B_r corresponding to A' will be available. The air gap will have demagnetization effect, when the magnet is installed in the machine. In the figure 2.7, B' corresponds to no load line. The direct axis which is also magnetic axis, has demagnetization effect due to armature reaction, which will further reduce the air gap flux density. The worst case

demagnetization is represented by a load line as shown in figure 2.7. The demagnetization effect is removed once the operating point D is achieved. The magnet recovers along the recoil line, DA. Consequently, the stable operating point is determined by the ‘load line’ and ‘recoil line’ intersection. Therefore, magnet is permanently demagnetized at no load corresponding to vertical distance between A and A’. For the permanent magnet material having straight line demagnetization curve, the demagnetization line coincides with the recoil line and the permanent demagnetization will be negligible.

(B) Representation of d-q Axis of permanent magnet synchronous machine

In surface sinusoidal magnet machine, the permanent magnets are attached to the rotor and in case of interior magnet synchronous machine these magnets are mounted inside the rotor. The stator creates synchronously rotating air gap flux in the three phase sinusoidal winding. When prime mover rotates the machine, a three phase sinusoidal voltages are generated in the stator windings. The representation of d-q axis with permanent magnet synchronous machine are shown in figure 2.8 [38],[40]. In this figure, dotted damper windings represents the finite core loss.

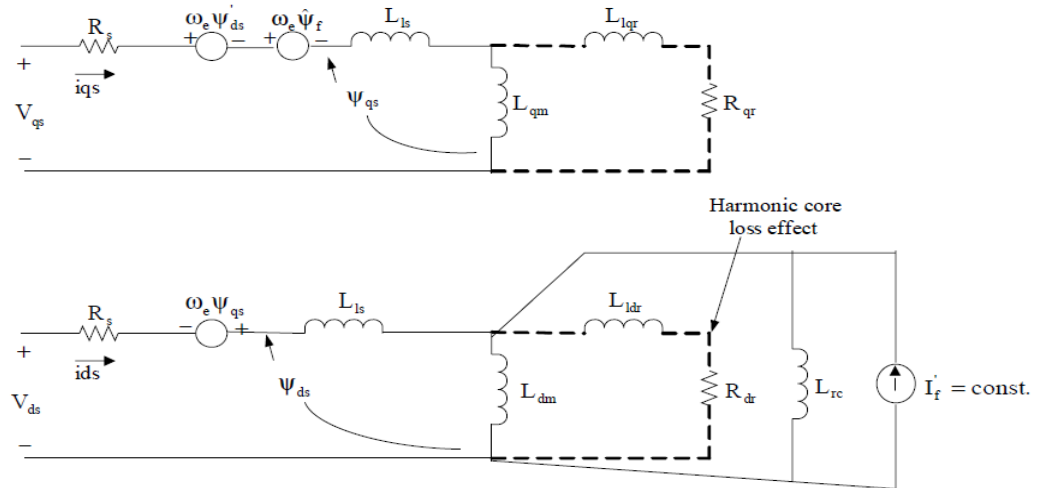


Figure 2.8 Equivalent circuits representing rotating frame of permanent magnet synchronous machine(PMSM).

The circuit equations after ignoring core loss can be written as (valid for both sinusoidal magnet machine($L_{dm}=L_{qm}$) as well as interior magnet machine):

$$V_{qs} = R_s i_{qs} + \omega_e \psi'_{ds} + \omega_e \psi_f + \frac{d\psi_{qs}}{dt} \dots \dots \dots (2.8)$$

$$V_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt} \dots\dots\dots (2.9)$$

Where the flux linkages are given by the following equations:

$$\psi_f = L_{dm} I_f' \dots\dots\dots (2.10)$$

$$\psi'_{ds} = i_{ds} (L_{ls} + L_{dm}) = i_{ds} L_{ds} \dots\dots\dots (2.11)$$

$$\psi_{ds} = \psi_f + \psi'_{ds} \dots\dots\dots (2.12)$$

$$\psi_{qs} = i_{qs} (L_{ls} + L_{qm}) = i_{qs} L_{qs} \dots\dots\dots (2.13)$$

The electromagnetic torque developed in the machine air gap is given by:

$$T_e = \frac{3}{2} \times \frac{P}{2} (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \dots\dots\dots (2.14)$$

Substituting equation (2.8),(2.9) in (2.11), (2.13) and (2.14) and simplifying, we get

$$\frac{di_{qs}}{dt} = \frac{1}{L_{qs}} [V_{qs} - R_s i_{qs} - L_{ds} \omega_e i_{ds} - \psi_f \omega_e] \dots\dots\dots (2.15)$$

$$\frac{di_{ds}}{dt} = \frac{1}{L_{ds}} [V_{ds} - R_s i_{ds} + \omega_e L_{qs} i_{qs}] \dots\dots\dots (2.16)$$

$$T_e = \frac{3P}{4} [\psi_f i_{qs} + (L_{ds} - L_{qs}) i_{qs} i_{ds}] \dots\dots\dots (2.17)$$

The rotor speed of the generator is obtained from the dynamics of the mechanical system as:

$$\frac{d\omega_r}{dt} = \frac{1}{J} (T_e - T_{shaft}) \dots\dots\dots (2.18)$$

Where, ω_e and ω_r are the electrical and mechanical angular velocities of the rotor in rad/sec. V_{ds} , V_{qs} , I_{ds} , I_{qs} are corresponding voltage and current components of d and q axis. L_{ds} and L_{qs} are the d and q axis respective inductances of the stator. L_{dm} is the mutual inductance of common d - axis of the stator lumped with the damper winding and the permanent magnet inductance L_{rc} .

I_f is an equivalent field current of the permanent magnets and I_f' is its equivalent referred to the stator side.

ψ_f ($\psi_f = L_{dm} I_f' = constant$) is the flux linkage induced by the permanent magnets of the rotor in stator phases.

J is the inertia of the rotor in $kg\cdot m^2$.

T_{shaft} is the shaft torque produced by the Microturbine in Nm.

T_e is the electric torque generated by the permanent magnet synchronous generator in Nm.
 P is the number of poles.

2.3 Power Electronics Interface

The interconnection of the hybrid system can be made possible only, when the frequency and the output voltage of the individual systems to be interconnected should be maintained at a predetermined level. The solution to this problem is to connect Power Electronics Interface with the individual system. Power Electronics interface has the ability to control output variables of the system such as voltage, frequency to match their reference values after the disturbance. The Power Electronics Interface comprises of an uncontrolled diode rectifier and controlled IGBT inverter. To satisfy the voltage regulation of the system, PWM (pulse width modulation) controller is used to control the inverter. Block diagram of the Power Electronics interface is shown in figure 2.9 [40].

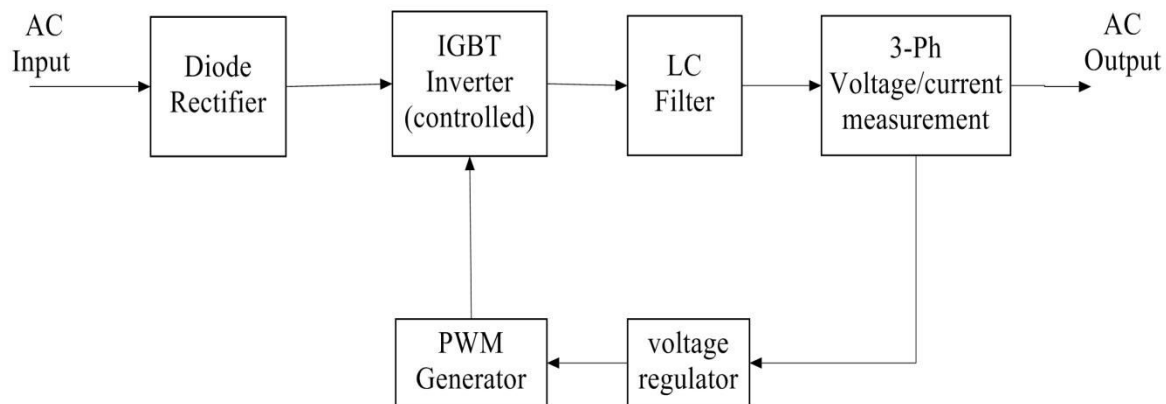


Figure 2.9 Block diagram of power Electronics interface.

REALIZATION OF THE HYBRID GENERATION SYSTEM

The incorporation of conventional sources of energy with the renewable ones is becoming more viable and potential source of distributed energy in the recent years. In the presented model, Microturbine generation is used as conventional source of energy with wind energy conversion system as the renewable source. The Microturbine generation system has the following salient features such as low initial cost, low emission levels, high operating efficiency and small size. And on the other hand wind generation is the clean source of energy but it has high installation costs.

3.1 Modelling of Micro-turbine

The concept of simulation model of Microturbine is based on the mathematical model of the gas turbine presented by Rowen [34]. He proposed a single shaft design of gas turbine driving a generator. This design includes the temperature control, speed control and fuel system.

The functions of these control systems of the Microturbine are:

1. Speed control acts under variable load conditions.
2. Temperature control acts as an upper power output limit.
3. Acceleration control is provided to avoid over speeding.

The output of all these control function blocks is the input to the least value gate (LVG), the output of this block is lowest of three inputs and as a result of this least amount of fuel is supplied to the compressor-turbine block as shown in figure 3.1.

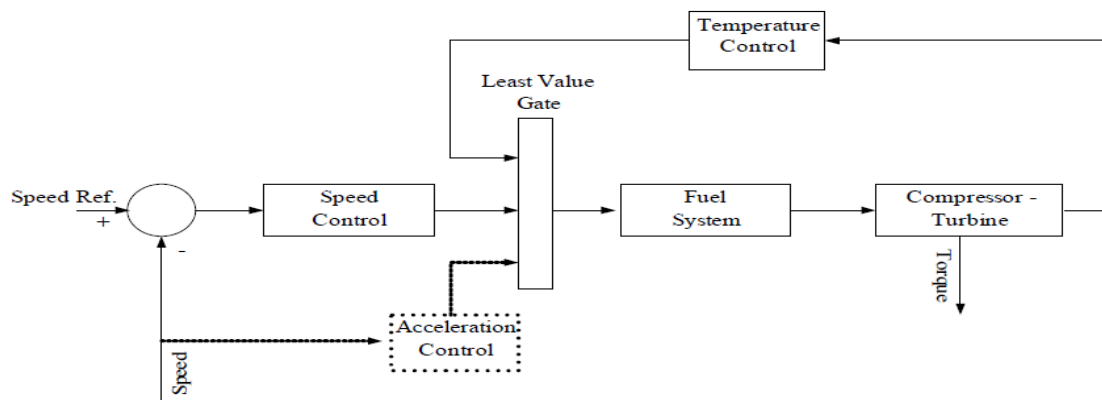


Figure 3.1 Block diagram of a micro-turbine.

In figure 3.1, per unit representation of Microturbine is shown with its control systems. Each subsystem of Microturbine is discussed in detail in following subsections.

3.1.1 Speed and acceleration control

The operation of the speed control is based on the speed error between the rotor speed (in per unit) of Microturbine generation system and a reference speed (one per unit). This control system is the primary mean for controlling Microturbine under variable load conditions. Modelling of speed control is usually done by using a lead-lag transfer function [34] or with a PID controller [23]. In the presented model lead-lag function is used to implement the speed controller, as shown in figure 3.2. In this figure, K is controller gain; T_1 and T_2 are the governor lead and lag time constants respectively and Z is constant representing the governor mode (isochronous or drooping). A droop governor is a direct proportional speed controller in which the output of the system is proportional to the speed error. And in case of isochronous governor, the rate of change of output is proportional to the speed error (acting as a proportional plus reset speed controller).

The acceleration control is primarily used to limit the rate of rotor acceleration before reaching the operating speed during the turbine startup. The acceleration control could be eliminated from the model, if the system runs close to the rated speed. In the proposed work, acceleration control is not used.

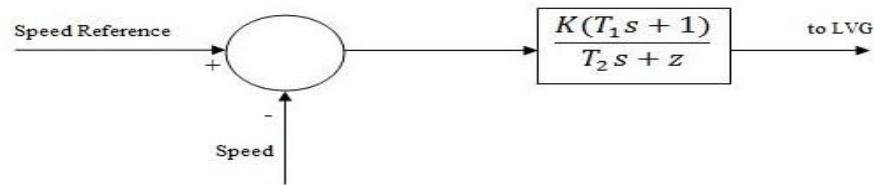


Figure 3.2 Speed controller for the micro-turbine

3.1.2 Fuel System

The fuel system comprises of main blocks i.e. fuel valve and the actuator. The inertia of the fuel valve positioner and the fuel system actuator is responsible for the fuel outflow from the fuel system. The equations for the fuel valve positioner and the fuel system actuator are given below.

The valve positioner transfer function is:

$$E_1 = \frac{K_v}{T_v + c} F_d \dots \dots \dots (3.1)$$

The fuel system actuator transfer function is:

$$W_f = \frac{K_f}{T_f + c} E_1 \dots \dots \dots (3.2)$$

In eq. (3.1) and (3.2), K_v represents valve positioner gain and K_f is the fuel system actuator gain. T_v, T_f are the valve positioner and fuel system actuator time constants, c is a constant, F_d and E_1 are the input and outputs of the valve positioner and W_f is the fuel demand signal in per unit.

The minimum amount of fuel for a particular point of operation is decided by the output of the least value gate and it is input to the fuel system. The turbine speed N acts as another input to the fuel system. The variation of mechanical power on the turbine is directly corresponded by the per unit value of V_{ce} under steady state conditions. The fuel control system is shown in figure 3.3.

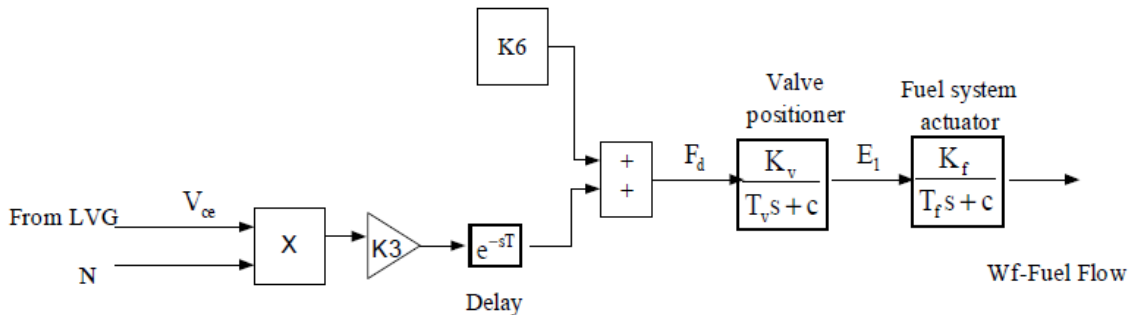


Figure 3.3 Block diagram of the fuel control system.

The gain K_3 ($K_3=1-K_6$) is provided to V_{ce} , and then the output of gain block is delayed and offset by the minimum amount of fuel flow K_6 that is required to ensure the continuous combustion process. K_6 is the minimum amount of fuel required at no load and rated speed.

3.1.3 Compressor-Turbine System

The compressor-turbine is a linear and non dynamic device. It is also the heart of the micro-turbine. A small transport delay T_{CR} is provided to the combustion reaction time. T_{CD} is the time

lag which is associated with the compressor discharge volume and T_{TD} is a transport delay for the transport of gas from the combustion system. The block diagram of compressor-turbine system is shown in figure 3.4. The torque and the exhaust temperature characteristics shown in the figure 3.4 for single shaft gas turbine are essentially linear with respect to fuel flow and turbine speed. These characteristics are given by the following equations.

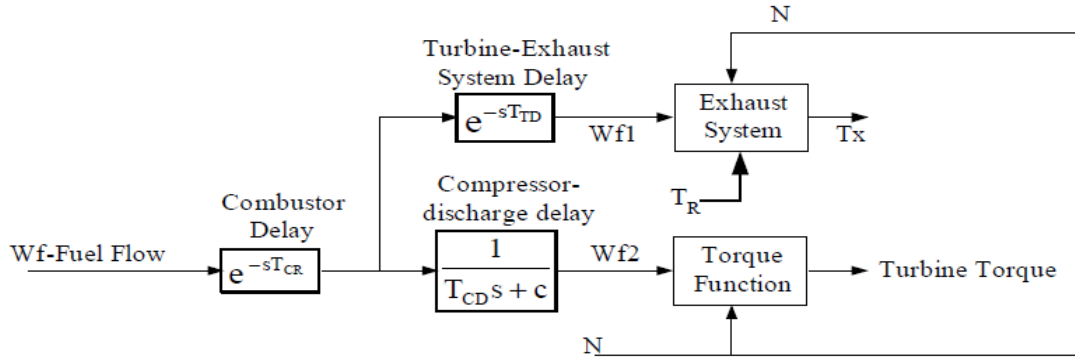


Figure 3.4 Compressor-Turbine system of a micro-turbine

Torque function of the Microturbine is given by:

$$\text{Torque} = K_{HHV} (W_{f2} - 0.23) + 0.5(1 - N) \text{ (Nm)} \dots \dots \dots (3.3)$$

Exhaust system function for exhaust temperature is given by:

$$\text{Exhaust Temp., } T_X = T_R - 700(1 - W_{f1}) + 550(1 - N) \text{ (}^\circ\text{F)} \dots \dots \dots (3.4)$$

Where, K_{HHV} is the coefficient that depends on the enthalpy or higher heating value of the gas in the combustion chamber. T_R is the reference temperature. In the torque expression, the K_{HHV} and the constant 0.23 cater for the typical power/fuel characteristic, which varies linearly from zero power at 23% fuel flow rate to the rated output at 100% fuel flow rate. For this system, input is fuel demand signal in per unit and outputs are the per unit turbine torque and exhaust temperature ($^\circ\text{F}$).

3.1.4 Temperature control

Temperature control limits the Microturbine output power at a predetermined firing temperature. It is independent of variation in fuel characteristics or ambient temperature. The turbine torque and the exhaust temperature are the resultant of fuel burned in the combustion chamber. A series

of thermocouples incorporating radiation shield are used to measure exhaust temperature as shown in figure 3.5.

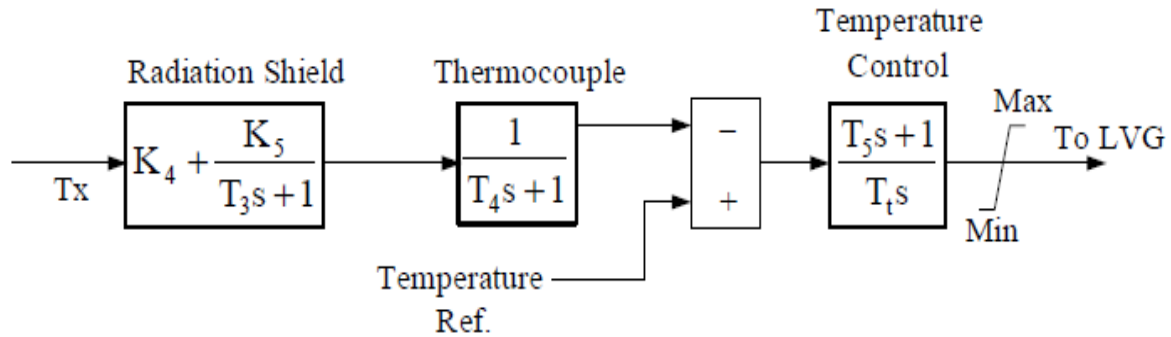


Figure 3.5 Temperature control in Microturbine system.

In figure 3.5,

T_1 represents the temperature controller integration rate.

T_3 and T_4 are the time constants associated with the radiation shield and thermocouple.

K_4 and K_5 are constants associated with radiation shield.

T_5 is the time constant associated with temperature controller.

The reference temperature is compared with the output from the thermocouple. Generally the reference temperature is higher than the output of the thermocouple. This forces the output of the temperature control to stay on the higher side allowing the dominance of speed control through the least value gate (LVG). The temperature controller output starts decreasing only when the thermocouple output exceeds the reference temperature. When output of this system becomes lower than speed controller output, then this output will pass through the least value gate to limit the turbine output. At this time, turbine is operating on temperature control. The exhaust temperature ' T_x ' acts as input and the temperature control signal to the least value gate is the output of the temperature controller.

3.1.5 Simulation model of the Microturbine system

The simulation model of the Microturbine with its whole system representation, along with its control system interconnections is shown in figure 3.6

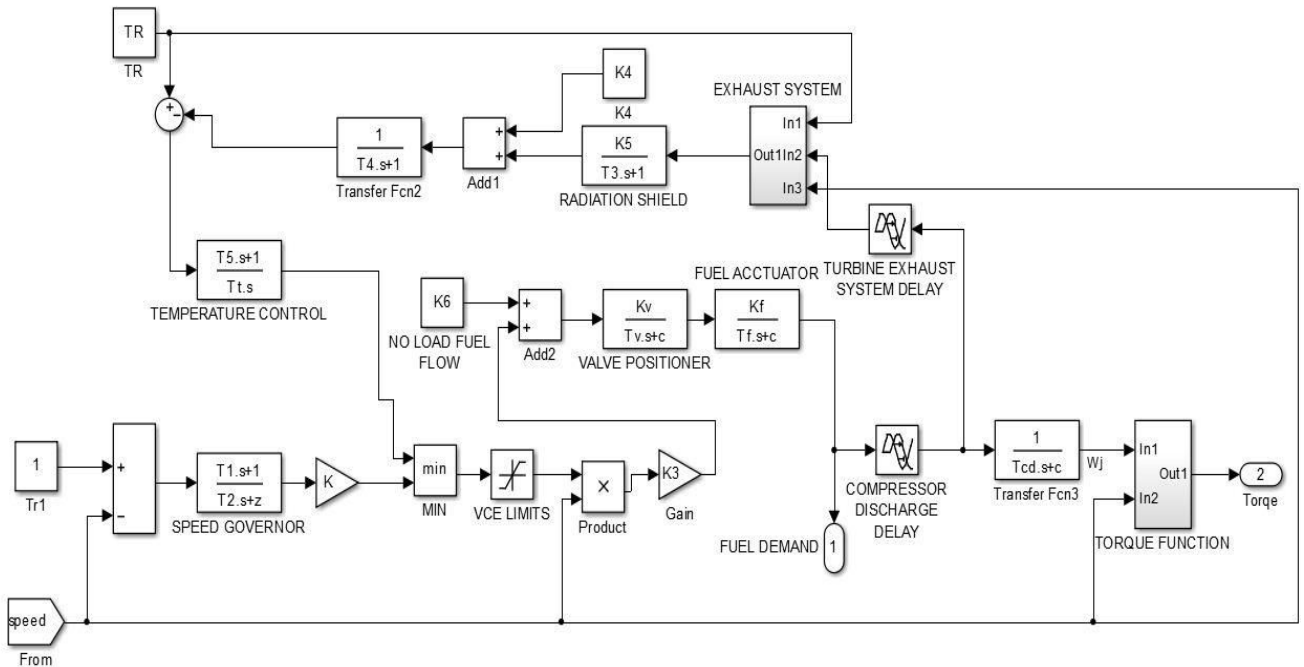


Figure 3.6 simulation model of a Micro-turbine

3.2 Modelling of Microturbine Generation System

The Microturbine generation system has the following main components required for its simulation in MATLAB environment.

1. Microturbine system
2. Permanent Magnet Synchronous Generator
3. Power Electronics interface
4. Variable Load

The block diagram of the Microturbine generation system is shown in the figure 3.7.

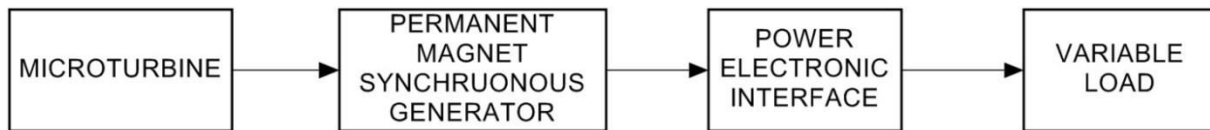


Figure 3.7 Block diagram of Microturbine generation system

3.2.1 Simulation Parameters of the Microturbine Generation System

Simulation parameters of the various components of the components of the Microturbine generation system are given in the following tables.

Table 3.1 Parameters of Microturbine System [34]

SPEED CONTROLLER PARAMETERS	Controller Gain (K)	25
	Governor Lead Time Constant (T ₁)	0.4
	Governor Lag Time Constant (T ₂)	1
	Constant Representing Governor Mode (Z)	3
FUEL SYSTEM PARAMETERS	Valve Positioner Gain (K _v)	1
	Fuel System Actuator (K _f)	1
	Valve Positioner Gain Time Constant (T _v)	0.05
	Fuel System Actuator Time Constant (T _f)	0.04
FUEL SYSTEM PARAMETERS	Constant (c)	1
	Gain (K ₃)	0.77
	Gain (K ₆)	0.23
COMPRESSOR TURBINE PARAMETERS	Combustor Delay (T _{CR})	0.01
	Combustor Discharge Delay (T _{CD})	0.2
	Turbine Exhaust System Delay (T _{TD})	0.04
	Coefficient (K _{HHV})	1.2
TEMPERATURE CONTROL PARAMETERS	Radiation Shield Constant (K ₄)	0.8
	Radiation Shield Constant (K ₅)	0.2
	Radiation Shield Time Constant (T ₃)	15
	Thermocouple Time Constant (T ₄)	2.5
TEMPERATURE CONTROL PARAMETERS	Temp. Controller Integration Rate (T _t)	450
	Temp. Controller Time Constant (T ₅)	3.3
	Reference Temperature (T _R)	950

Table 3.2 Parameters used for the Simulation of Permanent Magnet Synchronous Generator (PMSG) [37].

Stator Phase Resistance R_s (ohms)	0.0125
Armature Inductance (H)	165×10^{-6}
Flux Linkage (wb)	0.2388
Number of poles	4
Inertia (kg-m^2)	0.011

Table 3.3 Parameters used for the Simulation of Power Electronics interface [40].

VOLTAGE REGULATOR	K_p	0.4
	K_i	500
PWM GENERATOR	Carrier frequency (Hz)	2000
	Sampling Time (sec)	$2\mu\text{sec}$

3.3 Modelling of Hybrid Generation System

The hybrid generation system is modeled using a Microturbine generation system illustrated in the section 3.2 and wind generation system. Both the generation systems are connected to the load with a Power Electronics interface on Microturbine side.

Simulation model of the hybrid generation System is shown in figure 3.8. This system contains three subsystems Microturbine, Power Electronics Interface, and Wind Energy Conversion System. Microturbine system is same as shown in figure 3.6. The rest two systems are shown in figure 3.9 and 3.10.

The Wind Energy Conversion System and Microturbine Generation System are connected to the load through their respective buses. The current and voltage measurements from these buses are feed to the power computation block to calculate their respective powers.

important to match the system frequency and voltage with the other system with which interfacing has to done.

The other subsystem of the hybrid generation system is wind energy conversion system. This is the renewable system used as the main generation source in the hybrid system. This system runs on the variable wind inputs to the wind turbine producing useful torque required for running asynchronous generator. Feedback of the generator speed is given back to the wind turbine. Wind turbine runs on the constant pitch angle of 10° . A capacitor is connected after the asynchronous generator to improve the power factor of the system. The simulation model of the wind energy conversion system is shown in Figure 3.10.

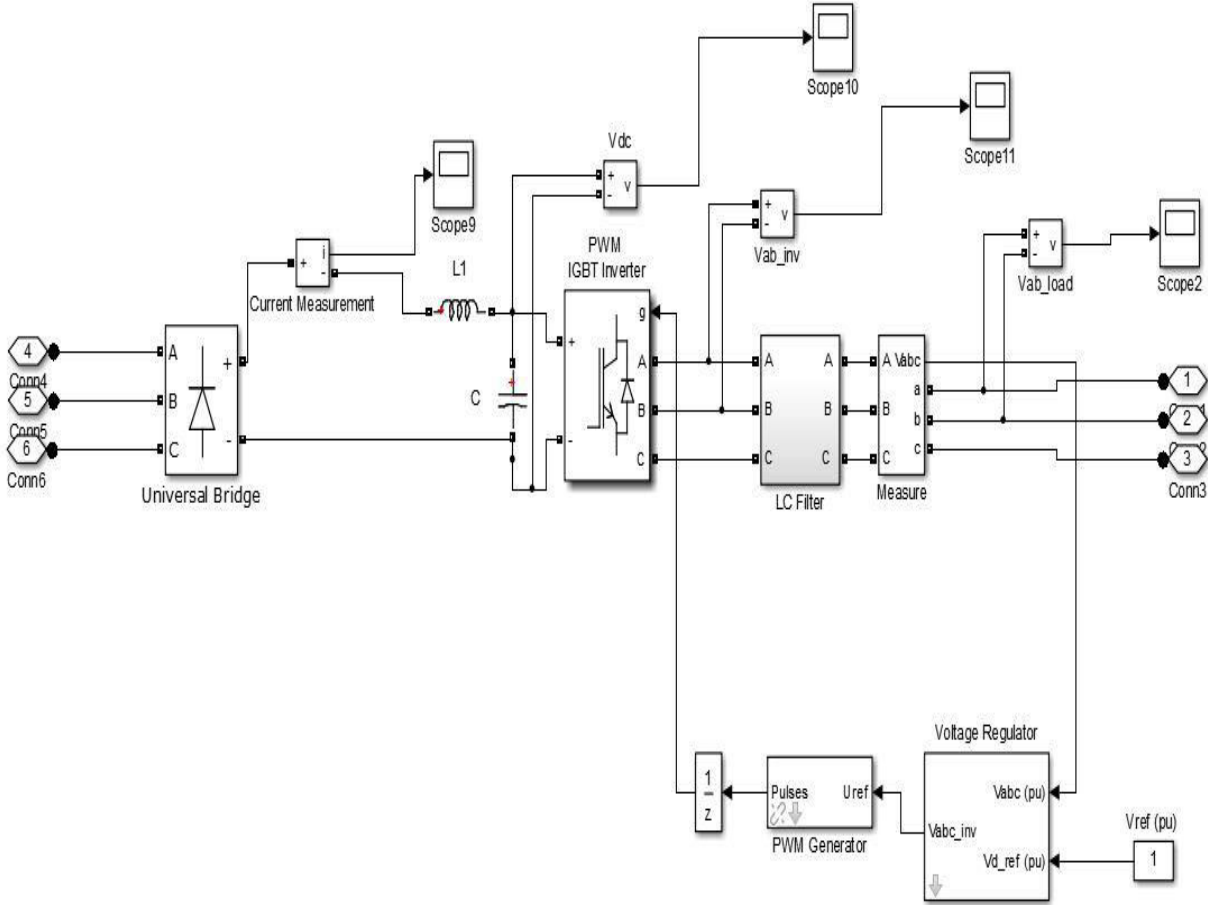


Figure 3.9 Simulation of the power Electronics interface

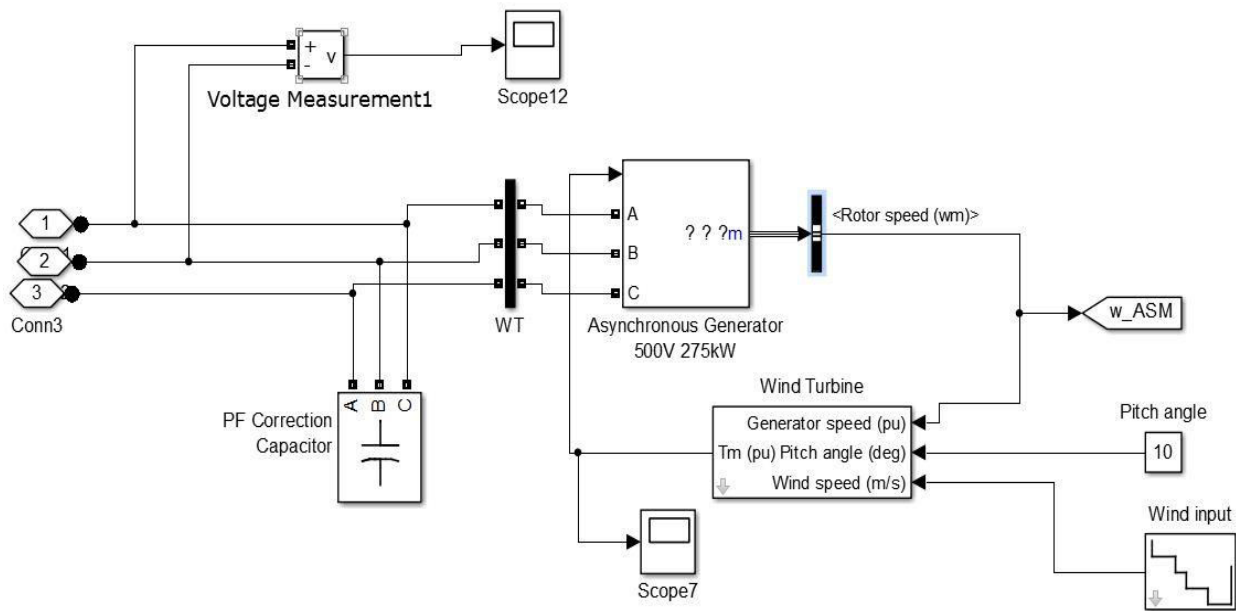


Figure 3.10 Simulation model of the wind energy conversion system.

The parameters for asynchronous generator of Wind energy conversion system are listed in the below mentioned table.

Table 3.4 Parameters for simulation of Asynchronous Generator [40].

ASYNCHRONOUS GENERATOR	Nominal Power (kVA)	275
	Nominal Voltage ' V_{rms} ' (volts)	380
	Frequency (Hz)	50
	Stator Resistance ' R_s ' (p.u)	0.016
	Stator Inductance ' L_s ' (p.u)	0.06
	Rotor Resistance ' R_r ' (p.u)	0.015
	Rotor Inductance ' L_r ' (p.u)	0.06
	Mutual Inductance ' L_m ' (p.u)	3.5

DISCUSSION OF SIMULATION RESULTS

Simulation of hybrid Wind-Microturbine generation system is performed using MATLAB/SIMULINK. The system runs under variable wind conditions and characteristics of both the generation system are studied.

The system is run for 10 seconds under variable wind data as shown in figure 4.1. At T=0 seconds wind speed is 25 m/sec and varying at t=3, 4, 6, 8 seconds. The system is operating under constant pitch angle of 10° .

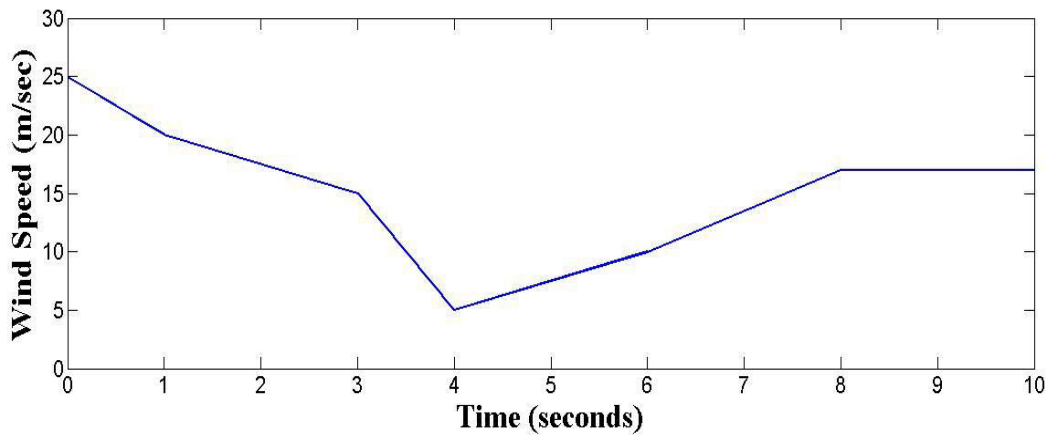


Figure 4.1 Wind speed input to the wind turbine

The output voltage of the asynchronous generator operating by the torque supplied from the wind turbine is shown in the figure 4.2.

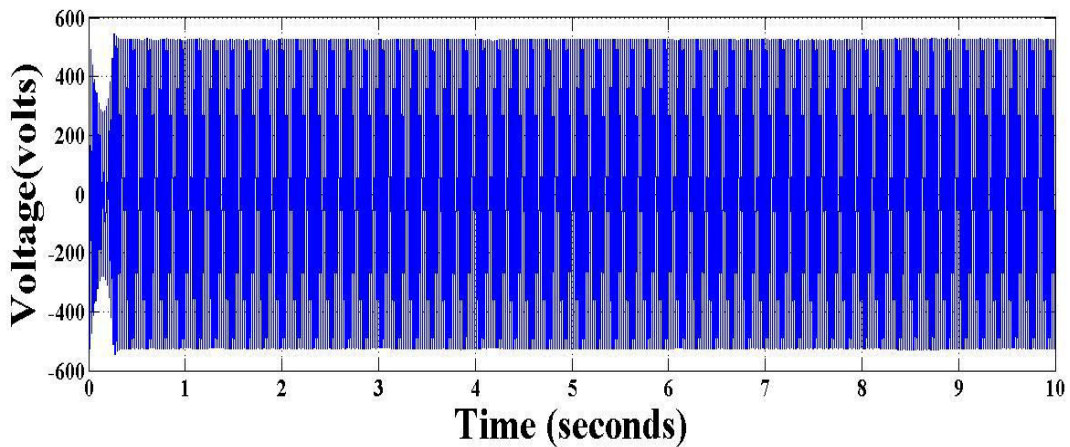


Figure 4.2 Output voltage of the wind energy conversion system

From figure 4.2 and 4.3 shows that the output voltage and frequency of both the generation systems is equal for full simulation time.

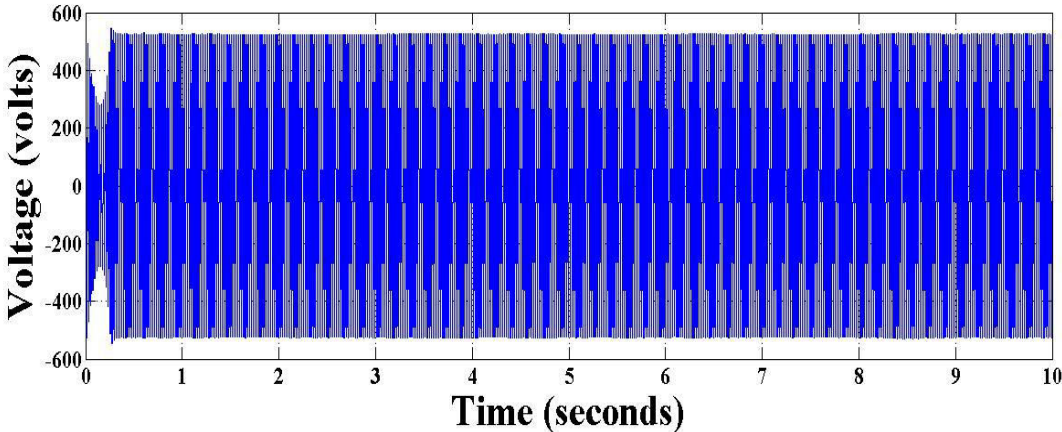


Figure 4.3 Output voltage of the Microturbine Generation system

The output voltage of the Microturbine generation system is obtained by using a rectifier inverter circuit. Inverter is controlled by voltage regulator and PWM control circuit. The waveforms of the system are shown in figure 4.4, 4.5, and 4.6.

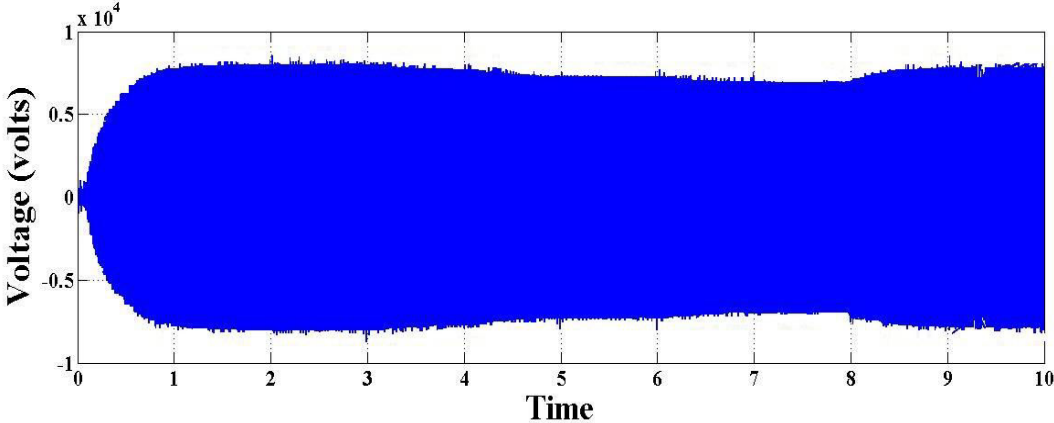


Figure 4.4 Stator terminals Voltage of Permanent Magnet Synchronous Generator

Figure 4.4 shows the high frequency voltage output of the permanent magnet synchronous generator. Due to such a high frequency of the order of 1600 Hz, the system is provided with the rectifier-inverter circuit. Inverter is controlled by the voltage regulator converting this output voltage to 380 V_{rms} and 50 Hz.

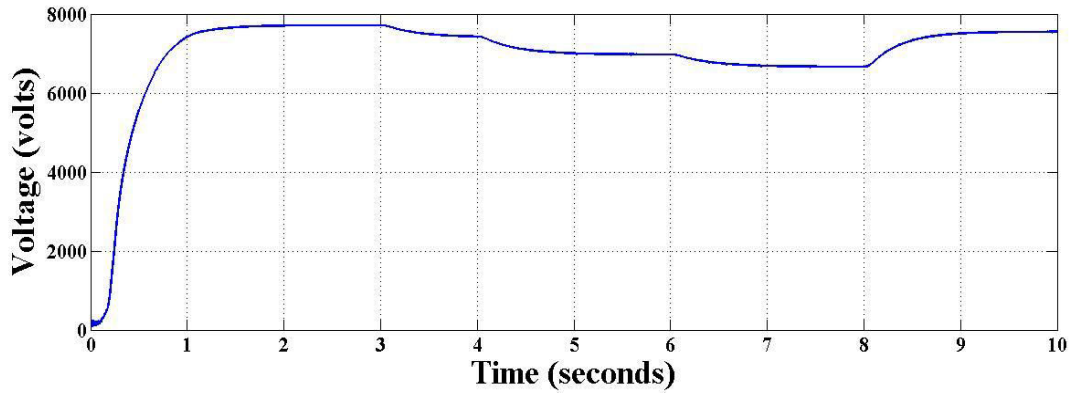


Figure 4.5 DC link voltage of the Power Electronics Interface

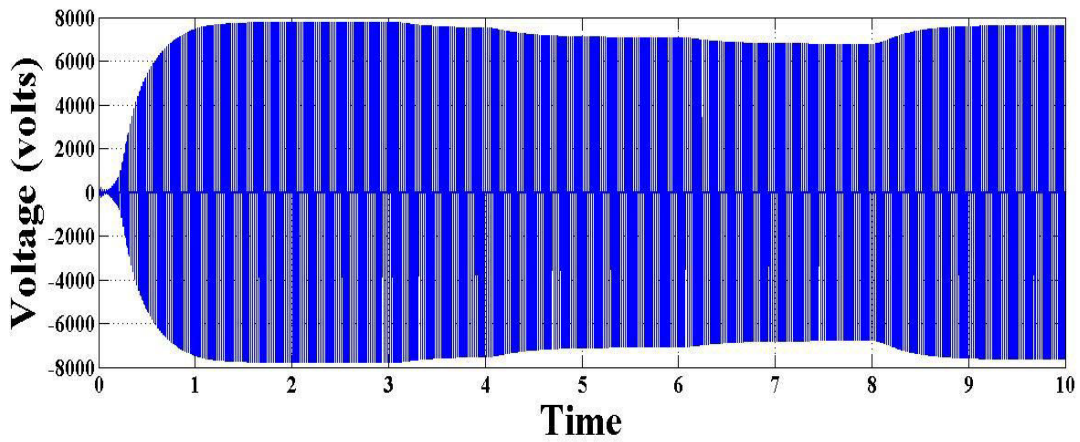


Figure 4.6 Inverter output voltage of Power Electronics Interface

Figure 4.4, 4.5 and 4.6 shows the stepwise conversion of high voltage i.e. 8000 V and high frequency (1600 Hz) to the required voltage shown in figure 3.3.

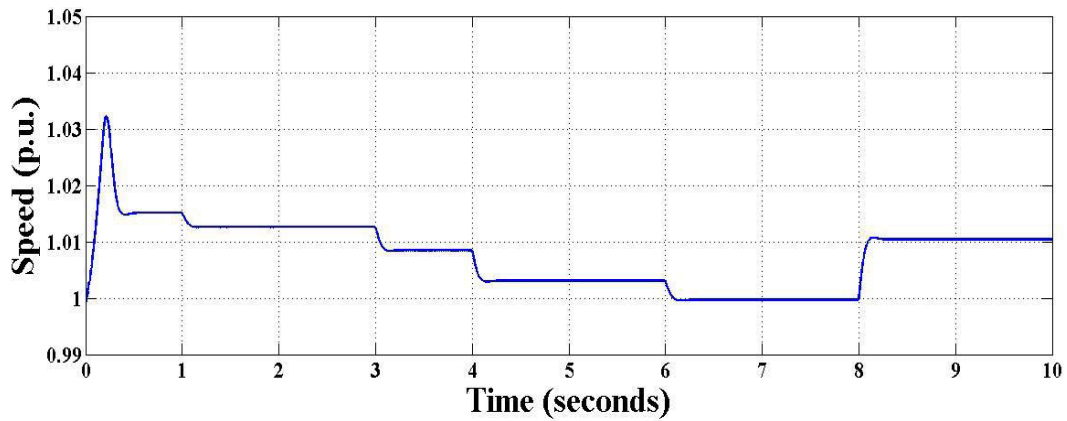


Figure 4.7 Rotor speed of the Asynchronous Generator

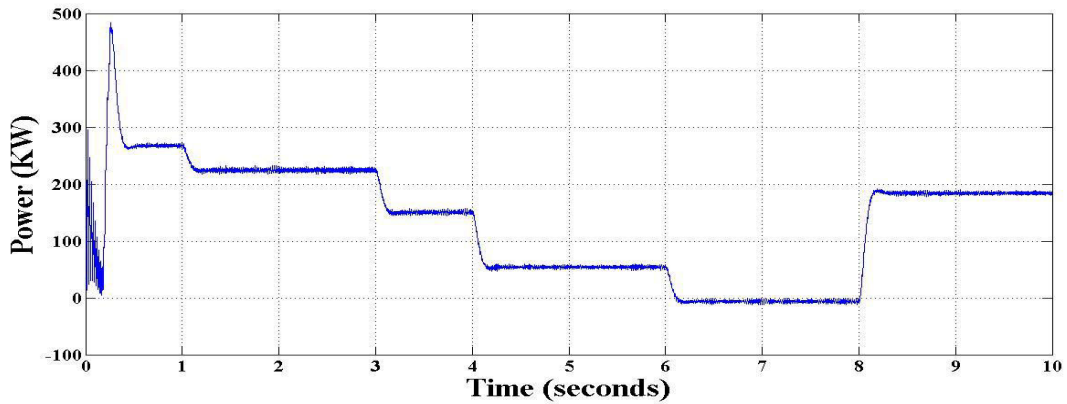


Figure 4.8 Power extracted from the wind energy conversion system

Figure 4.7 and 4.8 shows the variation of power supplied by the wind energy conversion system with the speed of the asynchronous generator. The system power decreases with the decrease in generator rotor speed.

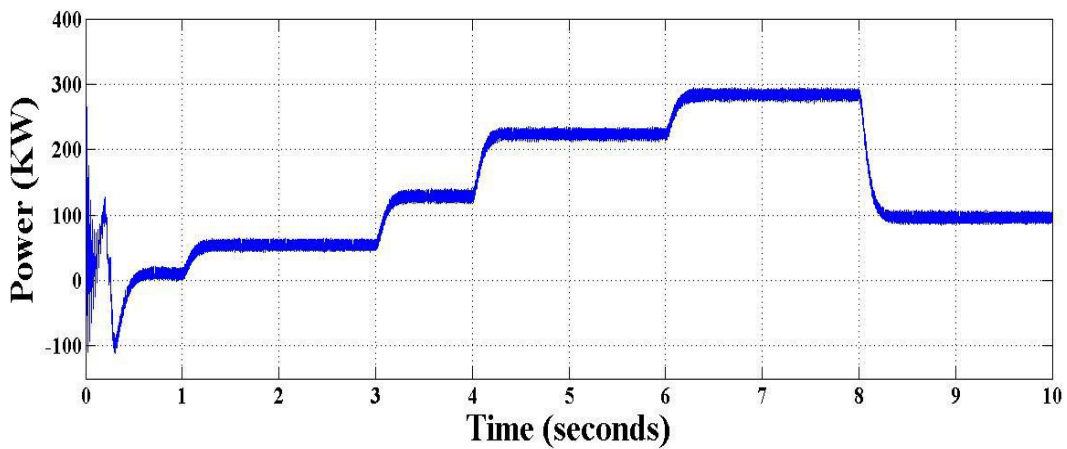


Figure 4.9 Power extracted from the Microturbine generation system

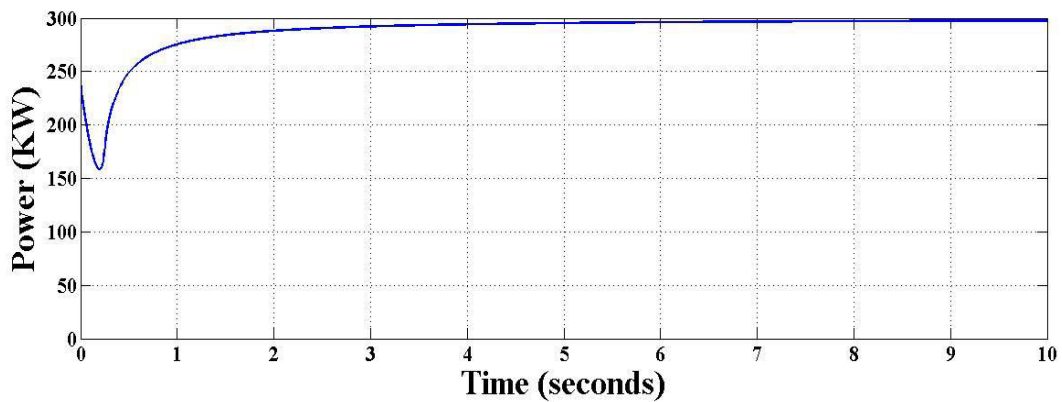


Figure 4.10 Power consumed by the load

Figure 4.8, 4.9 and 4.10 shows that both the generation systems are unstable till $t=0.4$ seconds. At $t=0.4$ seconds the Wind Turbine is supplying the major portion of power and Microturbine power share is about 30 kW. But as the wind speed is reduced to 20 m/sec at $t=1$ second, wind power is not sufficient to fulfill the load demand. At this time, the Microturbine starts producing the deficient power. In the same way the Microturbine increases or decreases its output power according to the output of the wind power.

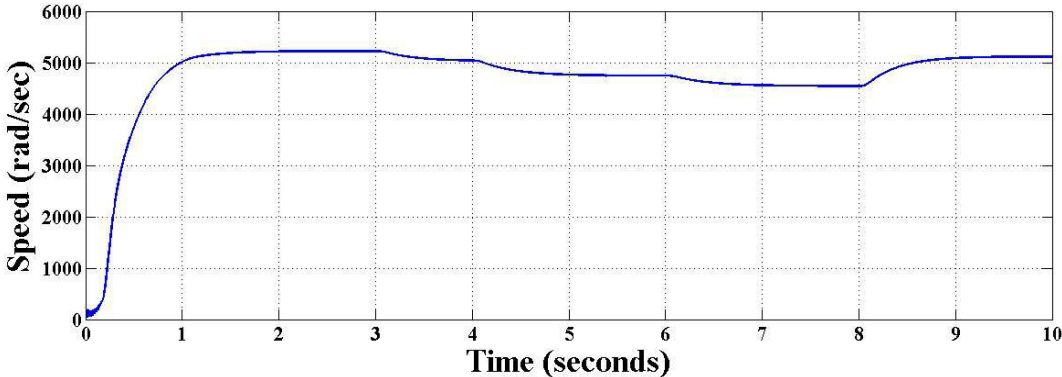


Figure 4.11 Rotor speed of the permanent magnet synchronous generator

Figure 4.11 represents the rotor speed of the permanent magnet synchronous generator. In this figure, the rotor rotates at rated speed at no load and speed of generator decreases as the load increases. This rotor speed is converted to per unit and sent to Microturbine system to control its fuel demand.

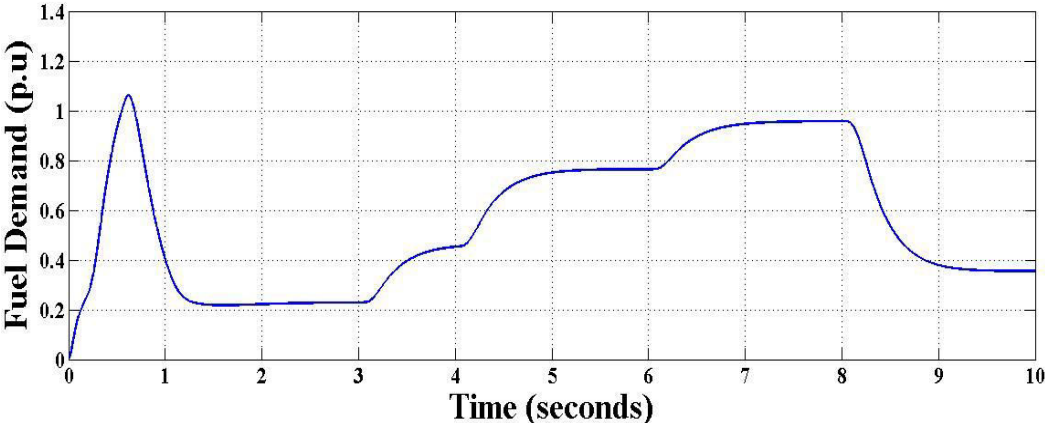


Figure 4.12 Fuel demand of the Microturbine system

In figure 4.12, the system requires fuel little more than rated value for the purpose of starting and after that fuel demand varies with the rotor speed input. As the speed of the rotor decreases the fuel demand increases and vice versa.

The asynchronous generator also requires the reactive power supply for excitation purpose during starting. This reactive power is supplied by the micro-turbine.

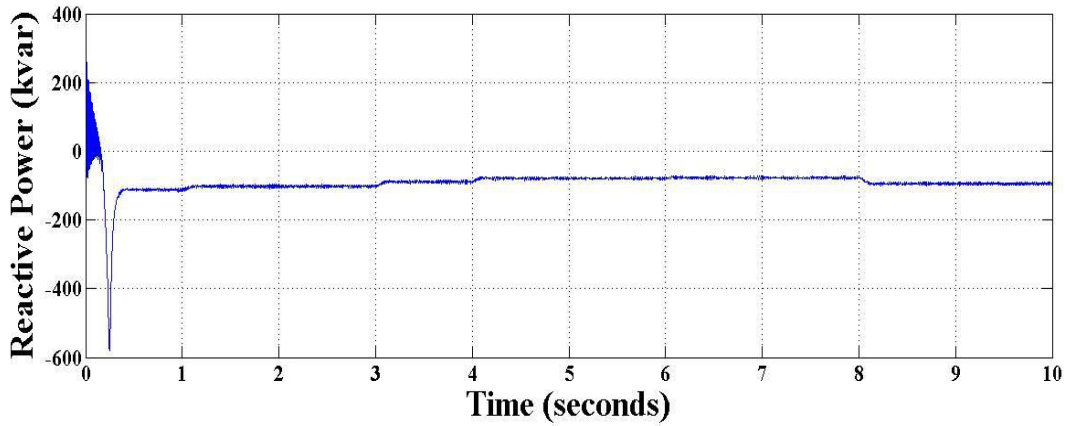


Figure 4.13 Reactive Power characteristics of Wind energy conversion system

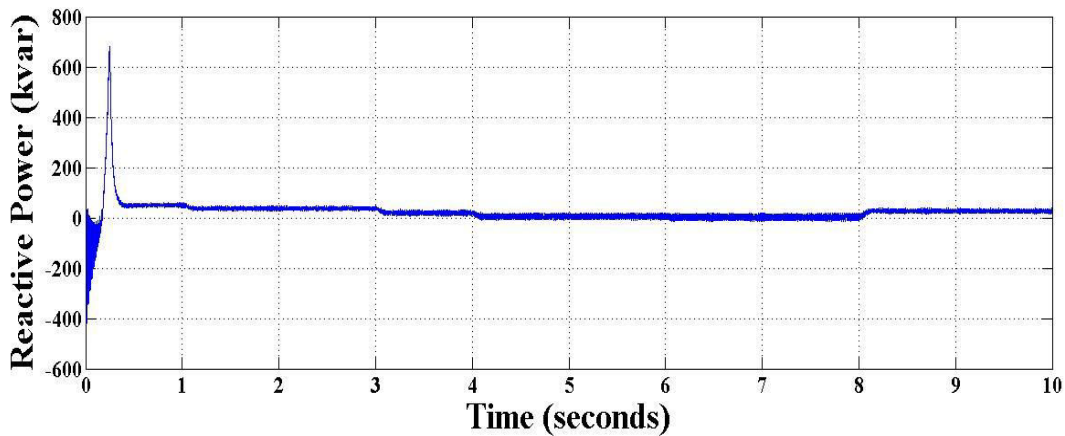


Figure 4.14 Reactive Power characteristics of Microturbine generation system

Figure 4.13 and 4.14 shows that the reactive power requirement of the asynchronous generator during starting is compensated by the Microturbine generation system. After starting, the 75kvar capacitor connected in parallel to the asynchronous generator supplies the most of the reactive power and if more required; it is supplied by the Microturbine system.

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

In this dissertation, a simulation model of a hybrid generation system comprising Microturbine generation system and wind energy conversion system is presented. This model is tested for evaluating the performance of the proposed hybrid generation system under varying wind speeds. Simulation results of the system show that the system is able to supply a constant power to the load irrespective of the wind speed input. This system also varies its fuel demand according to the load variations, resulting in low consumption of fuel. The system is also capable of meeting its reactive power demand, as asynchronous generator requires reactive power for excitation purpose. Hence, this hybrid Wind-Microturbine generation system is suitable for stand-alone operation as both the generation systems very well co-ordinate with each other.

5.2 Future Scope

The power management of the system is well illustrated in this dissertation. The work can be further progressed in following areas:

1. As the output power of the Microturbine generation system is not smooth. For this, some compensating device such as DSTATCOM can be added to the system.
2. Other renewable energy sources can also be connected in the same system or in place of wind energy conversion system.

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