PERFORMANCE EVALUATION OF WIND ENERGY CONVERSION SYSTEM USING FUZZY BASED MODEL

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
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(With Specialization in Power System Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this dissertation report, entitled **"Performance Evaluation of Wind Energy Conversion System Using Fuzzy Based Model"** is submitted in partial fulfillment of the requirements for the award of the Degree of Master of Technology with specialization in "**Power System Engineering**" to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried under the esteemed guidance of **Dr. E. Fernandez, Department of Electrical Engineering, Indian institute of Technology Roorkee,** Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University/Institute.

Singh

Dated: 30/06/2008 (YASHPAL SINGH DEWRI)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

This thesis presents the development and test of an approach for improving the output performance of wind energy conversion system by regulating the frequency and voltage of a wind power generation system that considers stand alone wind-turbines equipped with self excited squirrel cage induction generators and a controlled secondary load without the use of energy storage devices. Since operating conditions in wind energy conversion system are kept changing, it is a challenge to design a control for reliable operation of the overall system. This control strategy is based on a fuzzy controller using the frequency as the input variable for the closed loop control and the power of a resistive secondary load as the controlled variable. The secondary load is a simple controllable load capable of absorbing real power from the wind energy conversion system. The purpose of this secondary load is to quickly absorb any excess wind power, thus helping to control the system frequency. To consider variable operating conditions, Mamdani fuzzy operator is taken into account to represent time-varying system, partitioned by linguistic rules. For improving the voltage profile synchronous condenser is used.

The proposed system is simulated in MATLAB 7.5.0. In the simulation study, the frequency, voltage, generated and consumed power profiles during startup and production are discussed. The proposed controller is compared with a conventional proportional-integral derivative (PID) controller. Simulation results show that the proposed controller is more effective against disturbances caused by wind speed and load variation than the PID controller, and thus it contributes to the better performance of wind energy conversion system.

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CHAPTER 1
INTRODUCTION

1.1 Introduction:

Wind energy is known as a clean energy source with higher generation cost than certain conventional generation plants. The development and utilization of wind energy to satisfy the electrical demand has received considerable attention in recent years, owing to the concerns regarding the dwindling energy resources and enhanced public awareness of the potential impact of the conventional energy systems on the environment. Improvements in wind generation technologies will continue to encourage the use of wind energy in both the grid-connected and stand-alone systems. Owing to the random nature of the wind, the wind generators behave quite differently from the conventional generators. The unpredictability in output power of wind turbines because of varying wind speeds is a major constraint for the future of wind energy.

In remote locations where the utility grid does not exist, stand alone wind energy conversion scheme can be used to feed the local electrical load. In stand-alone wind energy conversion systems, two main problems arise concerning frequency regulation. First, the mechanical power delivered by the turbines can vary. Second, and most important, the loads supplied by such systems are variable by nature. The self-excited induction generator (SEIG) used in stand alone wind energy conversion system has the inherent problem of fluctuations in the magnitude and frequency of its terminal voltage with changes in wind velocity and load. This results in an appreciable amount of fluctuation in the magnitude and frequency of the wind energy conversion system due to its dependence on the generator rotor speed which is governed by the wind speed and the pulsating input torque from the vertical axis wind turbine. This fluctuation in frequency and voltage magnitude is objectionable to sensitive loads.

Regulating frequency is essentially a matter of maintaining an instantaneous balance of real power (kW) in the system at all times, while voltage regulation involves maintaining an instantaneous balance of reactive power (kVAr) as well as maintaining the real power at all times. For a grid connected system, the frequency control is automatically obtained because the utility controls the load seen by the wind turbine.

In low and medium penetration wind energy conversion systems, where the diesel (or other dispatchable) generator is running at all times, the diesel genet's governor controls the generator frequency. Diesel generators are very expensive to operate because of the high maintenance and fuel costs. Batteries are also expensive because of the relatively high maintenance and the climate control need. They need to be replaced every four to five years depending on their discharge cycle. Storage devices such as batteries, flywheels, have all been considered for frequency control [9] but are often rather expensive and complex to control. The other solution for controlling the frequency by matching the input and output power is to use a load controller, which feeds a secondary load, enabling the total power supplied by the generator to match the sum between the consumer's loads and secondary load. As the active power balance is achieved, the frequency is satisfactory regulated.

In high penetration wind energy conversion system, where the dispatchable generator is absent or frequently shut down, frequency control is performed by high speed secondary load controllers. For improvement in voltage and frequency regulation the load controllers are required to operate on high penetration wind energy conversion system with different power ratings.

Over the years, several load controller topologies have been developed for voltage and frequency regulation, and are briefly presented as follows [2, 27]. The load controller can be a binary weighted resistor with several branches in parallel. According to system's behavior, these branches are switched on and off. These controllers are simple and distortion free. Other solutions use electronic devices to adjust the frequency's value. The secondary load consists of a three-phase resistor bank feed on each phase by a back-to-back converter with thyristors. The dumped power is controlled by adjusting the thyristor's firing angle. A similar solution uses a controlled rectifier - also based on thyristors – which feeds a single phase resistance [10].

For the control and analysis of a complex system, the commonly used approach is to use a model of the system. However, because the different complex characteristics of the system, it is difficult to use the traditional quantitative techniques to build a quantitative model of the system. This is the motivation for more flexible methods for the complex systems. These models are basically linguistic models which are based on fuzzy IF-THEN rules and fuzzy inference. The fuzzy linguistic models can qualitatively describe two kinds of complex system behavior, namely, the nonlinear relationship between the input and the output of the system, and the uncertainty in the system. Fuzzy systems can be used to represent a nonlinear deterministic function. Fuzzy systems can have two forms. One is the conventional linguistic model; another is the functional representation of fuzzy IF-THEN rules. These functional representations are called fuzzy-neural systems which in fact are nonlinear deterministic functions. Two kinds of fuzzy-neural systems are generally used. One is the Mamdani type fuzzy model which uses the series expansions of fuzzy basis functions to represent the fuzzy systems. The other is the Takagi- Sugeno type fuzzy model. Fuzzy control is robust and non linear and therefore is able to function well across wide operating range [2, 14, 16].

A controller is needed for controlling any system. The controller compares the output from the process with that from a reference model. The error is then used for adjusting the parameters of the controller through some control algorithm, which is either based on physical laws or parameter estimation method. The common difficulty of this approach lies in many cases at the attempt to formulate the input-output relationship by means of a mathematical model. These models may be too complex to compute even when developed.

After facing these problems, investigators realized that incorporating human intelligence into automatic control systems would be a more efficient solution, and this led to the development of fuzzy control algorithms. The fuzzy algorithm is based on intuition and experience, and can be regarded as a set of "heuristic decision rules" Such nonmathematical control algorithms can be implemented easily in a computer. They are straightforward and do not involve any computational problems. [2, 14, 17]

1.2 Literature Survey:

For improving the performance of the system, wind energy systems need controls due to the real time variation of input energy and load,

Pandiaraj et al [12] have concluded the requirement of control methods to improve the performance and maintain stability in wind power system. He has proposed the application of load control using a novel frequency and voltage sensing device. The device uses a low cost microcontroller to monitor the system frequency and voltage. Load switching is carried out based on this information.

Singh[1] have attempted modeling of an electronic load controller (ELC) for a self-excited induction generator in wind energy conversion system, used for power balancing at varying consumer load as required for these generators. The implemented ELC consists of a rectifier-chopper system feeding a resistive dump load whose power consumption is varied through the duty cycle of the chopper.

Krishnan et al [12] have attempted optimum design of advanced distributed load control system using a low cost, microcontroller based, frequency and voltage-sensing device. Each load control device is based on a PIC16C711 microcontroller with no direct communication between them. Individual single-phase loads are connected to the supply through these devices. Distributed load control systems can be more robust than centralized systems because if one load controller fails the system can continue to function. *Marinescu [11]* aims to establish a common way in improving the electric energy quality generated in wind power systems. The considered situation deals with the self excited induction generators. The research investigates a power control, in order to control the frequency regulation; a frequency control circuit was designed for the switching of the secondary load. For the control study, simulations were made for variable loads. The considered control circuit performs the voltage and frequency regulation, separately and together. *Szeidert et al [20]* presents a comparative study regarding the control (using an adaptive neuro-fuzzy controller and a PID controller) based on the simulation of wind energy conversion systems functioning. There are considered several simulations based on asynchronous generator usage.

Sangko et al [18] proposes modeling and controller design approach for a hybrid wind power generation system that considers a fixed wind-turbine and a dump load. To consider variable operating conditions, Takagi-Sugeno (TS) fuzzy model was taken into account to represent time-varying system by expressing the local dynamics of a nonlinear system through sub-systems, partitioned by linguistic rules.

The squirrel cage induction generator in self-excited mode is found to be the most suitable option as generator due to such advantages as low cost, simple construction, ruggedness, brushless rotor, absence of DC source, maintenance-free nature, and self-protection against short circuits [1]. *Chan [19]* have attempted a steady-state performance analysis of a stand-alone three-phase self excited induction generator supplying unbalanced loads. Using the method of symmetrical components, the complex three-phase generator-load system is reduced to a simple equivalent passive circuit. The proposed method enables practically all cases of unbalanced operation.

Kumar [13] describes a variable speed wind generation system where fuzzy logic principles are used for light load efficiency improvement and optimization. A squirrel cage induction generator feeds the power to an improved topology of matrix converter which pumps power to a utility grid or can supply to an autonomous system. The power factor at the interface with the grid is controlled by the matrix converter to ensure purely active power injection into the grid for optimal utilization of the installed wind turbine capacity. Furthermore, the reactive power requirements of the induction generator are satisfied by the matrix converter to avoid self-excitation capacitors. The generation system has fuzzy logic control with vector control in the inner loops. *Mayosky [25]* proposed a direct adaptive control strategy for WECS control. It is based on the combination of two control actions: a radial basis z function network-based adaptive controller, which drives the tracking error to zero with user specified dynamics, and a supervisory controller, based on crude bounds of the system's nonlinearities. The supervisory controller fires when the finite neural-network approximation properties cannot be guaranteed.

Nehrir et al [21] reports the development of a computer approach for evaluating the general performance of stand-alone wind/photovoltaic generating systems. Simple models for different system components are developed, integrated, and used to predict the behavior of generating systems based on available wind/solar and load data. The model is useful for evaluating the performance of stand-alone generating systems and gaining a better insight in the component sizes needed before they are built. *Cristea et al [24]* investigates the dynamic behavior of a mixed system consisting of a wind farm and a diesel group supplying a load, under different disturbances. They implemented the diesel group model and its afferent control system.

Besheer et al [22] addresses the problem of regulating wind energy conversion system by using fuzzy output feedback controller. First, a Takagi-Sugeno fuzzy model is employed to represent the nonlinear dynamics of the wind energy conversion system. Then, based on the fuzzy model and utilizing the concept of parallel distributed compensation, a fuzzy observer based fuzzy controller is developed to stabilize the nonlinear system. Sufficient condition for stability of wind energy conversion system fuzzy model using fuzzy output feedback controller are derived. The fuzzy observer and fuzzy controller are capable of disturbance rejection.

Fuzzy logic is applied to wind farm control with the goal of pass-through the complex, non-linearity and uncertainty of these control systems. In [23] are present some limitations of conventional controllers as: nonlinear models are computationally intensive and have complex stability problems. A plant does not have accurate models due to uncertainty and lack of perfect knowledge, uncertainty in measurements and multivariable and multi loops systems have complex constraints and dependencies.

In this thesis a fuzzy logic technique is used for regulating the frequency and voltage in a high penetration stand alone wind energy conversion system. This new technique is based on a fuzzy controller using the frequency as the input variable for the closed loop control and the power of a resistive secondary load as the controlled variable.

1.3 Outline of Chapters:

Chapter 1: This chapter presents the frequency and voltage related issues in the stand alone wind energy conversion system. This chapter also deals the literature review, presents the studies related to wind energy conversion system.

Chapter 2: This chapter deals the wind energy conversion system, its types, different components used in wind energy conversion system, and different factors affecting its performance.

Chapter 3: This chapter presents the introduction of the fuzzy logic and fuzzy controllers. Different types of fuzzy set, operations, membership functions, fuzzification and defuzzification techniques are discussed.

Chapter 4: This chapter deals the fuzzy load regulator for improving the performance of the wind energy conversion system by controlling the frequency .Fuzzy control of secondary load has been discussed in detail.

Chapter 5: This chapter deals the simulation results and the discussions. SIMULINK model of proposed model is presented. The generated and load powers, frequency and voltage profiles by the fuzzy controller are discussed and compared with the PID controller.

Chapter 6: This chapter concludes the whole dissertation work.

WIND ENERGY CONVERSION SYSTEM

2.1 General:

Wind energy is considered to be a very promising alternative for power generation because of its tremendous environmental, social, and economic benefits. Electrical power generation from wind energy behaves quite differently from that of conventional sources because of the varying nature of the wind. A wind energy conversion system (WECS) converts the natural energy available in the wind into electrical energy. The first use of wind power was to sail ships in the Nile some 5000 years ago. The Europeans used it to grind grains and pump water in the 1700s and 1800s. Today, large wind-power plants are competing with electric utilities in supplying economical clean power in many parts of the world. The average turbine size of the wind installations has been 300 kW until the recent past. The newer machines of 500 to 1,000 kW capacities have been developed and are being installed. Improved turbine designs and plant utilization have contributed to a decline in large-scale wind energy generation costs from 35 cents per kWh in 1980 to less than 5 cents per kWh in 1997. At this price, wind energy has become one of the least-cost power sources. The major advances in wind energy conversion system those have made it highly competitive to other power sources are:

1. Variable-speed operation of electrical generators to capture maximum energy.
2. Improved plant operation, pushing the availability up to 95 percent economy of scale, as the turbines and plants are getting larger in size.
3. High-strength fiber composites for constructing large low-cost blades.
4. Accumulated field experience (the learning curve effect) improving the capacity factor.
5. Falling prices of the power electronics.

2.2 Types of Wind Power Plants:

2.2.1 Grid Connected Wind Power Plants:

Grid-connected systems are large utility-scale power plants directly connected to the grid. The utility interconnection improves the overall economy and the load availability of the renewable plant. The synchronous generators of the grid system supply magnetizing current for the induction generator. The variable-frequency generator output of wind power plant is first rectified into DC and then inverted into a fixed-frequency A.C. The frequency reference for the inverter firing and the voltage reference for the rectifier phase-angle control are taken from the grid lines.

2.2.2 Stand Alone Wind Power Plants:

Stand alone wind plants have the major application in remote areas where utility lines are uneconomical to install due to terrain, the right-of way difficulties or the environmental concerns. The wind power output can fluctuate on an hourly or daily basis. The stand-alone system must, therefore, have some means of storing energy, which can be used later to supply the load during the periods of low or no power output.

2.2.3 Hybrid Wind Power Plants:

Hybrid wind power plants combine other energy sources like diesel engine, solar energy and battery backups etc. to satisfy the load demand. Most hybrids use diesel generator, since diesel provides more predictable. Reductions in fuel costs, as well as reductions in operation and maintenance costs, make the hybrid system very economical. Both achieved through the use of these systems. The key factor that leads to achieving these two cost reductions is the decreased operating hours of a diesel generator due to increased reliance on renewable energy resources. Hence hybrids are becoming increasingly popular among energy planners dealing with remote areas where a continuous and safe power supply is needed.

2.3 Penetration Level in Wind Energy Conversion Systems:

Low penetration or high penetration refers to the ratio of renewable energy generated to the primary electric demand. The ratio of the total renewable power output (kW) to the primary load at any given moment is the instantaneous penetration. The ratio of the total renewable energy generated (kWh) to the total energy consumed by the primary load over a period of time is the average penetration. According to penetration level wind energy conversion systems are basically three types.

2.3.1 Low penetration wind power plants:

In a low wind penetration system, the total wind power output generally never exceeds 30-40% of the load, and the average penetration will generally not exceed 10-15%. An example of a low wind penetration system is a few 100 kW wind turbines on a 2 MW diesel mini-grid .The wind turbine output is never enough to significantly affect the operation of the diesel plant, and no additional controls are required to maintain power quality and ensure system stability.

2.3.2 Medium penetration wind power plants:

In a medium penetration wind energy conversion system, the peak output of the wind generators is high enough to require additional control strategies and/or stabilizing components to avoid disrupting the operation of the diesel generators. For example, a secondary load is often used during high wind or low load periods to absorb excess wind power and thereby prevent the diesel from operating too lightly loaded. In medium penetration systems, the maximum instantaneous penetration is in the range 50-100%, and the average penetration generally ranges from 20-50%.

2.3.3 High penetration wind power plants:

A high penetration wind energy conversion system is designed to all of the primary electric demand with wind energy itself. The actual average wind energy output may actually exceed the average load. Typically high penetration systems incorporate some form of energy storage, but not always. What is universally true about high penetration systems is that they are designed to meet the load exclusively with renewably generated power a significant fraction of the time .In high penetration systems, the maximum instantaneous penetration is in the range 100-400%, and the average penetration generally ranges from 50-150%.

2.4 Wind Turbines:

A wind turbine is a device for extracting kinetic energy from the wind. By removing some of its kinetic energy the wind must slow down but only that mass of air which passes through the rotor disc is affected. The turbine power depends on the cube of the wind speed. The wind is characterized by its speed and direction, which are affected by several factors. Wind turbines interact with the wind, capturing part of its kinetic energy and converting it into usable energy. The turbine rating is important as it indicates to the system designer how to size the induction generator, the plant's transformer, connecting cables to the substation, and the transmission link interfacing the grid. The power system must be sized on the peak capacity of the generator and the generator is rated in a different manner than the wind turbine.

Depending on the position of the rotor axis, wind turbines are classified into vertical-axis and horizontal-axis ones.

2.4.1 Horizontal-axes Wind Turbine:

Most wind turbines being used are the horizontal-axis type.Horizontal-axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive a generator. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Horizontal turbines have variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.

2.4.2 Vertical-axis Wind Turbine:

Vertical-axis wind turbines (VAWT) are a type of wind turbine where the main rotor shaft runs vertically. Among the advantages of this arrangement are that generators and gearboxes can be placed close to the ground, and that vertical-axis wind turbine do not need to be pointed into the wind. It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is generally slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten the service life.

2.4.3 Power Extracted by the Wind Turbine:

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power production capacity. Obviously, sites with steady high wind produce more energy over the year.

The power in moving air is the flow rate of kinetic energy per second. The power in air of mass "m" moving with speed v is given by the following equation.

$$\text{Power} = \frac{1}{2}.(\text{mass flow rate per second}).v^2 \tag{2.1}$$

The actual power extracted by the rotor blades of wind turbine is the difference between the upstream and the downstream wind powers which is given by the equation(2.2).

$$\mathrm{P}_0 = \frac{1}{2}.(\text{mass flow rate per second}).\{v^2 - v_0{}^2\} \tag{2.2}$$

Where P_o= mechanical power extracted by the rotor or the turbine output power.

v = upstream wind velocity at the entrance of the rotor blades.

v_o = downstream wind velocity at the exit of the rotor blades.

The air velocity is discontinuous from v to v_o at the "plane" of the rotor blades in the macroscopic sense. The mass flow rate of air through the rotating blades is, therefore, derived by multiplying the density with the average velocity. That is:

$$\text{mass flow rate} = \rho.A.\frac{v + v_0}{2} \tag{2.3}$$

The mechanical power extracted by the rotor, which is driving the electrical generator, is therefore.

$$P_0 = \frac{1}{2}[\rho.A.\frac{(v + v_0)}{2}].(v^2 - v_0{}^2) \tag{2.4}$$

The above expression can be algebraically rearranged as:

$$P_0 = \frac{1}{2}\rho.A.v^3 \frac{(1 + \frac{v_0}{v})[1 - (\frac{v_0}{v})^2]}{2} \tag{2.5}$$

Where

$$\frac{(1 + \frac{v_0}{v})[1 - (\frac{v_0}{v})^2]}{2} = C_p \tag{2.6}$$

The factor Cp is called the power coefficient of the rotor or the rotor efficiency which is the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind. For a given upstream wind speed, the value of C_p depends on the ratio of the down stream to the upstream wind speeds, that is (v_o/v). C_p has the maximum value of 0.59 when the (v_o/v) is one-third.

2.4.4 Wind Turbine SIMULINK model:

Wind turbine output power depends on both wind speed and turbine rotational speed. The SIMULINK model is based on the steady-state power characteristics of the turbine. The stiffness of the drive train is infinite and the friction factor and the inertia of the turbine is combined with those of the generator coupled to the turbine. The output power of the turbine is given by the following equation.

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}v^3_{wind} \tag{2.7}$$

Where

P_m= Mechanical output power of the wind turbine in watt.

C_p = Performance coefficient of the turbine.

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

β = Blade pitch angle (deg).

ρ = Air density (kg/m^3).

A= Turbine swept area (m^2).

v_{wind} = Wind speed (m/s).

The SIMULINK model of the turbine is illustrated by figure2.1. The first input is the generator speed in per unit of the generator base speed. The second input is the blade pitch angle in degrees. The third input is the wind speed in m/s. The output is the torque applied to the generator shaft in per unit of the generator ratings. The turbine inertia is added to the generator inertia.

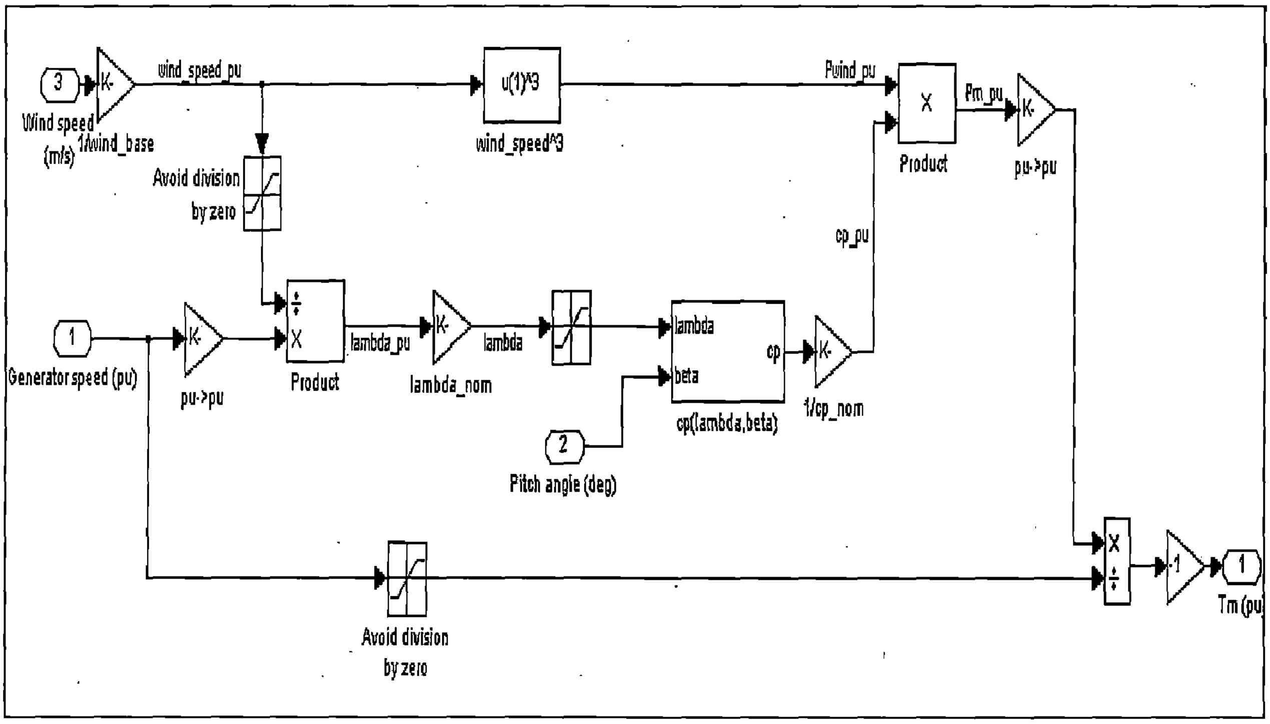


Fig.2.1 Wind Turbine SIMULINK model

The performance coefficient Cp of the turbine is the mechanical output power of the turbine divided by wind power and a function of wind speed, rotational speed, and pitch angle. Cp reaches its maximum value at zero pitch angle. The tip speed ratio λ in per unit is obtained by the division of the rational speed in per unit of the base rotational speed and the wind speed in m/s. The pitch angle beta, in degrees, used to display the power characteristics. Pitch angle is always greater than or equal to zero. Fig.2.2 shows the wind-turbine power characteristics for a pitch angle of zero degrees.

It can be observed from Fig.2.2, that when the rotation speed increases above the value resulting in maximum output power at particular wind speed, the turbine output power would drastically reduce. This is also true for turbine output torque.

2.4.4.1 Rotor Swept Area:

According to the wind turbine power equation (eq.2.7), the output power of the wind turbine varies linearly with the rotor swept area. For the horizontal axis turbine,

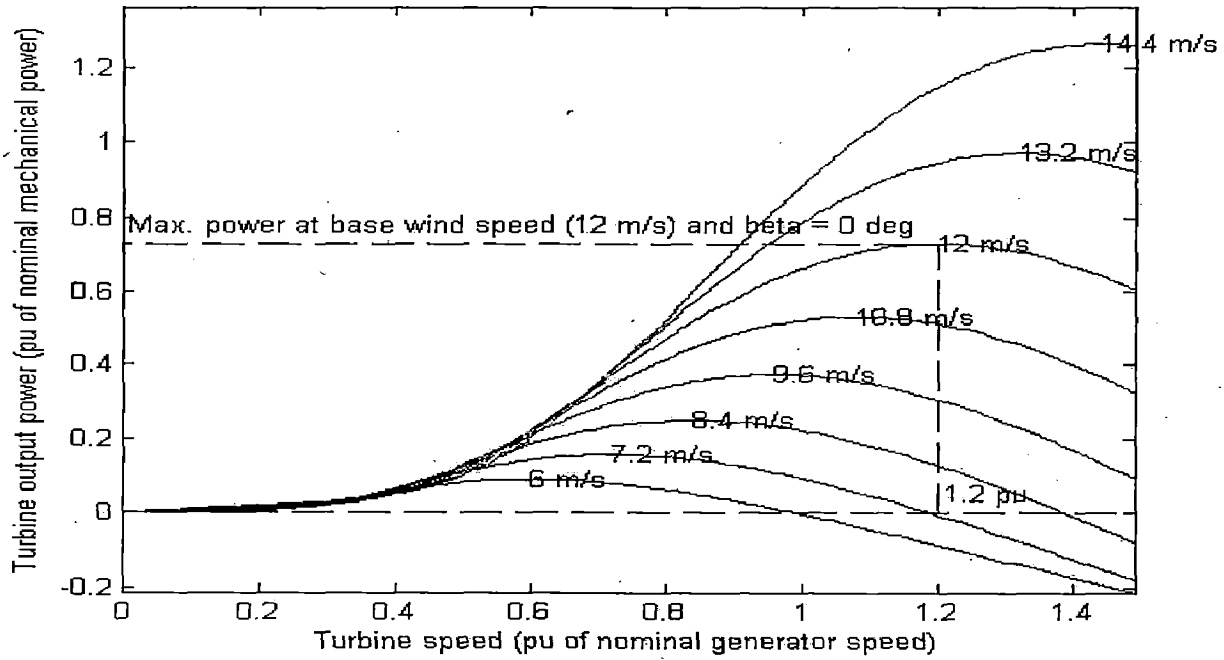


Fig.2.2 Wind Turbine Characteristics

The rotor swept area is given by:

$$A = \frac{\pi}{4} D^2 \qquad (2.8)$$

For the vertical axis wind turbine, determination of the swept area is complex, as it involves elliptical integrals. However by approximating the blade shape as a parabola, the swept area is given as:

$$A = \frac{2}{3} w \, . h \qquad (2.9)$$

Where w =maximum rotor width at the center and h is the height of the rotor.

The wind turbine efficiently intercepts the wind energy flowing through the entire swept area even though it has only two or three thin blades with solidity between 5 to 10 percent. The solidity is defined as the ratio of the solid area to the swept area of the blades. The modern 2-blade turbine has low solidity ratio. Hence, it requires little blade material to sweep large areas.

2.4.4.2 Air Density:

The wind power varies linearly with the air density sweeping the blades. The air density (ρ) varies with pressure and temperature. The air density at sea level, one atmospheric pressure and 60°F is 1.225 kg/m^3. Using this as the reference is ρ corrected for the site specific temperature and pressure. The temperature and the pressure both in turn vary with the altitude. Their combined effect on the air density is given by the following equation,

$$\rho = \rho_0 - 1.194 . 10^{-4} . H_m \qquad (2.10)$$

Where H_m =site elevation in meters.

The air density correction at high elevations can be significant. For example, the air density at 2,000-meter elevation would be 0.986 kg/m3, 20 percent lower than the 1.225 kg/m3 value at sea level.

2.4.5 Performance of wind turbine:

The performance of a wind turbine can be characterized by the manner in which the three main indicators power, torque and thrust vary with wind speed. The power determines the amount of energy captured by the rotor; the torque developed determines the size of the gear box and must be matched by whatever generator is being driven by the rotor. The rotor thrust has great influence on the structural design of the tower.

Since the wind turbine output power is directly proportional to the performance coefficient of the turbine (C_P). The usual method of presenting power performance is the non dimensional C_P- λ curve, Where λ is the tip speed ratio of the rotor blade tip speed to wind speed. The C_P- λ curve for a typical, modern, three-blade turbine is shown in fig. 2.3. It can be observed from Fig.2.3 that the maximum value of C_P is only 0.47, achieved at a tip speed ratio of 7.

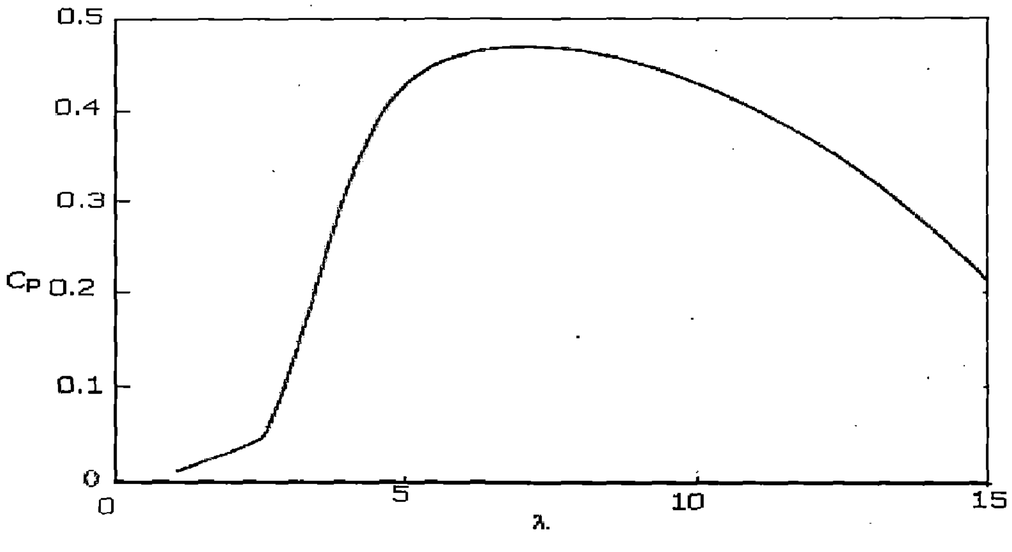


Fig.2.3 C_P- λ performance curve

2.4.6 The effect of solidity on wind turbine power:

The solidity is defined as the ratio of the solid area to the swept area of the blades. Solidity is the direct indication of number of blades. More number of blades result to the higher solidity. Figure 2.4 shows the C_P-λ curve where curve-1 represents for two blade turbine curve-2 for three blades, and curve-3 for five blade turbine.

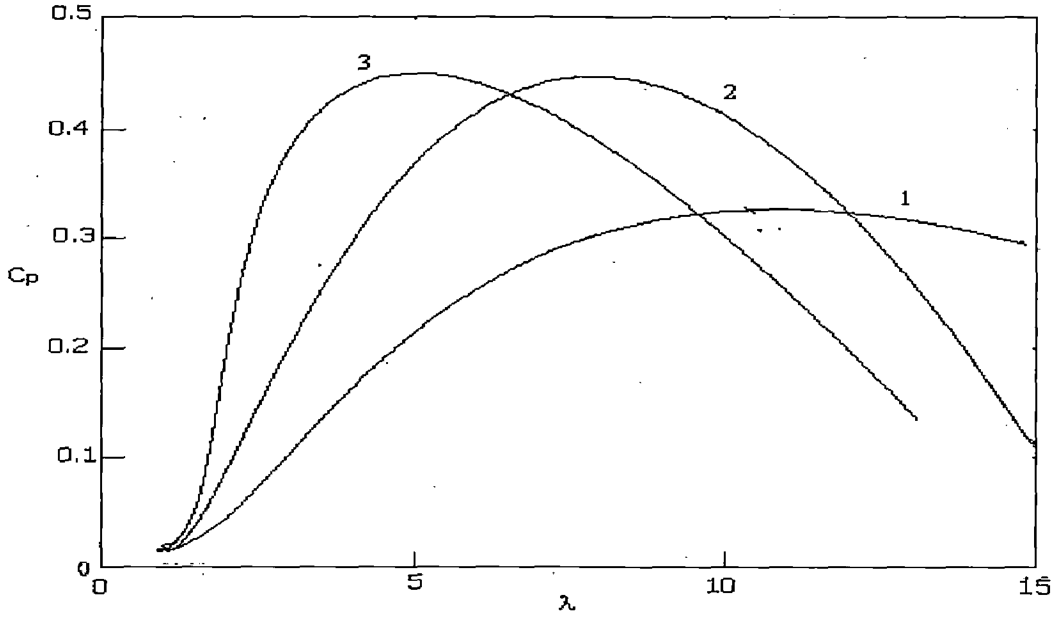


Fig.2.4 C_P-λ performance curve with different solidities

The main effects to observe of changing solidity are as follows:

1. Low solidity produces a broad, flat curve which means that the C_P will change very little over a wide tip speed ratio range but the maximum C_P is low because the drag losses are high (drag losses are roughly proportional to the cube of the tip speed ratio).

2. High solidity produces a narrow performance curve with a sharp peak making the turbine very sensitive to tip speed ratio changes and, if the solidity is too high, has a relatively low maximum CP. The reduction in C_{Pmax} is caused by stall losses.

3. An optimum solidity appears to be achieved with three blades, but two blades might be an acceptable alternative because although the maximum C_P is a little lower the spread of the peak is wider and that might result in a larger energy capture.

It might be argued that a good solution would be to have a large number of blades of small individual solidity but this greatly increases production costs and results in blades which are structurally weak and very flexible.

2.4.7 Effect of pitch angle change in Turbine Power:

Another parameter which affects the wind turbine power output is the pitch setting angle of the blades. Blade designs almost always involve twist but the blade can be set at the root with an overall pitch angle. The effect of a few degrees of pitch is shown in Fig. 2.5. Small changes in pitch setting angle can have a dramatic effect on the power output. Positive pitch angle settings increase the design pitch angle and so decrease the angle of incidence. Conversely, negative pitch angle settings increase the angle of incidence and may cause stalling to occur as shown in Fig2.5. A turbine rotor designed to operate optimally at a given set of wind conditions can be suited to other conditions by appropriate adjustments of blade pitch angle and rotational speed.

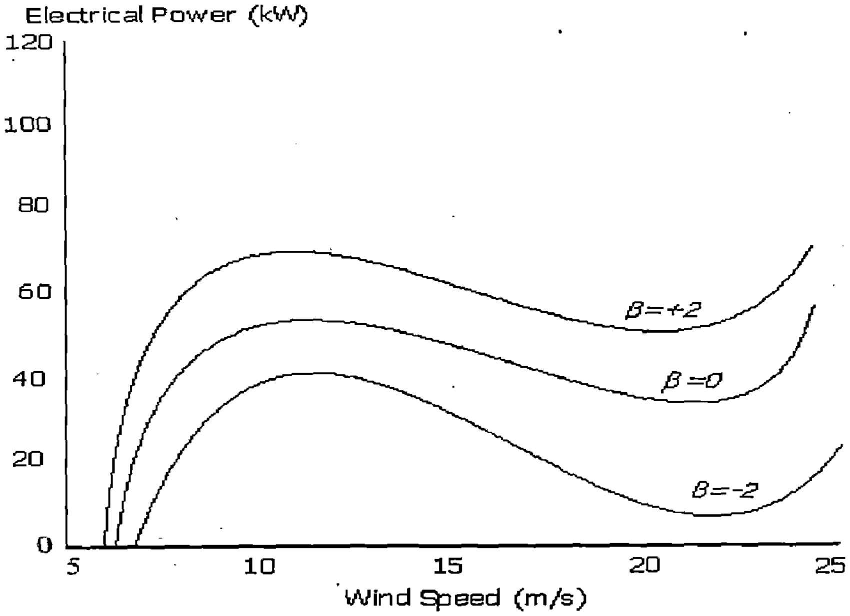


Figure.2.5: Effect of Blade Pitch Angle on Extracted Power

2.4.8 Pitch Controller:

Many of the shortcomings of fixed pitch/passive stall regulation can be overcome by providing active pitch angle control. The most important application of pitch control is for power regulation but pitch control has other advantages also. By adopting a large positive pitch angle a large starting torque can be generated as a rotor begins to turn. A 90^0 pitch angle is usually used when shutting down because this minimizes the rotor idling speed at which the parking brake is applied.

The pitch actuator is a nonlinear servo that generally rotates all the blades or part of them in unison. In closed loop the pitch actuator can be modeled as a first-order dynamic system with saturation in the amplitude and derivative of the output signal is as given by the following equation

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta_d \tag{2.11}$$

Where β and β_d are the actual and desired pitch angles respectively. Typically, β ranges from -2° to 30° and varies at a maximum rate of $\pm 10^\circ$/s. $(1/\tau)$ is the feedback gain. Power regulation may demand fast and large corrections of the pitch angle. Consequently, the bounds on the rate of change and amplitude of the pitch angle have appreciable effects on the power regulation features. To reduce the risks of fatigue damage, these limits should not be reached during normal operation of the turbine. Figure 2.6 shows the pitch angle controller.

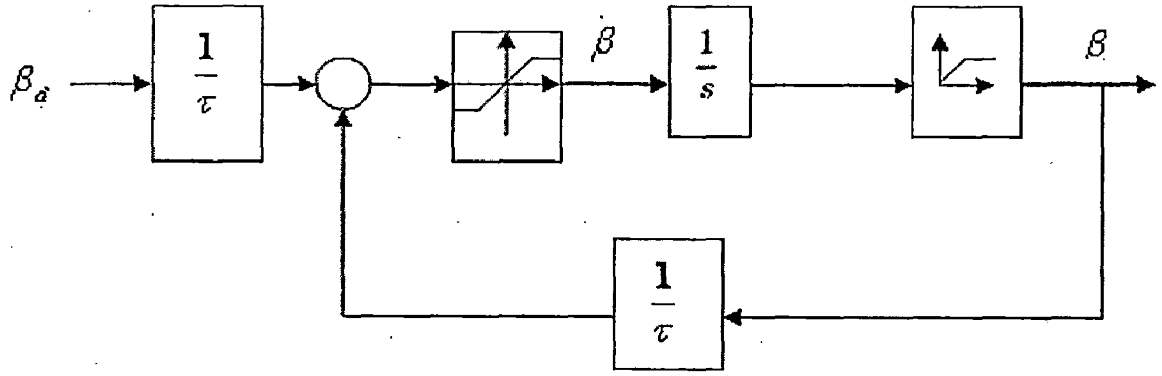


Fig.2.6 Model of the pitch angle actuator

2.4.9 Wind Turbine Speed Control

Wind turbines must have simple, low cost power and speed control. The speed control methods fall into the following categories.

1. **No speed control:** In this method, the turbine, the electrical generator, and the entire system is designed to withstand the extreme speed under gusty wind.
2. **Yaw Control:** In Yaw control rotor axis is shifted out of the wind direction when the wind speed exceeds the design limit.

3. **Pitch control**: In pitch control the pitch of the blade changes with the changing wind speed to regulate the rotor speed.
4. **Stall control**: In this method of speed control, when the wind speed exceeds the safe limit on the system, the blades are shifted into a position such that they stall. The turbine has to be restarted after the gust has gone.

2.5 Tower:

The wind tower supports the turbine and the nacelle containing the mechanical gear, the electrical generator, the yaw mechanism, and the stall control. The height of tower in the past has been in the 20 to 50-meter range. For medium and large size turbines, the tower is slightly taller than the rotor diameter. Small turbines are generally mounted on the tower a few rotor diameters high. Otherwise, they would suffer due to the poor wind speed found near the ground surface. Both steel and concrete towers are available and are being used. The main issue in the tower design is the structural dynamics. The tower vibration and the resulting fatigue cycles under wind speed fluctuation are avoided by design. This requires careful avoidance of all resonance frequencies of the tower.

2.6 Induction Generator:

Self excited induction generators are today frequently considered as the most economical solution for powering costumers isolated from the utility grid. At the present time self excited induction generator technology is replacing conventional generators based on permanent magnet technology because of their low unit cost, robustness, ease of operation and maintenance. The electrical part of the machine is represented by a fourth-order state-space model and the mechanical part by a second-order system. All electrical variables and parameters are referred to the stator. Based on the electrical topology, wind-driven induction generators can be organized into three main categories.

2.6.1 Directly coupled squirrel-cage induction generator:

The squirrel-cage induction generator (SQIG) connected directly to the grid is a very reliable configuration because of the robust construction of the standard squirrel-cage machine and the simplicity of the power electronics. By this reason, this is the topology adopted in WECS based on the Danish concept having three blade turbines.

In this scheme the voltage V_s and frequency f_s at the generator terminals are imposed by the grid. The steady-state torque - speed characteristic is given by equation1.10

$$T_g = -\frac{3}{2}\frac{V_s^2}{\omega_s}\cdot\frac{\frac{R_r}{s}}{(\frac{R_r}{s})^2 + (\omega_s.L_{lr})^2} \tag{2.12}$$

Where $\omega_s = 2\pi f_s$ is the angular line frequency, R_r and L_{lr} are the resistance and leakage inductance of the rotor windings, respectively, and s is the generator slip.

Squirrel-cage induction generator operates as generator at super-synchronous speeds and as motor at sub-synchronous speeds. In both cases, the slip also represents the fraction of the mechanical power that is dissipated by the rotor resistance. Thus, large slip implies low efficiency. Consequently, SCIG work in normal operation with very low slip.

2.6.2 Stator-controlled Squirrel-cage Induction Generator:

In this scheme a frequency converter is interposed between the generator and the AC grid. Thus, the WECS is completely uncoupled from the grid frequency. In this scheme, the frequency converter must handle all the energy supplied to the utility. In practice, the converter is rated up to 120% of nominal generator power. This is the main drawback of this scheme. The frequency converter consists of two independent converters connected to a common DC-bus. The grid side converter transforms the three-phase AC grid voltage into a DC voltage. Additionally, the converter can potentially be controlled to produce or consume reactive power provided the apparent power does not exceed the converter rating. Therefore, the larger is the active power, the lower is the capability of the converter to handle reactive power. The stator side converter provides a three-phase voltage source of frequency f_s and voltage V_s uncoupled from the AC grid. Conventionally, this converter is controlled using V/f control technique.

2.6.3 Rotor-controlled Doubly-fed Induction Generator:

In this scheme the stator windings are connected directly to the AC grid whereas the rotor windings are coupled through a partial scale back-to-back converter. Actually, this configuration accepts a wide range of power converters ranging from the early Kramer drive to four-quadrant pulse width modulated (PWM) frequency converters. The control capabilities increase with the converter complexity. The main advantage of this scheme is that the power electronics devices have to manage just a fraction of the captured power.

CHAPTER 3

FUZZY LOGIC

3.1 Introduction:

Fuzzy Logic was initiated in 1965 [5], by Lotfi A. Zadeh, professor of computer science at the University of California in Berkeley. Basically, Fuzzy Logic (FL) is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, etc. The general methodology of reasoning in fuzzy logic and expert systems by "IF...THEN..."statements are same therefore, it is often called "fuzzy expert system". Fuzzy logic deals with the problems that have fuzziness or vagueness.

3.2 Fuzzy Sets:

A fuzzy set is a set without crisp clearly defined boundary. It can contain elements with only partial degree of membership. In fuzzy sets many degrees of membership are allowed. The degree of membership to a set is indicated by number between 0 and that is a number in the interval [0, 1]. The purpose of fuzzy sets is to deal with "classes" that have no "sharply defined criteria of class membership." A fuzzy set is completely defined by its fuzzy membership function, $\mu(x)$, which gives the degree of membership of an element x, in a fuzzy set. The classic example is that of the set of tall people. The height of a person will indicate whether or not a person is tall, but the boundary between tall people and short people can not be drawn at some exact height. Fuzzy sets allow the construction of system models when the sets that comprise the model are not clearly defined.

3.2.1 Empty fuzzy set:

A fuzzy set A is called empty (denoted as A=Φ) if its membership function is zero everywhere in its universe of discourse X, that is

$$A=\Phi \qquad \text{if} \quad \mu_A(x)=0 \quad \forall\ x \in X \qquad (3.1)$$

Where "$\forall\ x \in X$" is a short notation indicating "for any element x in X".

3.2.2 Normal fuzzy set:

A fuzzy set is called normal if there is at least one element x0 in the universe of discourse where the membership function equals one- that is,

$$\mu_A = 1, \tag{3.2}$$

More then one element in the universe of discourse can satisfy the condition.

3.2.3 Equality of fuzzy sets:

Two sets are equal if their membership functions are equal everywhere in the universe of discourse- that is

$$A=B \text{ if } \mu_A(x) == \mu_B(x) \tag{3.3}$$

3.2.4 Union of fuzzy sets:

Union of two fuzzy sets A and B defined over the the same universe of discourse X is a new fuzzy set is a new fuzzy set $A \cup B$ also on X, with every membership function which is the maximum of the grades of membership function of every x to A and B-that is,

$$\mu_{A \cup B}(x) = \mu_A(x) \vee \mu_B(x) \tag{3.4}$$

Where the symbol "v" is a maximum operator. This is equivalent to Boolean OR logic.

3.2.5 Intersection of fuzzy sets:

The intersection of two fuzzy sets A and *B* is a new fuzzy set $A \cap B$ with membership function which is minimum of the grades every x in X to the sets A and B. that is,

$$\mu_{A \cap B}(x) = \mu_A(x) \wedge \mu_B(x) \tag{3.5}$$

Where "Λ" is a minimum operator. This is equivalent to Boolean AND logic.

3.2.6 Complement of a fuzzy set:

The complement of a given set A in the universe of discourse *X* is denoted by $\bar{A}$ and has the membership function ,

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x) \tag{3.6}$$

This is equivalent to the negation (NOT) operation in Boolean logic.

3.2.7 Product of two fuzzy sets:

The product of two fuzzy sets A and B defined in the same universe of discourse X is a new fuzzy set, A.B, with a membership function that equals the algebraic product of the MFs of A and B,

$$\mu_{A.B}(x)=\mu_A(x).\mu_B(x) \tag{3.7}$$

The product of two fuzzy sets can be generalized to any number of fuzzy sets in the same universe of discourse.

3.2.8 Multiplying a Fuzzy Set by a Crisp Number:

The MF of fuzzy set A can be multiplied by a crisp number n to obtain a new fuzzy set called product n.A. Its membership function is

$$\mu_{nA}(x)=n\ \mu_A(x) \tag{3.8}$$

3.2.9 Power of a Fuzzy Set:

We can raise fuzzy set A to a power n (positive real number) by raising its membership function to n. The n power of A is a new fuzzy set, A^n, with MF given by

$$\mu_A{}^n(x)=[\mu_A(x)]^n \tag{3.9}$$

3.2.10 Concentration:

The concentration of a fuzzy set A defined over a universe of discourse X is denoted as CON(A) an is a new fuzzy set with membership function given by

$$\mu_{CON(A)}(x)=[\mu_A(x)]^2 \tag{3.10}$$

3.2.11 Dilation:

The dilation of a fuzzy set A, is denoted as DIL(A), produces a new fuzzy set in X, with membership defined as the square root of he membership function of A, that is

$$\mu_{DIL(A)}(x)=\sqrt{\mu_A(x)} \tag{3.11}$$

3.3 Membership Functions:

The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Figure 3.1 shows some typical shapes of membership functions.

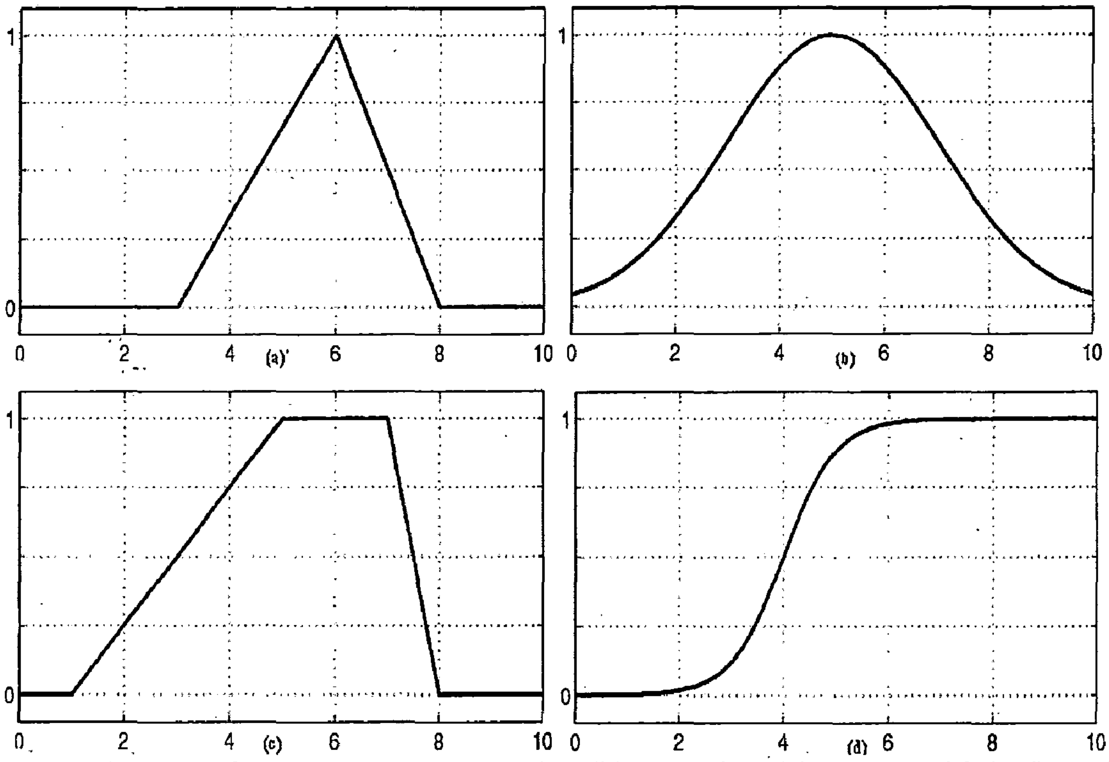


Fig.3.1 Membership functions.(a) Triangular (b)Gaussian (c) Trapezoidal (d) S-shaped

The trapezoidal fuzzy membership function is the most popular. Trapezoids are easily specified and calculated. The Gaussian probability function is useful in problems requiring adaptation because it is everywhere differentiable. Usually, the choice is based more on personal preference than any mathematical justification.

The simplest and most commonly membership function used is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal membership function (symmetrical or unsymmetrical) has the shape of a truncated triangle. Two membership functions are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian curves. The bell membership function with a flat top is somewhat different from a Gaussian function. Both the Gaussian and bell functions are smooth and non-zero at all points. A sigmoidal-type membership function can be open to the right or left. Asymmetrical and closed (not open to the right or left) membership function can be synthesized using two sigmoidal functions, such as difference sigmoidal (difference between two sigmoidal functions) and product sigmoidal (product of two sigmoids)

3.4 Fuzzy Controller:

Fuzzy controller is used in nonlinear systems which can not be accurately modeled and has more inputs, uncertain factors and inaccurate property. The objective of the fuzzy control is to design a system with acceptable performance characteristics over a wide range of uncertainty [8]. The fuzzy control is basically nonlinear and adoptive in nature, giving robust performance in the face of parameter variation and load disturbance effects. Many researchers [8], [9] have reported that the fuzzy logic control yields results which are superior to those obtained using conventional control algorithm. Figure: 3.2 shows the block diagram of fuzzy controller, the controller is in between a preprocessing block and a post processing block.

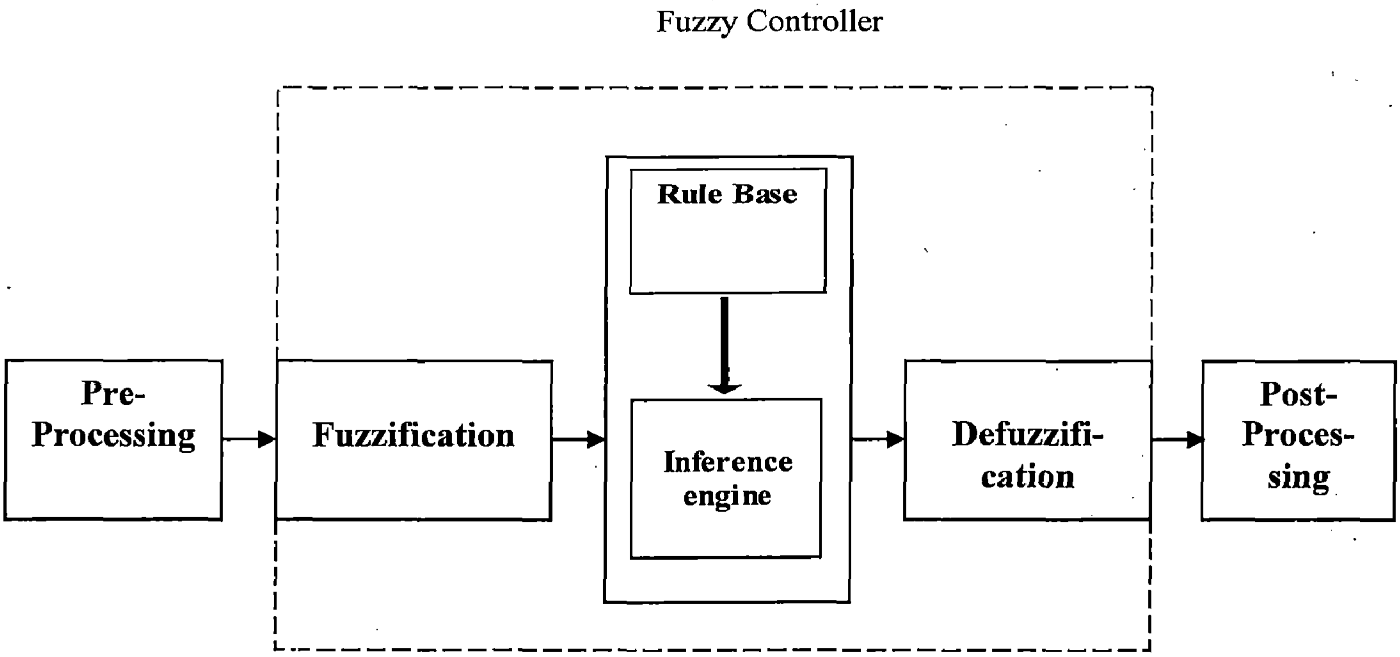


Fig.3.2 Block diagram of fuzzy controller

3.4.1 Preprocessing:

The inputs are most often hard or FULVS measurements from some measuring equipment, rather than linguistic. A preprocessor, the first block in Fig.2.2, conditions the measurements before they enter the controller. Examples of preprocessing are:

- Quantization in connection with sampling or rounding to integers;
- Normalization or scaling onto a particular, standard range;
- Filtering in order to remove noise;
- Averaging to obtain long term or short term tendencies;
- A combination of several measurements to obtain key indicators; and
- Differentiation and integration or their discrete equivalences.

3.4.2 Fuzzification:

The first block inside the controller is fuzzification block, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The fuzzification block thus matches the input data with the conditions of the rules to determine how well the condition of each rule matches that particular input instance. There is a degree of membership for each linguistic term that applies to that input variable. A fuzzifier is needed in cases where the input to the system is in the form of numerical data. This would be the case when the inputs are coming from sensors which are measuring physical quantities in the system. In some cases, the input to the fuzzy system may not come in the form of numerical data, but as fuzzy sets.

3.4.3 Rule Base:

The rule base is the most important part of any fuzzy system. The rule base encodes the knowledge of the expert into if/then rules of the form,

"IF condition THEN result"

Where the condition is called the antecedent and the result is called the consequent.

The rules may use several variables both in the condition and the conclusion of the rules. The controllers can therefore be applied to both multi-input-multi-output (MIMO) problems and single-input-single-output (SISO) problems. The typical SISO problem is to regulate a control signal based on an error signal. The controller may actually need both the error, the change in error and the accumulated error as inputs, but it is called the single-loop control, because in principle all three are formed from the error measurement.

To simplify, this it is assumed that the control objective is to regulate some process output around a prescribed set point or reference. The presentation is thus limited to single-loop control.

3.4.3.1 Rule Formats:

Basically a linguistic controller contains rules in the IF-THEN format, but they can be presented in different formats. A typical rule is given as
"If error is Neg and change in error is Neg then output is NB"

Where Neg stand for negative and NB stands for negative big.

3.4.3.2 Connectives:

In fuzzy, sentences are connected with the words AND,OR, IF-THEN ,IF and only IF, or modifications with the word NOT. These five are called connectives. It also makes a difference how the connectives are implemented. The most prominent is probably multiplication for fuzzy "NOT" instead of minimum.

3.4.3.3 Modifiers:

A linguistic modifier is an operation that modifies the meaning of a term. The modifier VERY can be defined as squaring the subsequent membership function, that is

$$\text{VERY } a = a^2$$

3.4.3.4 Universe:

Elements of a fuzzy set are taken from a "Universe of discourse" or just "Universe".

The universe contains all elements that can come into consideration.

3.4.4 Defuzzification:

After the processing of input in the controller by the control algorithm the result is a fuzzy output $\mu_{out}(u)$. Selecting a crisp number u* representation of $\mu_{out}(u)$ is a process known as defuzzification. Defuzzification method may have a significant impact on the speed and accuracy of a fuzzy controller. There are several defuzzification methods.

3.4.4.1Center of area (COA) defuzzification:

In the center of gravity method of defuzzification, the crisp output u* of the u variable is taken to be the geometric center of the output fuzzy value $\mu_{out}(u)$ area, where $\mu_{out}(u)$ is formed by taking the union of all the contributions of rules whose degree of fulfillment is greater then zero. The general expression for center of area center of area defuzzification is,

$$u^* = \frac{\sum_{i=1}^{n} u_i \cdot \mu_{out}(u_i)}{\sum_{i=1}^{n} \mu_{out}(u_i)} \qquad (3.12)$$

3.4.4.2 Center of sums defuzzification:

This method takes into account the overlapping areas more then once. The general expression for center of sums defuzzification is

$$u^* = \frac{\sum_{i=1}^{n} u_i \sum_{k=1}^{n} \mu_{Bk}(u_i)}{\sum_{i=1}^{n} \sum_{k=1}^{n} \mu_{Bk}(u_i)} \qquad (3.13)$$

Where $\mu_{Bk}(u_i)$ is the membership function resulting from the firing of the k^{th} rule.

3.4.4.3 Mean of maxima defuzzification:

In mean of maxima defuzzification the highest membership function component in the output is considered. The mean of maxima method determines the average of the crisp points that maximize the output membership function.

$$u^* = \sum \frac{u_m}{M} \qquad (3.14)$$

Where u_m is the m^{th} element in the universe of discourse, where the membership function of $\mu_{out}(u\ )$ is at the maximum value, and M is the total number of such elements.

3.4.5 Output variables:

The defuzzified output at ant time k is $\Delta u^*(k)$, the overall crisp output of the controller is given as:

$$u(k)=u(k-1)+\Delta u^*(k)$$

3.4.6 Post processing:

Output scaling is also relevant. In case the output is defined on a standard universe this must be scaled to engineering units, for instance, volts, meters, or tons per hour. An example is the scaling from the standard universe [-1, 1] to the physical units [-10, 10] watts. The post processing block often contains an output gain that can be tuned, and sometimes also an integrator.

CHAPTER 4

FUZZY LOAD REGULATOR

4.1 General:

Wind is an unreliable resource which is likely to vary over time. Wind speeds are not predictable, except as an approximation. User loads are also unpredictable, which keep changing every time. Wind energy conversion systems use Self-excited induction generators which are good candidates for wind powered electric generation application specially in remote areas, because they do not need external power supply to produce the magnetic field. Permanent magnet generators can also be used for wind energy applications but they suffer from uncontrollable magnetic field, which decays over a period due to weakening of the magnets, and the generated voltage tends to fall steeply with load. The self-excited induction generators have a self-protection mechanism because the voltage collapses when there is a short circuit at its terminals. Further, the Self-excited induction generators have more advantages such as cost, reduced maintenance, rugged and simple construction, brush-less rotor (squirrel cage), etc.

An increase in load in wind power plant increases the load in the Self-excited induction generator. If the load on the Self-excited induction generator increases for a constant wind speed its speed decreases and hence the voltage and frequency will decrease. Similarly an increase in wind speed for a constant load will lead to the voltage and frequency shoot up. The decrease in voltage and frequency is undesirable and a sharp increase in voltage and frequency may be harmful for the connected appliances. Also a sudden increase or decrease in the wind speed or in load results in rapid increase in rotor speed leading to a severe braking procedure that again lead to large and rapid forces, e.g., a bending moment.

To avoid the above discussed problems a balance between input power and output power must be set. This can be achieved by a controlled secondary load connected in parallel with the main load. The secondary load is switched whenever there is an unbalance between the input and output powers.

If the wind speed is low, the energy produced by the self-excited induction generator will be low; in this case the power consumed by the secondary load should be lower. When the wind speed is high, the energy consumed by the secondary load should be high. The system should be designed with estimates of inputs and outputs appropriately matched and with strategies in place to deal with the variations in the wind speed and the load.

There are basically two techniques used for balancing the input and output powers.

1. In the first technique the secondary load comprises a single resistive load circuit of magnitude equal to the full load rated output of the generator. This load is permanently connected to the system. This technique uses a phase delay action and detects the unbalance in the input and output powers as a result the firing angle of the power electronic switching devices is adjusted. This changes the average voltage applied to the secondary resistor and hence the power dissipated by the secondary load.

   In this technique the switching of power electronic switches introduces harmonics into the electrical system. These harmonics are continuously present to some extent as long as the secondary load is energized. These harmonics cause overheating of electrical equipments connected to the system.

2. In the second technique the secondary load itself is a variable resistor and is made up from the switched combination of a binary arrangement of separate resistive loads. The main advantage of this technique is that waveform distortion is not produced .Since the secondary load is only varied in steps the voltage and frequency is controlled only within a range .In this technique the full system voltage is applied to the next step of the secondary load which produces no or a little harmonics in the system.

In this chapter the design of a fuzzy load regulator (secondary load regulator) system is discussed which controls the frequency in the wind energy conversion system.

4.2 Fuzzy control of secondary load:

The control algorithm of a process that is based on fuzzy logic or a fuzzy inference system is defined as a fuzzy control. For control applications fuzzy logic has a number of advantages over conventional controllers. For analyzing any system, system model is necessary. Once a model of a system is obtained, it is easy to predict the behavior of the system, its performance etc. The past few years have witnessed a rapid growth in the number of varieties of applications of fuzzy logic. Fuzzy logic is a convenient way to map an input space to a output space. Some other techniques like linear systems, expert systems, neural networks, differential equations, can also be used for this purpose. But in all fuzzy is the best due to the following reasons.

1. Fuzzy control is automatic control with rules rather than equations, fuzzy control strategy is in words or rules rather than in equation, it makes it easier to understand. The rules can be changed any time so is the characteristic of the fuzzy controller.
2. Fuzzy controllers cover a wider range of operating condition also they are cheaper then the conventional controllers.
3. Fuzzy controllers do not need a well defined mathematical model of the system. This makes fuzzy controller less complex then the conventional controllers.
4. Fuzzy controller is flexible.
5. Fuzzy logic can model nonlinear functions of arbitrary complexity. It is easy to create a fuzzy system to match any set of input output data.
6. Fuzzy logic can be built by the experience of experts who already understand about the system.
7. The conventional PI controller generally requires operational amplifiers circuits. These circuits have the tendency to drift with age and temperature causing degradation of the system performance. But fuzzy controllers give same performance over the years.
8. The conventional PI controller requires quite a bit of tuning obtaining a fast and dynamically acceptable response.

4.2.1 Principle of operation:

The principle of operation of fuzzy secondary load controller depends upon the principle of frequency regulation. The entire wind power system can be seen as an electro mechanical entity as given by the Figure4.1. The wind generator is connected to the synchronous machine which is working as a synchronous condenser. The induction generator, synchronous machine and load system can be modeled by taking the synchronous machine as reference. The rate of change of angular speed of synchronous machine can be given by the following equation

$$\frac{d\omega_s}{dt} = \frac{1}{J_s}[T_m - T_s - D\omega_s] \qquad (4.1)$$

Where J_s and D are inertia and frictional damping coefficients of synchronous machine. And T_m and T_s are the mechanical torque applied and air gap torque of the synchronous machine.

Since the synchronous machine is working as a synchronous condenser(T_m=0) .So equation 4.1 can be written as

$$\frac{d\omega_s}{dt} = \frac{1}{J_s}[-D\omega_s - T_s] \tag{4.2}$$

The air gap torque of the synchronous generator T_s can be represented as

$$T_s = \frac{P_s}{\omega_s} = \frac{P_L + P_{SL} - P_{ind}}{\omega_s} \tag{4.3}$$

Where P_{SL}, P_s, and P_{ind} are the power of secondary load, the synchronous machine, and the induction generator, respectively, and ω_s is proportional to frequency f_s.

Applying (4.3) into (4.2), the equation 4.2 becomes

$$\frac{d\omega_s}{dt} = \frac{1}{J_s}[-D\omega_s + \frac{P_{ind} - P_L}{\omega_s} - \frac{1}{\omega_s}P_{SL}] \tag{4.4}$$

The rate of change of frequency depends upon the wind generator (induction generator) generated power, the load power, damping of synchronous machine and the secondary load. If the synchronous machine damping is ignored the wind generator power must be equal to the main load power and the secondary load power. At all times the balance must be established between the input and the output power. If the wind speed is higher, induction generator power will be higher than the used power, according to equation4.4, the difference will be stored in the mechanically revolving components; hence their revolving speed ω will increase till the new equilibrium speed is reached.

The electrical consequence of this is that the AC frequency will increase with the same amount. The principle of frequency regulation is arising from the above considerations is that to keep the frequency constant, it is necessary to keep the total output active power equal to the total input active power by varying the secondary load.

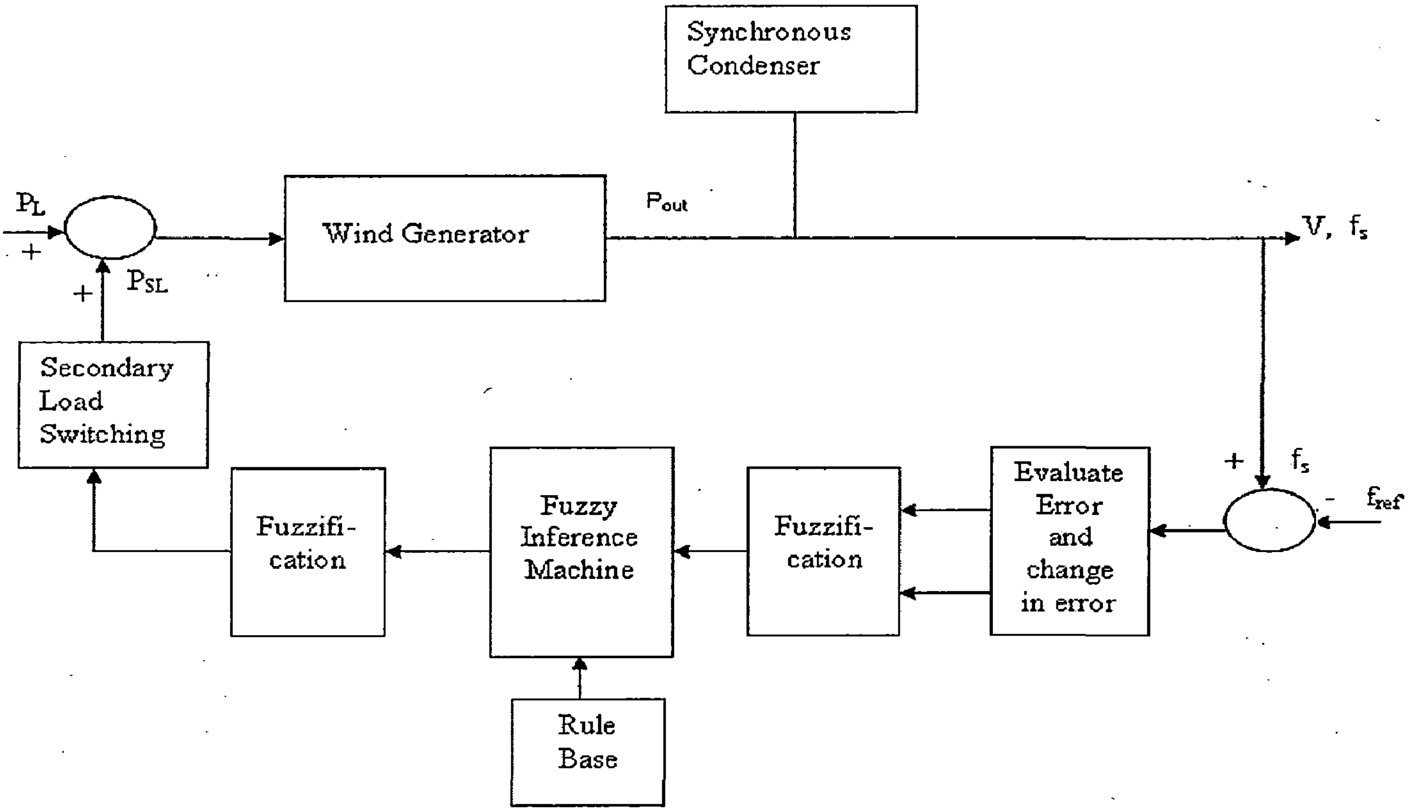


Fig.4.1 Block diagram of wind energy conversion system with secondary load

4.2.2 Fuzzy Load Regulator Model:

Figure 4.2 shows the SIMULINK model of fuzzy load regulator. The fuzzy controller is basically a fuzzy P-I controller. The regulator's output represents the desired power of the secondary load. The frequency regulator input is represented by the voltage's frequency. There is used a three-phase Phase Locked Loop (PLL) system to measure the frequency of the 3-phase voltage of the network. Therefore, the measured frequency is compared to the reference frequency in order to obtain the frequency error. The fuzzy controller adopts two input variables the error in frequency 'ef' and the change in this error 'df' which is related to the derivative of error 'ef' and corresponding power updating signal "DP" as the output variable.

The fuzzy controller observes the pattern of the frequency error signal and correspondingly updates the output 'DP' so that the control signal (P) matches the power required by the secondary load. This signal is summed or integrated to generate the actual control signal (P) which controls the power consumed by the secondary load.

Since the fuzzy controller is basically an input-output static nonlinear mapping, the output of fuzzy controller is a function of error in frequency (ef) and the derivative of this error (df) so the output of fuzzy controller can be written in the form.

$$DP = K_1(ef) + K_2(df) \tag{4.5}$$

Where K1 and K2 are nonlinear coefficients or gain factors. The output of the integrator is given as

$$\int DP = \int K_1(ef)dt + \int K_2(df)dt$$

$$= \int K_1(ef)dt + \int K_2(\frac{d(ef)}{dt})dt$$

Or

$$P = K_1 \int (ef)dt + K_2(ef) \tag{4.6}$$

Which is a fuzzy P-I controller with output (P) and two inputs error in frequency (ef) and derivative of error (df).

4.2.3 Pulse Decoder and Sampling System:

After the integration of fuzzy controller output (DP) The obtained signal (P) is an analogue signal which is fed to the “Pulse Decoder” and “Sampling System”. The pulse decoder circuit decodes the scalar input 'code' into a vector output 'pulses' based on the specified number of bits to decode. Element 1 of vector output is the least significant bit. Here the numbers of bits to decode are eight, which gives a binary progression of eight bits.

These eight pulses are given to the sampling system circuit, where these pulses are converted to a three phase 8-bit signal that commands the switching elements of the secondary load. The regulator’s output represents the desired power of the secondary load. The output of pulse decoder and sampling system is directly fed to the secondary load. Figure4.3 [26] shows the SIMULINK model of Pulse decoder and sampling system.

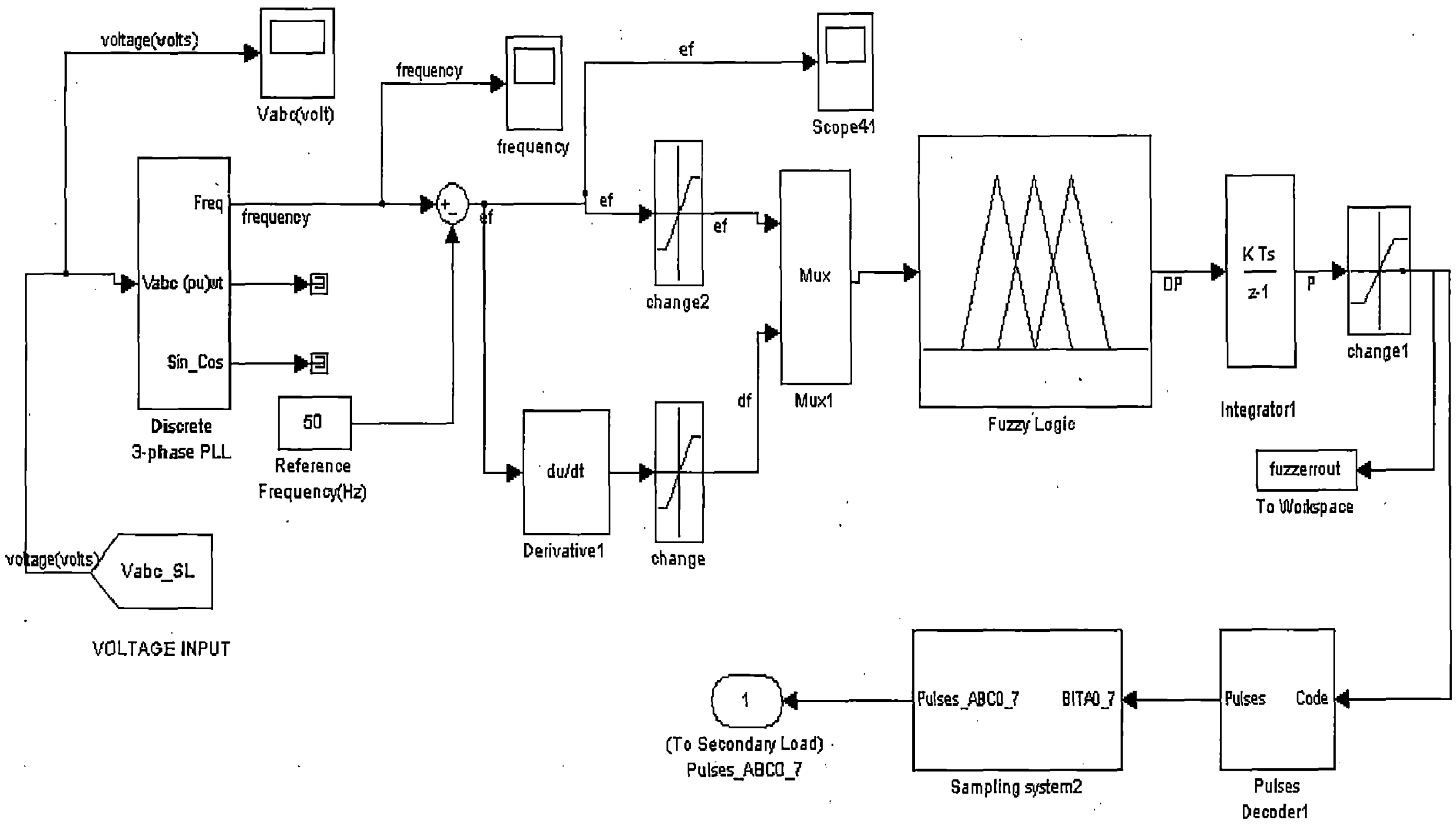


Fig.4.2 SIMULINK Fuzzy Load Regulator Model

4.2.4 Controlled Secondary Load:

A secondary load is any electric load that the power system itself has control over, as opposed to the primary load, which is dictated by the end users. Wind energy conversion systems use secondary loads for two reasons.

1. First, they provide a sink for excess wind power since the frequency and voltage control(for resistive loads) require that the input and output real power must be kept in balance at all times.

2. Second, they can improve the economic return of the system by allowing excess renewable energy to meet an on-site energy need that would otherwise have to be met with fuel or some other energy source. Examples of secondary loads that are used in wind energy conversion systems:

- Hot water boiler (for space heating)
- Steam boiler (for process heat)
- Absorption chiller (for air conditioning or process cooling)
- Ice-making (for thermal storage of fish packing)

- Water desalination (for coastal communities with limited fresh water supply)
- Water pumping (for irrigation or municipal water supply)

Figure 4.4 [26] is the three-phase controlled secondary load, where each phase consists of 8 forced commuted power electronic switches controlled resistor banks with binary resistor sizing in order to minimize quantum effects and provide more-or-less linear resolution.

The secondary load is a variable, three phase resistive load. The eight three-phase resistors (R_0, R_1, R_2, R_3, R_4, R_5, R_6, R_7) are connected in series with eight ideal switches (S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7) simulating forced commutated power electronic switches. The load variation uses an eight bit binary progression so that load power can be varied in steps from 0 to 255* Power per step (P_{step}).The values of eight resistors are given as

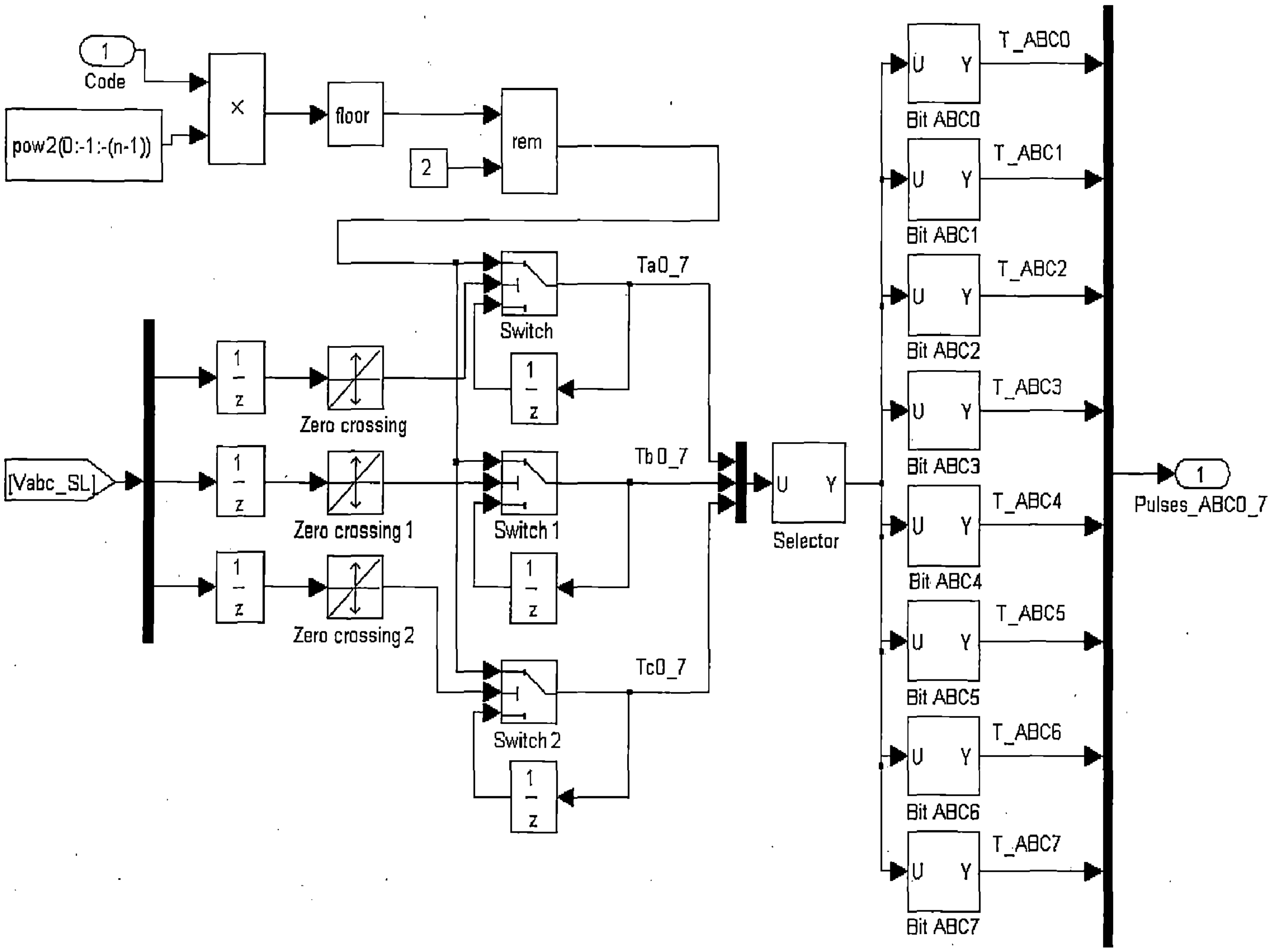


Fig.4.3 Pulse decoder and Sampling system

$$R_0 = R$$

$$R_1 = \left(\frac{1}{2}\right) * R$$

$$R_2 = \left(\frac{1}{2}\right)^2 * R.$$

In general

$$R_n = \left(\frac{1}{2}\right)^n * R \qquad n=0,\ 1,\ 2.....7 \tag{4.7}$$

Power per step consumed by the secondary load is given as

$$P_{step} = \frac{V^2}{R} \tag{4.8}$$

The Ideal Switch used in the secondary load is fully controlled by the control signal (P_$_{ABC_n}$).This Ideal Switch block turns on when the control signal input to it is high (1).In this mode it blocks the forward or reverse applied voltage with zero current flow giving no power dissipation in that particular resistor. And the switch turns off when the.

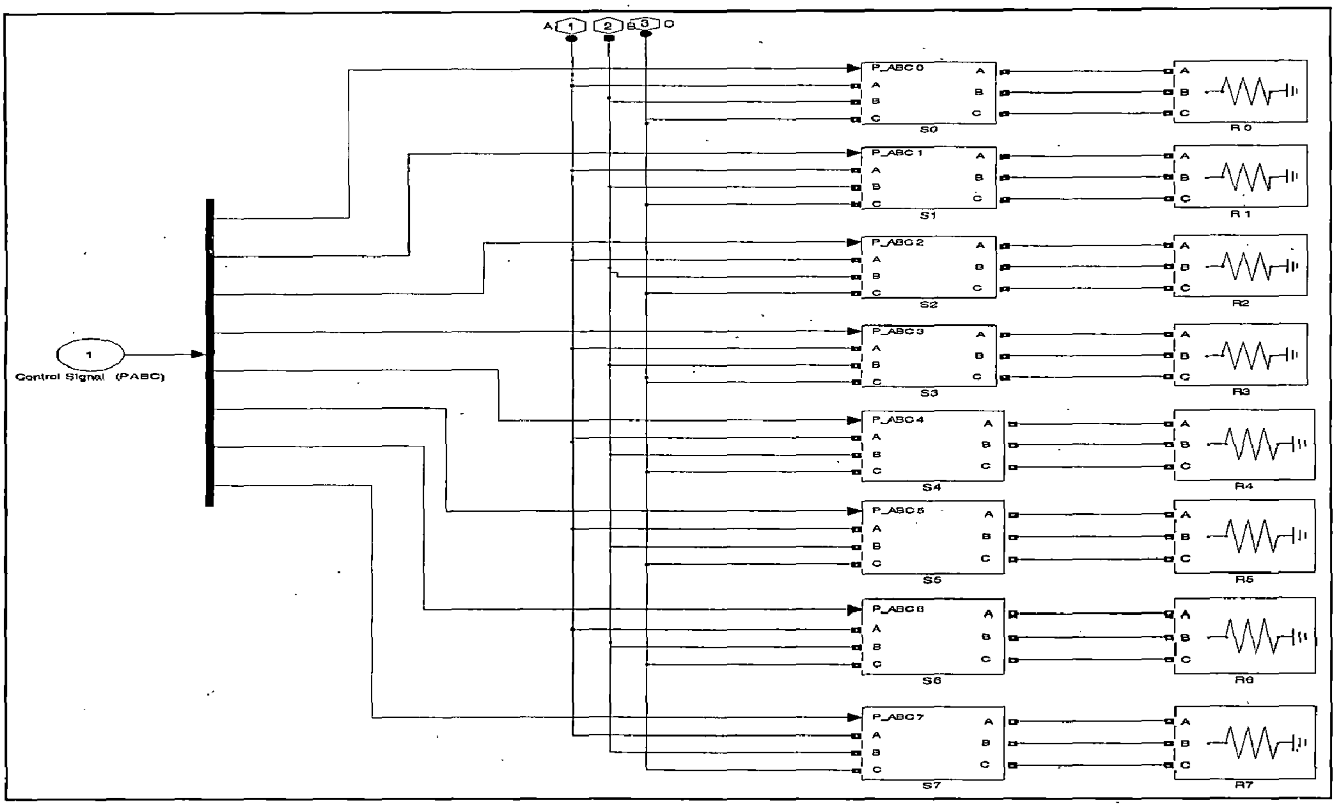


Fig4.4 Three phase controlled secondary load

control signal (P_{ABCn}) is low (0) in this mode switch conducts with some non zero current with quasi-zero voltage drop giving some fixed power dissipation across that resistor

The control signal (P_{ABC}) is input to the controlled resistor. This signal is a vector containing the eight three phase signals (P_{ABC0} , P_{ABC1}, P_{ABC2} , P_{ABC3} , P_{ABC4} , P_{ABC5} , P_{ABC6} , P_{ABC7}) control the eight three phase switches. All the three phase signals to any particular resistor are same at a time. P_{ABC0} is the least significant bit among all the phase signals. The phase signals P_{ABC0} , P_{ABC1}, P_{ABC2} , P_{ABC3} , P_{ABC4} , P_{ABC5} , P_{ABC6} , P_{ABC7} are the data input bits to the resistors R_0 ,R_1, R_3, R_4, R_5, R_6, R_7 respectively.

The net power consumed by the secondary load is given as

$$P_{SL}= P_{ABC0}*P_{step}+P_{ABC1}*2 * P_{step}+ P_{ABC2}*2^2 * P_{step}+ P_{ABC3}*2^3 * P_{step} + P_{ABC4}*2^4 * P_{step} + P_{ABC5}*2^5 * P_{step}+ P_{ABC6}*2^{6*} P_{step}+ P_{ABC7}*2^7 * P_{step}$$

$$P_{SL} = \sum P_{ABCn}.2^n.P_{step} \qquad n =0, 1, 2\ldots7 \qquad (4.9)$$

Where P_{step} is the step power of the secondary load or minimum change that is possible in the secondary load power.

4.2.5 Steps involved in fuzzy logic controller:

The fuzzy controller designer must define what information flows into the system (control/input/variable), how the information data is processed (control strategy and decision), and what information data flows out of the system.

The rule-based fuzzy logic controller to control the frequency in the wind energy conversion system under varying wind and varying load conditions uses two real time measurements, namely the error in frequency denoted by 'ef' and the derivative of error which is denoted by 'df', as the control input signals. These input signals are first "fuzzified" and expressed in fuzzy set notation using linguistic labels characterized by membership grades before being processed by the fuzzy logic controller. Using a set of rules and fuzzy set theory (the AND operator, the OR operator and the rule of composition) the fuzzy logic controller's output is obtained. This output, expressed as a fuzzy set using linguistic labels characterized by membership grade, is defuzzified and converted to an analog signal before being applied to the secondary load. The steps for constructing the fuzzy model for the secondary load control are described as follows

4.2.5.1 Determination of Input and Output Variables:

The input variables to the fuzzy controller are the error in frequency "ef" and the change in this error "df" which is the derivative of "ef" and power updating signal "DP" is the output variable. The input and output variables have been discussed in detail in section 4.2.2.

4.2.5.2 Membership Functions and Shapes:

The fuzzy logic controller requires that each control (input/output) variable which define the control surface be expressed in fuzzy set notations using linguistic labels. To simulate the nonlinear relationship between the input and output variables, the input variable "ef" is fuzzily divided into six zones and seven input membership functions as one s shape function, one z-shape function,
and five Triangular shape functions. Second input variable "df" is also divided into six zones and seven input membership functions as one s-shape function, one z shape function, and five triangular shape functions. Output variable "DP" is divided into eight zones and nine input membership functions as seven triangular shape functions, one s shape function and one z shape function.

These membership functions are used to decompose each system variable into fuzzy regions. The membership grade denotes the extent to which a variable belongs to a particular label. To have a smooth, stable control surface, an overlap between adjacent labels is provided such that the sum of the vertical points of the overlap should never be greater than one.

Membership functions of the input variable 'ef', 'df' and output variable 'DP' are shown in figure 4.5, 4.6, 4.7respectively.

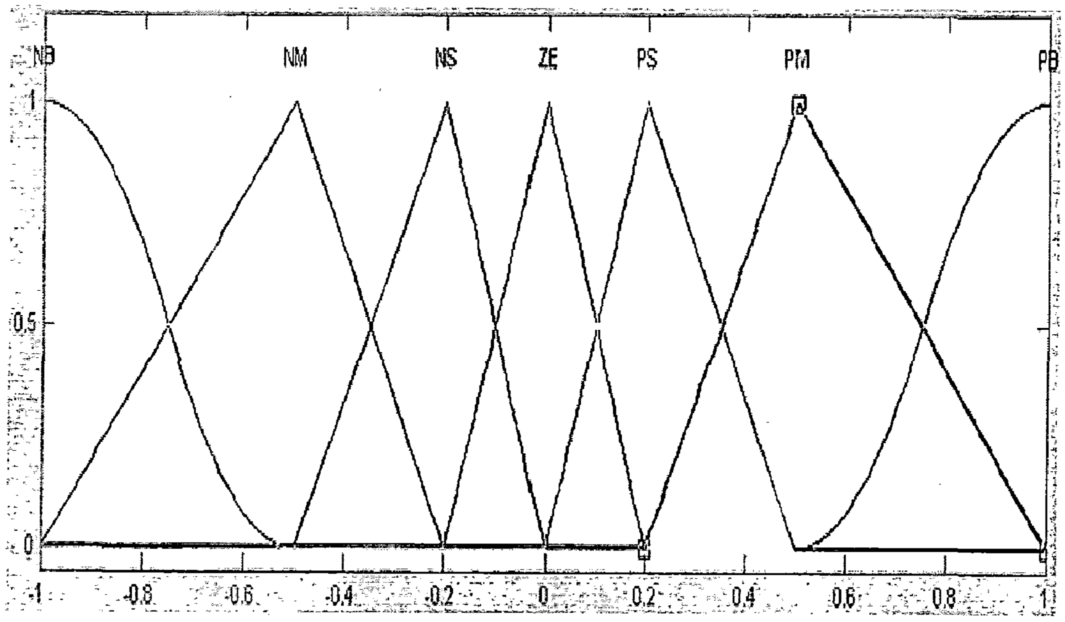


Fig.4.5 Degree of Membership of error in frequency (ef)

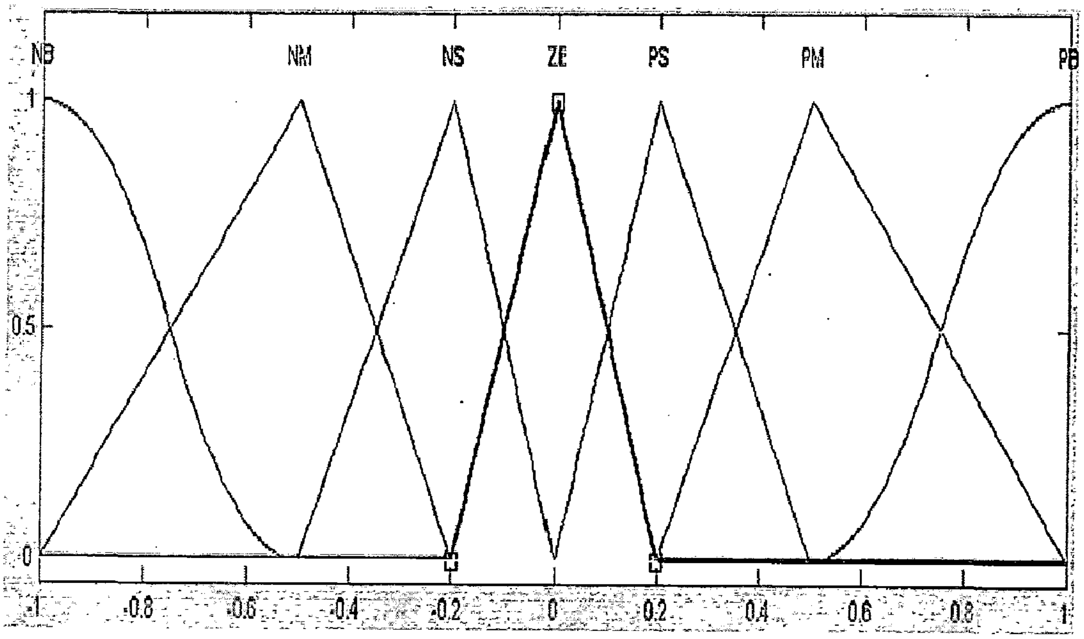


Fig.4.6 Degree of Membership of derivative of error in frequency (df)

The fuzzy input and output sets are defined as follows:

ZE = Zero Equal; PS = Positive Small; PM = Positive Medium.

PB = Positive Big; NS = Negative Small; NM = Negative Medium.

NB = Negative Big; PEB = Positive Extreme Big; NEB = Negative Extreme Big.

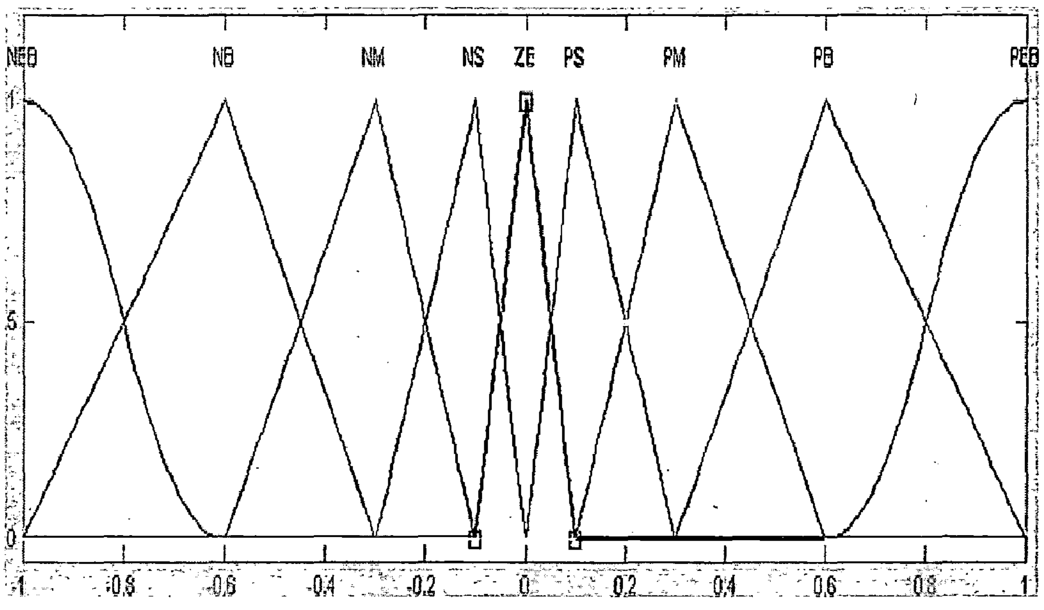


Fig.4.7 Degree of Membership of output variable (DP)

Following are the main considerations while defining the membership functions and shapes,

1. All the Membership Functions are asymmetrical because near the origin it shows the steady state where the signals require more precision.
2. The universe of discourse of all the variables, covering the whole region, is expressed in per unit values.
3. There are seven membership functions for the input "ef" and "df" signals, and nine membership functions for the output signal "DP". All the membership functions are symmetrical for positive and negative values of the variables.

Table 4.1 displays the universe of discourse *U* between the input variables 'ef', 'df' and output variable 'DP'. The range of all input and output variables is [-1 1].

4.2.5.3: Fuzzy Rule Base:

The fuzzy rule base contains a group of fuzzy rules with If–Then format and is appropriate to describe the I/O relationship. The linguistic fuzzy rule is also called as Mamdani fuzzy rule, which has been adopted with multi-input single-output (MISO) system.

Table 4.1 Input-Output Membership type and Universe of discourse

Classified I/O	**Membership function**	**Function type**	**Term**	**Universe of discourse**
Input(ef)	mf1	Triangular	NM	(-1,-0.5 -0.2)
	mf2	Triangular	NS	(-0.5 ,-0.2 0)
	mf3	Triangular	ZE	(-0.2 ,0, 0.2)
	mf4	Triangular	PS	(0 ,0.2, 0.5)
	mf5	Triangular	PM	(0.2 ,0.5, 1)
	mf6	S-shaped	PB	(0.5, 1)
	mf7	Z-shaped	NB	(-1, -0.5)
Input(df)	mf1	Triangular	NM	(-1,-0.5 -0.2)
	mf2	Triangular	NS	(-0.5 ,-0.2 0)
	mf3	Triangular	ZE	(-0.2 ,0, 0.2)
	mf4	Triangular	PS	(0 ,0.2, 0.5)
	mf5	Triangular	PM	(0.2 ,0.5, 1)
	mf6	S-shaped	PB	(0.5, 1)
	mf7	Z-shaped	NB	(-1, -0.5)
Output(DP)	mf1	Triangular	NB	(-1,-0.6 -0.3)
	mf2	Triangular	NM	(-0.6,-0.3,-0.1)
	mf3	Triangular	NS	(-0.3,-0.1,0)
	mf4	Triangular	ZE	(-0.1 ,0, 0.1)
	mf5	Triangular	PS	(0 ,0.1, 0.3)
	mf6	Triangular	PM	(0.1 ,0.3, 0.6)
	mf7	Triangular	PB	(0.3 ,0.6, 1)
	mf8	S-shaped	PEB	(0.6, 1)
	mf9	Z-shaped	NEB	(-1, -0.6)

The general considerations in the design of the fuzzy controller rules are:

1. If both the inputs (ef) and (df) are zero, then maintain the present control setting DP = 0.
2. If the error in frequency (ef) is not zero but is approaching this value at a satisfactory rate, then maintain the present control setting.
3. If error in frequency (ef) is growing, then change the control signal (DP) depending on the magnitude and sign of error in frequency (ef) and the derivative of this error (df) to force the error (ef) towards zero.

Table 4.2 shows the corresponding rule base table for the fuzzy controller. The top row and left column of the matrix indicate the fuzzy sets of the variables (ef) and (df), respectively, and the membership functions of the output variable (DP) are shown in the body of the matrix.

Table 4.2 Fuzzy Rule Base for Fuzzy Controller

(ef) **(df)**	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	**NEB**	**NEB**	**NEB**	**NB**	**NM**	**NS**	**ZE**
NM	**NEB**	**NEB**	**NB**	**NM**	**NS**	**ZE**	**PS**
NS	**NEB**	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**
ZE	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
PS	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**	**PEB**
PM	**NS**	**ZE**	**PS**	**PM**	**PB**	**PEB**	**PEB**
PB	**ZE**	**PS**	**PM**	**PB**	**PEB**	**PEB**	**PEB**

Each entry in the table is a rule and there are 49 rules that form the knowledge repository of the fuzzy logic controller. These rules are used to decide the appropriate control action. When a set of input variables are read, each of the rule that has any degree of truth (a nonzero value of membership grade) in its premises is fired and contributes to the forming of the control surface by appropriately modifying it. When all the rules are fired, the resulting control surface is expressed as a fuzzy set (using linguistic labels characterized by membership grades) to represent the controller's output. Where a typical rule reads as,

IF ef = PS AND df = NM THEN DP = NS

4.2.5.4: Inference Engine:

Fuzzy controller used here incorporates Mamdani's implication method. Fuzzy reasoning is mainly investigated, according to the conclusion from the known facts and to derive the fuzzy rules through the inference process. In the design of fuzzy controller forty nine fuzzy rules are adopted for modeling, and the corresponding fuzzy inference is demonstrated as follows:

If A, B and C denote the fuzzy sets for the input variables 'ef', 'df ' and the output variable 'DP' respectively, and any rule is given follows

Fuzzy rule R_i : IF ef is A_i AND df is B_i THEN DP is C_i

Here for any rule R_i (i=1, 2,...49) 'ef is A_i' and 'df is B_i'is the antecedent or premise and 'DP is C_i' is the consequence or conclusion. For any fuzzy rule 'Ri' the degree of fulfillment is given as:

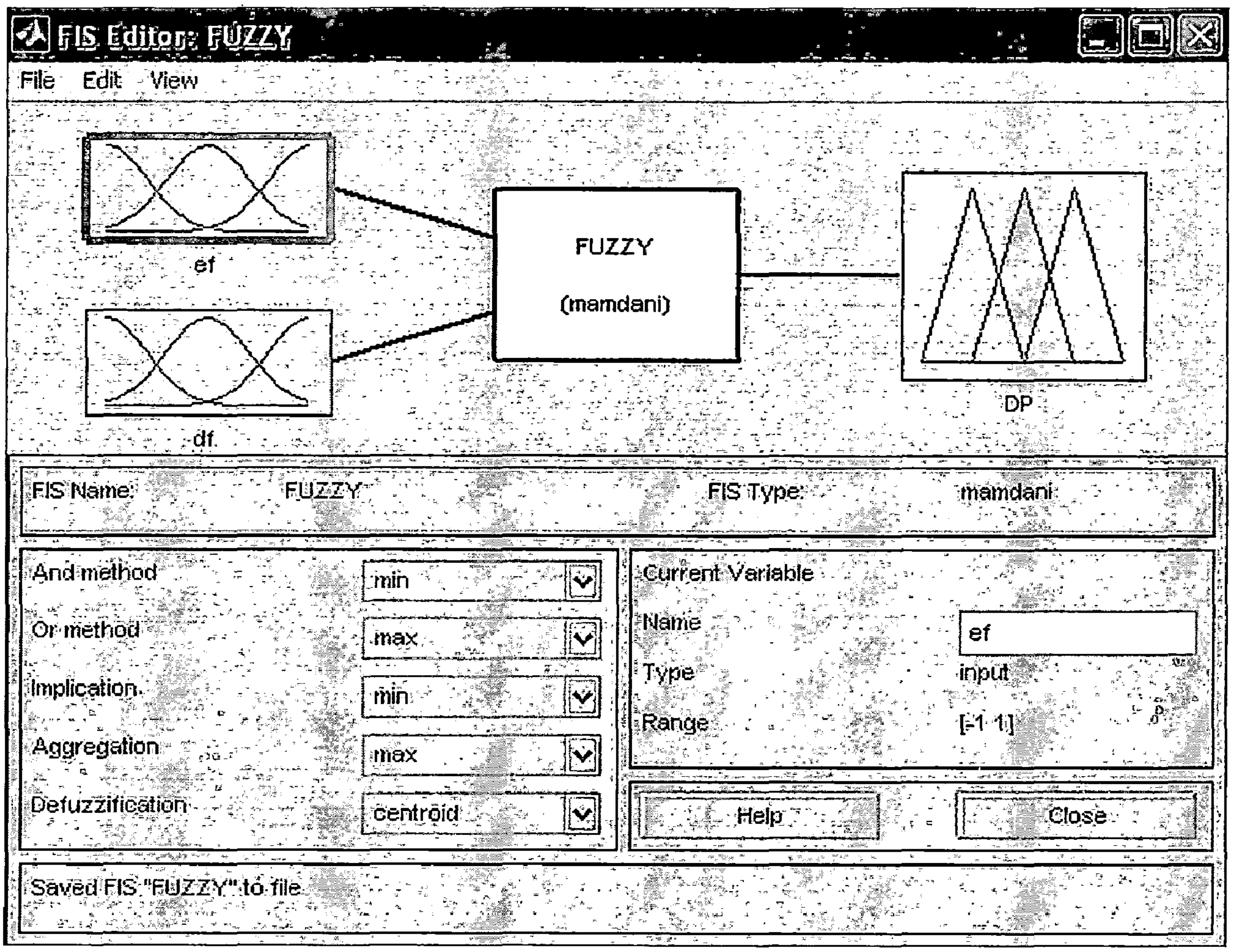
$$\mu_{ci}(DP)=\min \mu_{Ai}(ef).\mu_{Bi}(df) \qquad (4.10)$$

This procedure is repeated for all the 49 rules and the final grade of membership of the output is decided by taking the Maximum of the component Membership functions of all rules, that is

$$\mu_c(DP)=\underset{i}{Max}[\min[\mu_{Ai}(ef).\mu_{Bi}(df)]] \qquad i=1, 2,.....,n \qquad (4.11)$$

4.2.5.5: Defuzzification technique:

The output of fuzzy controller is changed into a crisp value by defuzzifier. Different type of defuzzification technique is discussed in detail in chapter 3. Here fuzzy set representing the controller output is defuzzified using the Centre of Area (COA) method.



FIS Name: FUZZY

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: ef

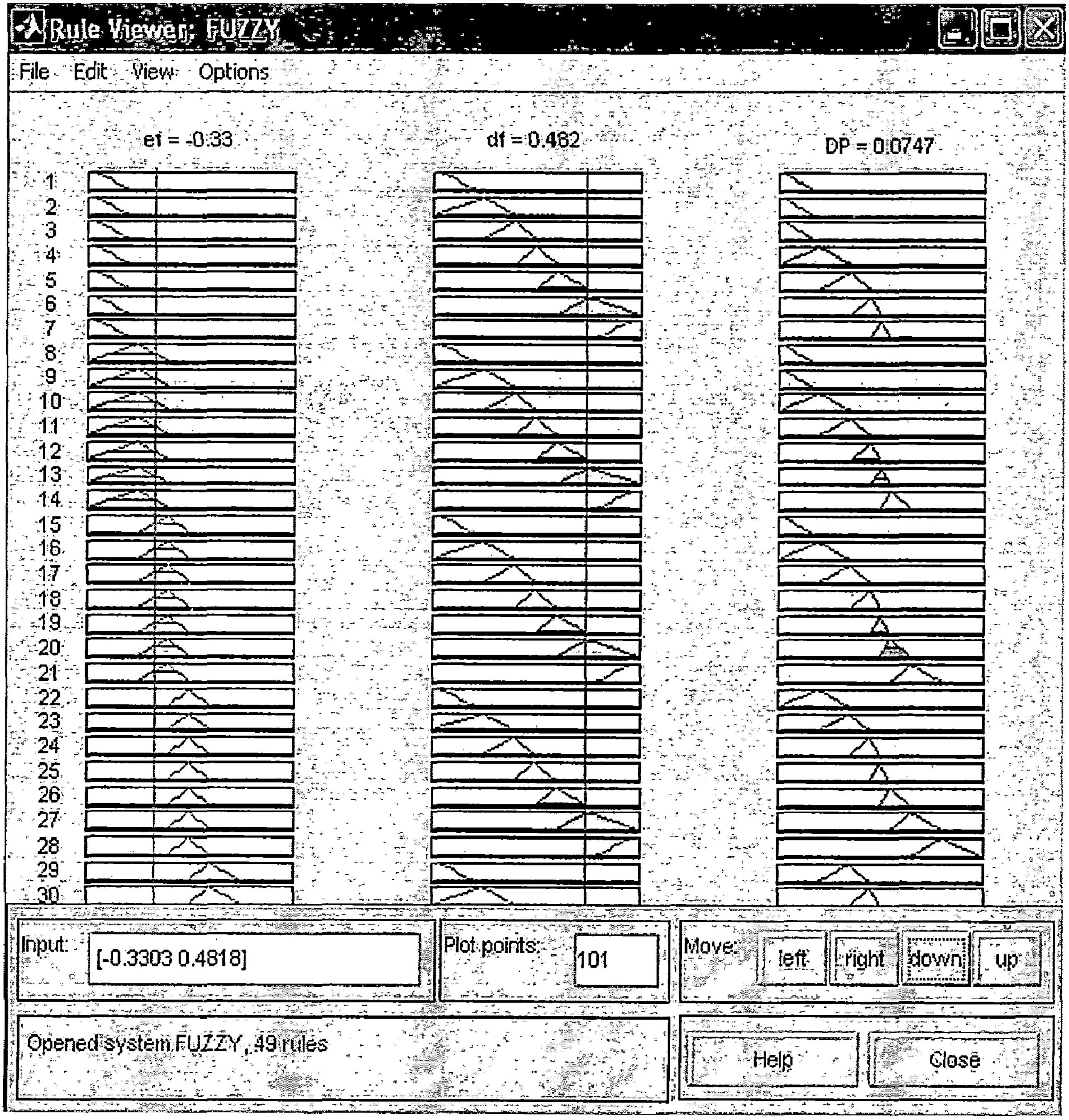
Type: input

Range: [-1 1]

Saved FIS "FUZZY" to file

Fig.4.8 Fuzzy toolbox view

Fuzzy controller is designed by using fuzzy toolbox in MATLAB7.5.0. FIS editor for designed controller is shown in Figure 4.8. Mamdani operator is used as fuzzy implication operator. Above diagram shows the inputs and output of designed fuzzy controller.



ef = -0.33

df = 0.482

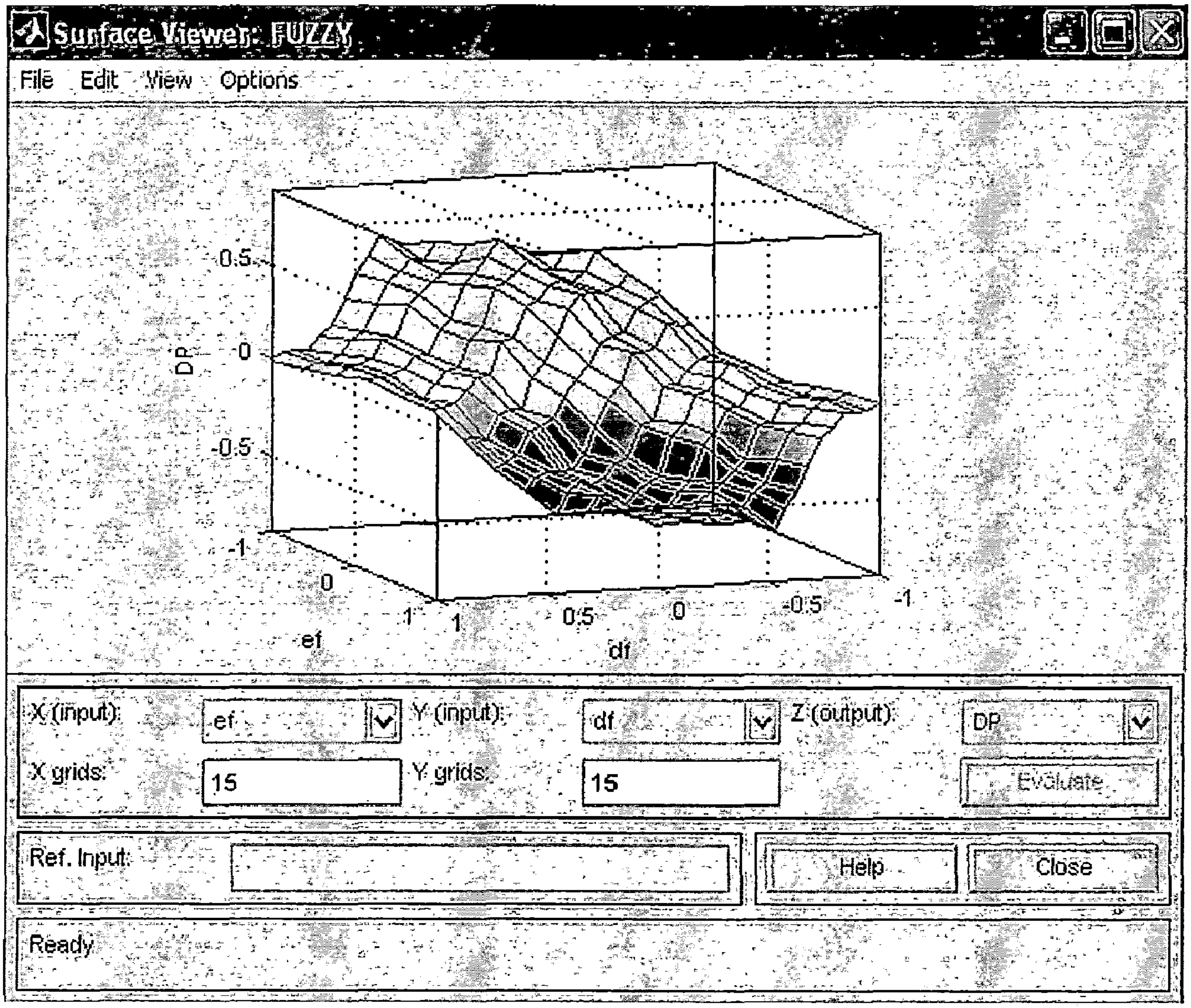
DP = 0.0747

Input: [-0.3303 0.4818]

Plot points: 101

Opened system FUZZY, 49 rules

Fig.4.9 Fuzzy Rule Viewer



X (input): ef

Y (input): df

Z (output): DP

X grids: 15

Y grids: 15

Ref. Input:

Ready

Fig.4.10 Fuzzy Output Surface Viewer.

Figure 4.10 shows the fuzzy output surface viewer for implemented fuzzy controller.

CHAPTER 5
RESULTS AND DISCUSSION

5.1: Simulation:

For the simulation MATLAB-SIMULINK version 7.5.0 has been used. The diagram of the simulated system is presented in Figure 5.1, which is basically a high penetration stand alone wind energy conversion system. For high penetration system wind generation is sufficient to feed the load, so no storage is required.

The model presented uses, three wind turbines. Each wind turbine drives a 400 V, 275 kVA induction generator. A minimum of 100 kW main load is applied to the system. The main load is assumed to be a maximum of 175 kW which can be varied in the steps of 25kW. The variable secondary load bank rating is set to a maximum of 446.25 kW. The secondary load block consists of eight sets of three-phase resistors connected in series with ideal GTO switches. The nominal power of each set follows a binary progression so that the load can be varied from 0 to 446.25 kW in steps of 1.75kW. The GTOs are simulated by ideal switches. The secondary load bank is used to regulate the system frequency by absorbing the wind power exceeding consumer demand. The secondary load is varied with the help of fuzzy frequency regulator.

The isolated power system also includes a 400 V, 300 kVA synchronous machine with an inertia constant H of 1 s (H range in synchronous condensers spans from 1 to 1.5 s) and with an IEEE type 1 Voltage regulator plus exciter. The synchronous machine is used as a synchronous condenser and its excitation system controls the system voltage at its rated value. A capacitor is used for the self excitation of asynchronous machine.

The frequency is controlled by the fuzzy frequency regulator block. This controller uses a standard three-phase Phase Locked Loop (PLL) system to measure the system frequency. The measured frequency is compared to the reference frequency of 50 Hz to obtain the error in frequency. This error in frequency and its derivative are fed to the fuzzy controller.

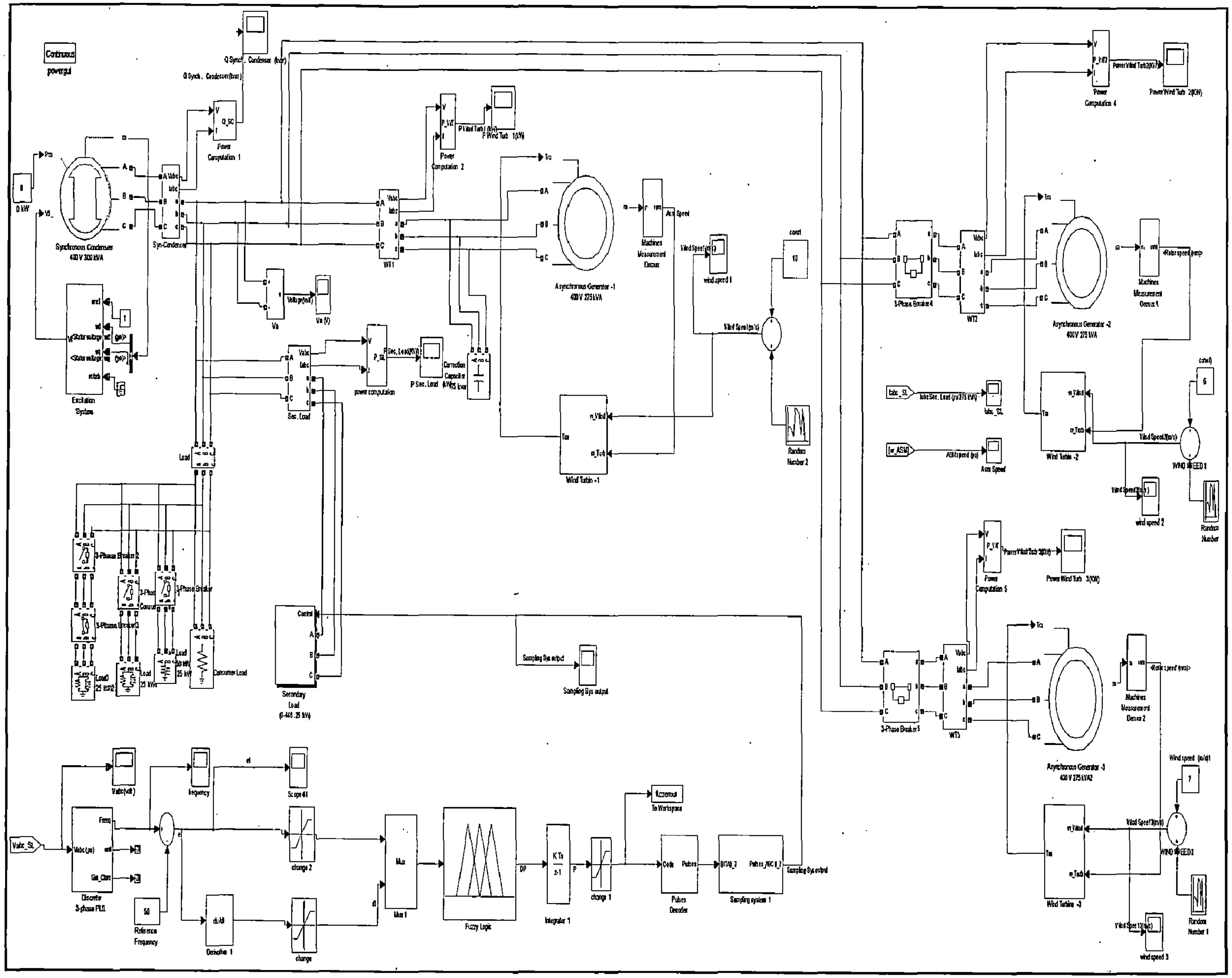


Fig. 5.1 Total SIMULINK Model of Stand Alone Wind Energy Conversion System

The output of fuzzy controller is integrated by an integrator. The output of integrator shows the required power of secondary load. This signal is converted to an 8-bit digital signal controlling switching of the eight three-phase secondary loads. In order to minimize voltage disturbances, switching is performed at zero crossing of voltage.

5.2 Results and discussions:

For the Simulation two cases have been taken. Ten graphs are shown for every case presented: the active power generated by the wind turbine generators, main load active power, controlled secondary load active power, synchronous condenser reactive power, system voltage and the frequency. For the wind turbine generators the active power is considered positive if produced and for the rest of components: main load and secondary load, positive if consumed. All the tests have the same starting point at t=0. The simulation results of the complete system using the SIMULINK in conjunction with MATLAB software package for both studied cases are given below:

5.2.1 Case 1: Change in load demand:

The first study case is considered the normal functioning regime at rated power and rated wind speed. The wind speed is considered having the average value of 10 m/s, 6m/s and 7 m/s with a random variation of ±1 m/s for wind turbine 1, 2 and 3 respectively during the simulation time period. For these wind speeds wind turbine generators produce an average of 210kW, 25kW, and 55 kW of powers respectively as shown in fig5.2, fig5.3 and fig5.4 respectively. The simulation interval is set to 10 seconds.

Figure 5.5, represents the evolution of the considered main load power. In the beginning there is connected only a main load of 100 kW. From the previous initial conditions, a positive step of 25 kW in the load is applied in t=0.2 second (a 25% of the previous load at=0) by closing a three phase breaker (3PB) shown in Fig.5.1. At t= 3 s and 6 s again positive steps of P=25 kW, Q=8kVAr is applied and at t=7 s a negative step of P=25 kW, Q= 8 kVAr is applied resulting a final main load with active power150 kW.

Figure 5.6 and figure 5.7 show the evolution of secondary active load power with PID controller and fuzzy controller respectively. As the changes in main load active power is applied at t=0.2s, 3s, 6s with a positive step change of 25 kW each time and at t=7s with a negative step change of 25 kW. It can be observed that in the condition of load changes at these instants power of secondary load with fuzzy controller is also changed to compensate the change in main load. At t= 3 s the secondary load power with fuzzy controller is reduced by about 25 kW within 0.25 second, and then becomes stable up to t= 6 s. Again at t=6 s the secondary load power is reduced by 25 kW and at t=7 s it is increased by about 25 kW and becomes stable within 0.25 seconds. With PID controller the secondary load power takes more time for stable operation, like at t=7 s the PID controller takes 2.5 for a 25 kW change in secondary load power. Table 5.1 shows the time taken by PID and fuzzy controllers for the required change in the secondary load.

Figure 5.8 and figure5.9 show the frequency response for both PID and fuzzy controllers. For all steps of main load change, the maximum frequency change (with respect to reference 50 Hz) and frequency settling time for both the PID and Fuzzy controller is given in table 5.2. As given in table 5.2 the maximum change in frequency for PID controller is 0.65 Hz whereas for fuzzy controller it is 0.4 Hz. The minimum settling time for fuzzy controller is 1 second whereas PID controller settles the frequency with a minimum time of 3 seconds.

Figure 5.10 and figure 5.11 show the reactive power supplied by the synchronous condenser and system voltage respectively. At t=3sec. and t=6 sec. reactive load of 8 kVAr is applied to the system and at t=7 sec. 8 kVAr reactive load is removed from the system. At these instants the excitation system changes the field voltage of synchronous condenser which results in changed over excitation and synchronous condenser delivers the reactive power to keep the system voltage constant at its rated value.

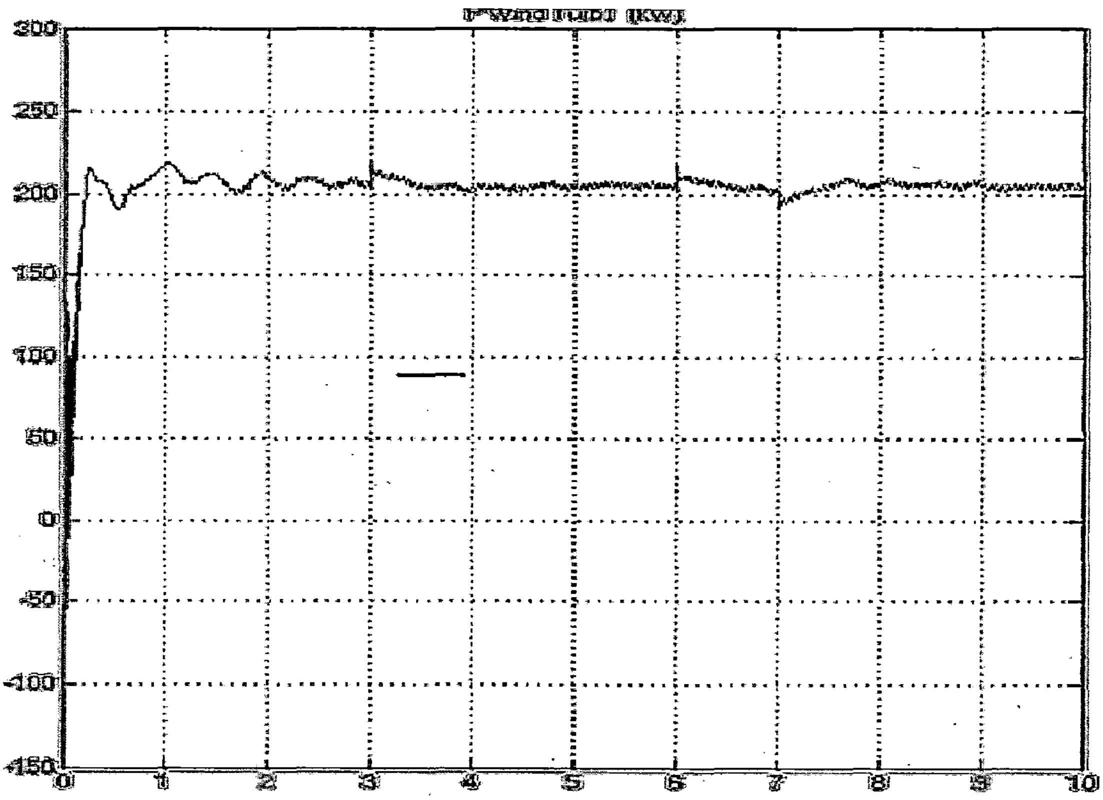


Fig.5.2 Power output of wind turbine-1(kW)

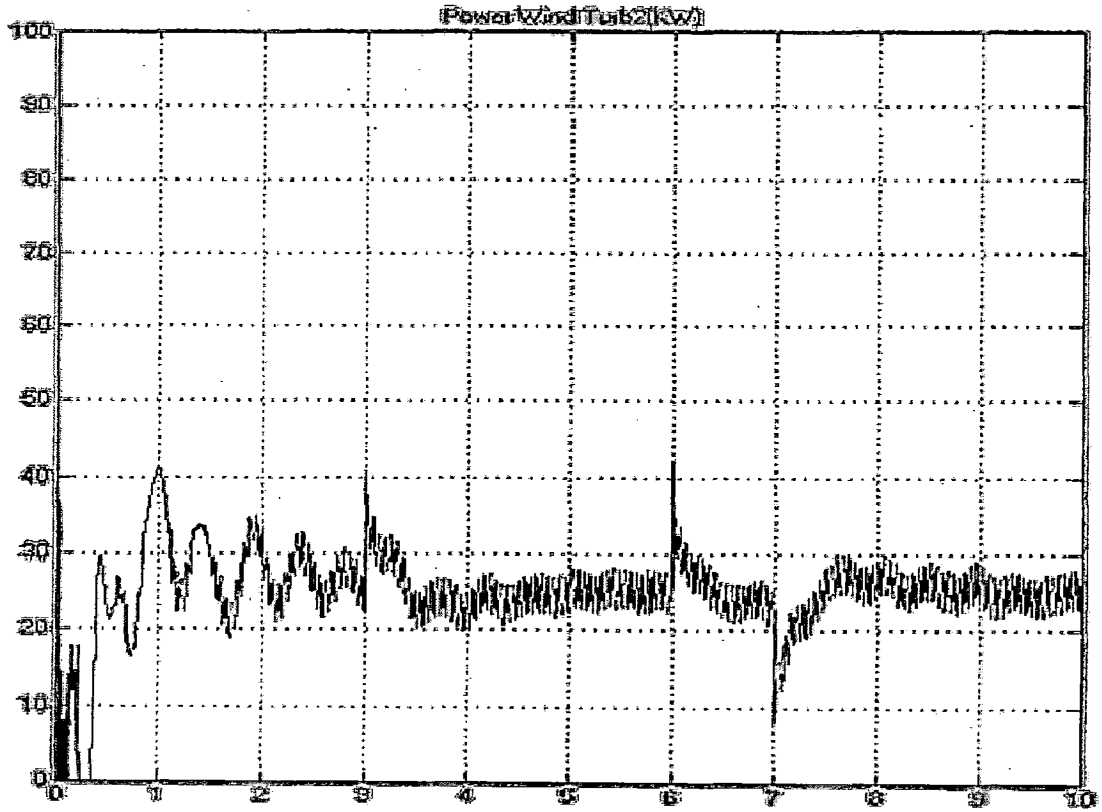


Fig. 5.3 Power output of wind turbine 2(kW)

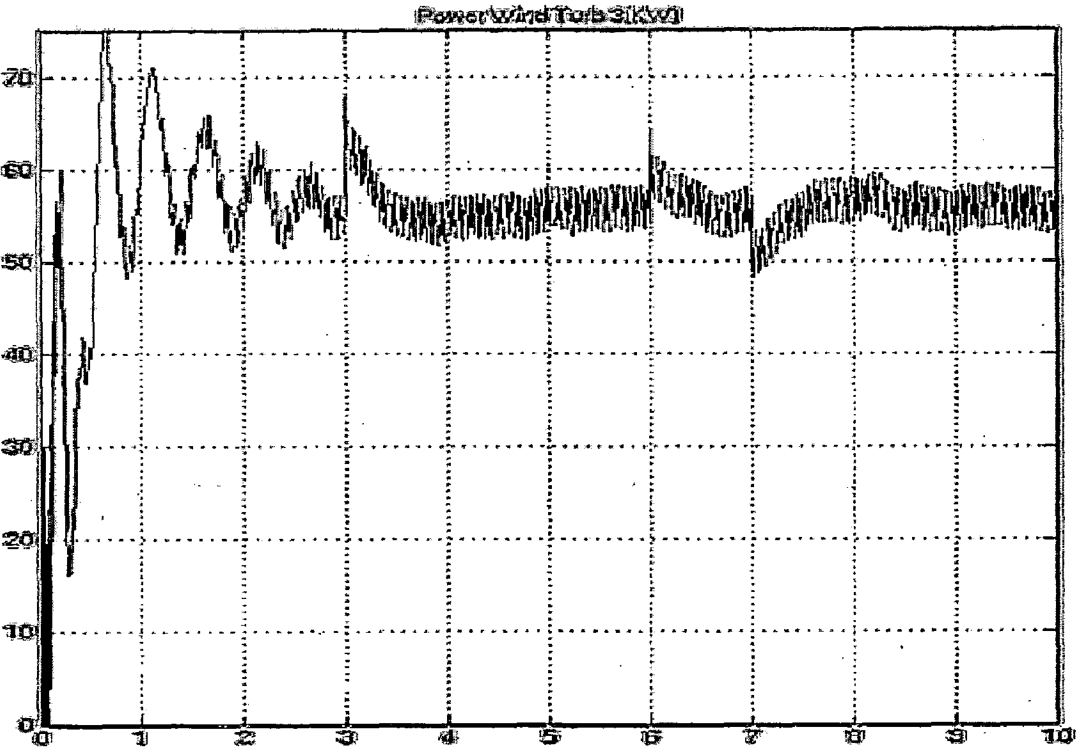


Fig.5.4 Power output of wind turbine 3(kW)

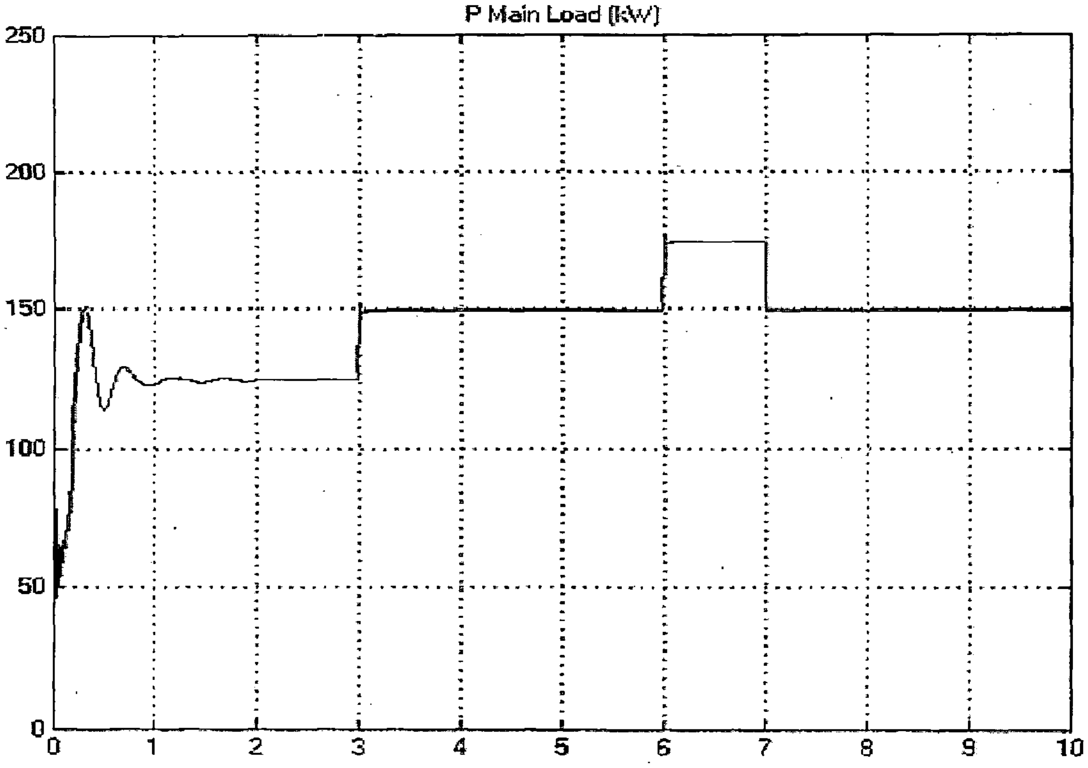


Fig.5.5 Main Load Power (kW)

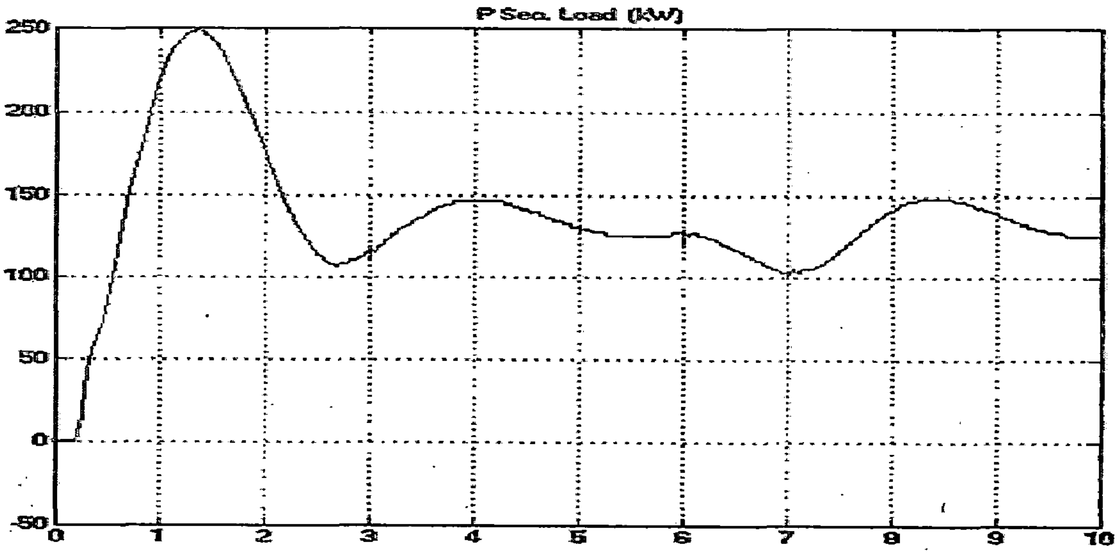


Fig.5.6 Secondary Load Power with PID controller (kW)

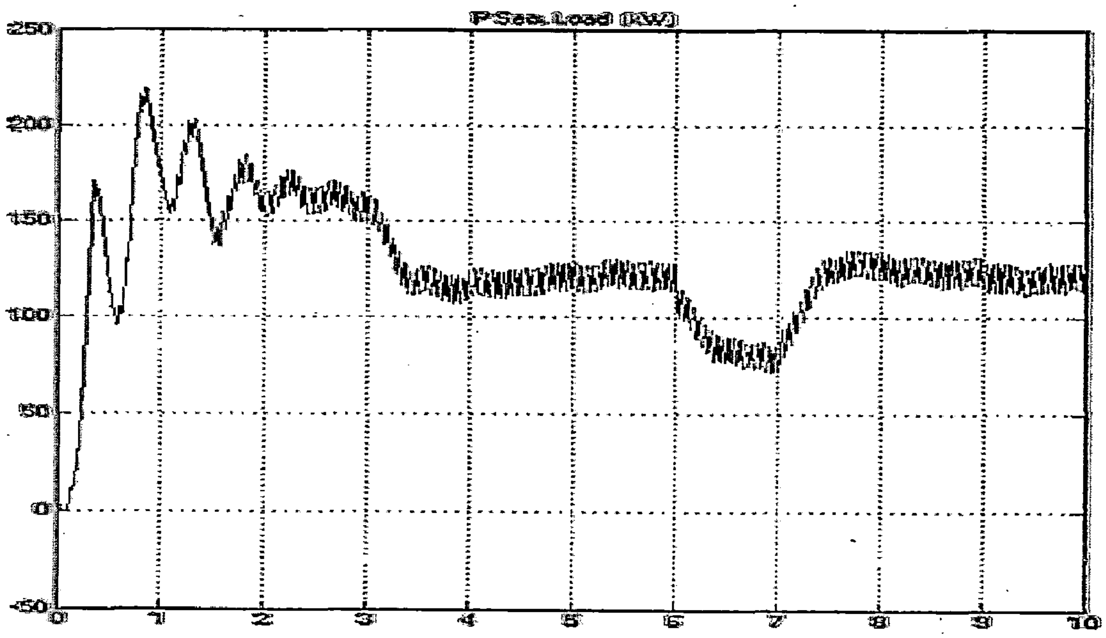


Fig.5.7 Secondary Load Power with fuzzy controller (kW)

Table5.1: Comarison of Time taken by PID and Fuzzy controllers for change in secondary load

Time	Required change in secondary load	Time taken by PID controller	Time taken by Fuzzy controller
0.2s.	-25	not stable	2 sec
3s	-25	not stable	0.25 sec
6s	-25	1 sec	1 sec
7s	+25	2.5sec	0.25 sec

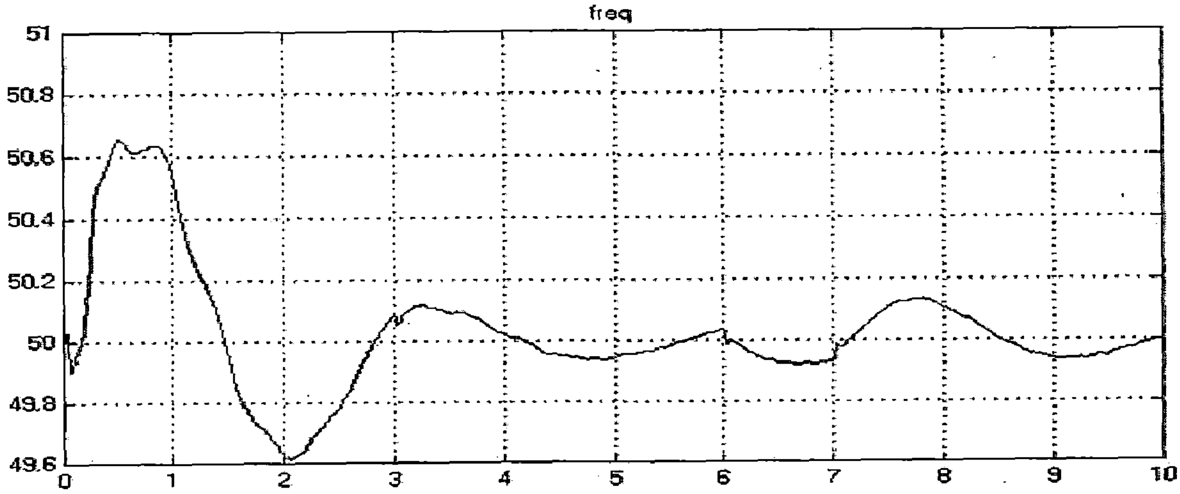


Fig.5.8 Frequency with PID controller (Hz)

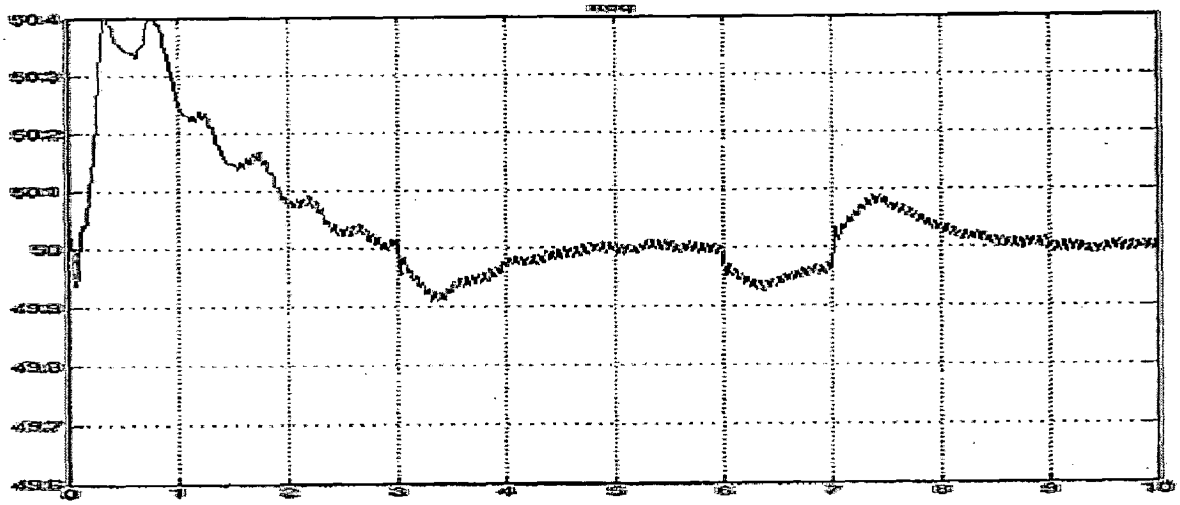


Fig.5.9: Frequency with Fuzzy controller (Hz)

Table 5.2: Comparison of Frequency with PID and Fuzzy controllers

Main load change at	PID controller		Fuzzy controller	
	Max frequency change	Frequency settling time	Max frequency change	Frequency settling time
0.2sec	+0.65 Hz	not stable	+0.4 Hz	2.8 sec
3sec	-0.18 Hz	not stable	-0.08 Hz	1.3 sec
6sec	-0.1 Hz	not stable	-0.07 Hz	1 sec
7sec	+0.18 Hz	not stable	+0.09 Hz	1.2 sec

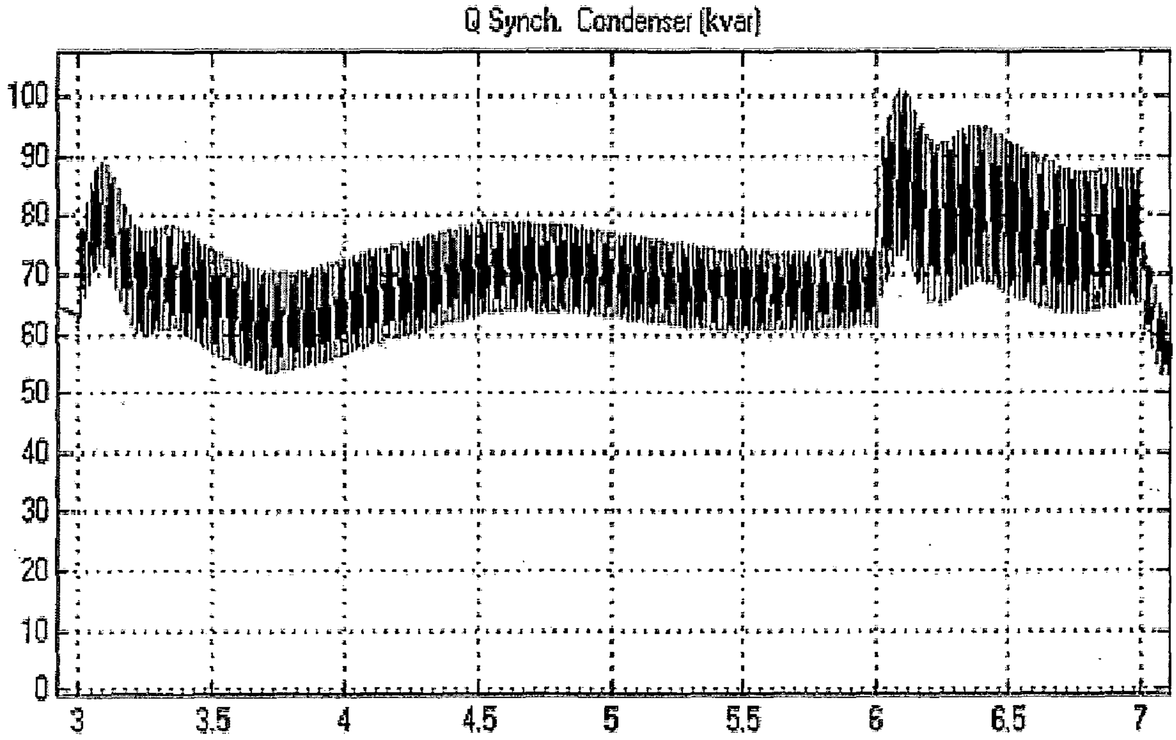


Fig.5.10 Synchronous condenser reactive power (kVAr)

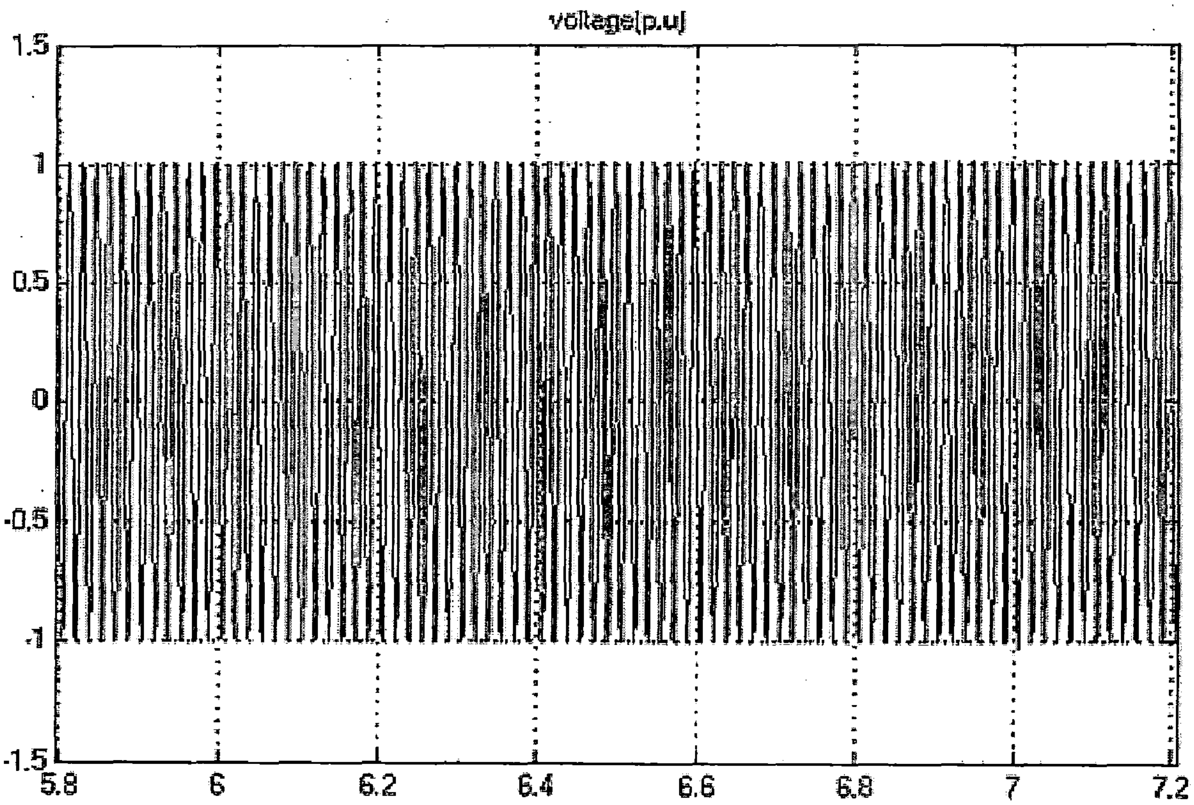


Fig.5.11 System Voltage (per unit)

5.2.2 Case 2: Change in wind turbine power:

In the second study case the input power is changed by reducing the power output of wind turbine 2 and 3 to 0 kW. The wind speed is again assumed 10 m/s, 6m/s and 7 m/s with a random variation of ± 1 m/s wind turbine 1, 2 and 3 respectively. For these wind speeds the wind generator output power is shown by as shown in fig5.12, fig5.13 and fig5.14 respectively. The main load demand is held constant at 125 kW after a load switching of 25 kW at 0.2 sec. The simulation interval is again set to 10 second. As shown in the figure 5.13 and figure 5.14 the wind turbine-2 power output is reduced to zero at t=3 second and turbine-3 power output is reduced to zero at t=7 second.

At t=3 sec and t=4 sec the input power is reduced by reducing the wind turbine-2 and wind turbine-3 output to zero. As the power produced by the wind turbine generators fall behind the nominal power of the main load the frequency starts decreasing below 50 Hz, which can be seen in figure 5.18 and figure 5.19 respectively.

To compensate this change in input power the controllers start reducing the secondary load at t=3sec and t=7 sec. With PID controller the secondary load power takes more time for stable operation while fuzzy controller takes less time for stable operation. Figure 5.16 and figure 5.17 show the evolution of secondary load power with PID controller and fuzzy controller respectively.

As the secondary load is reduced by the controllers the frequency again stabilizes at its rated value of 50 Hz. It can be observed with figure 5.18, figure 5.19 and table 5.4 that with fuzzy controller the frequency takes 1 second to stabilized after t=3 second whereas the PID controller takes 3 seconds. After t=3 second the maximum change in frequency in case of PID controller is 0.18 Hz whereas in case of fuzzy controller it is 0.05 Hz. Similarly after t=7 second fuzzy controller takes 1.3 second to stabilize the frequency with a maximum variation of 0.1 Hz, while the PID controller takes 3 seconds to stabilize the frequency and a maximum frequency variation of 0.25 Hz after t= 7 second. Reactive power supplied by the synchronous condenser and system voltage is shown by figure 5.20 and figure 5.21 respectively. Since there is no change in the reactive power of main load in this case, the reactive power supplied by the synchronous condenser is almost constant and the voltage is maintained constant at its rated value.

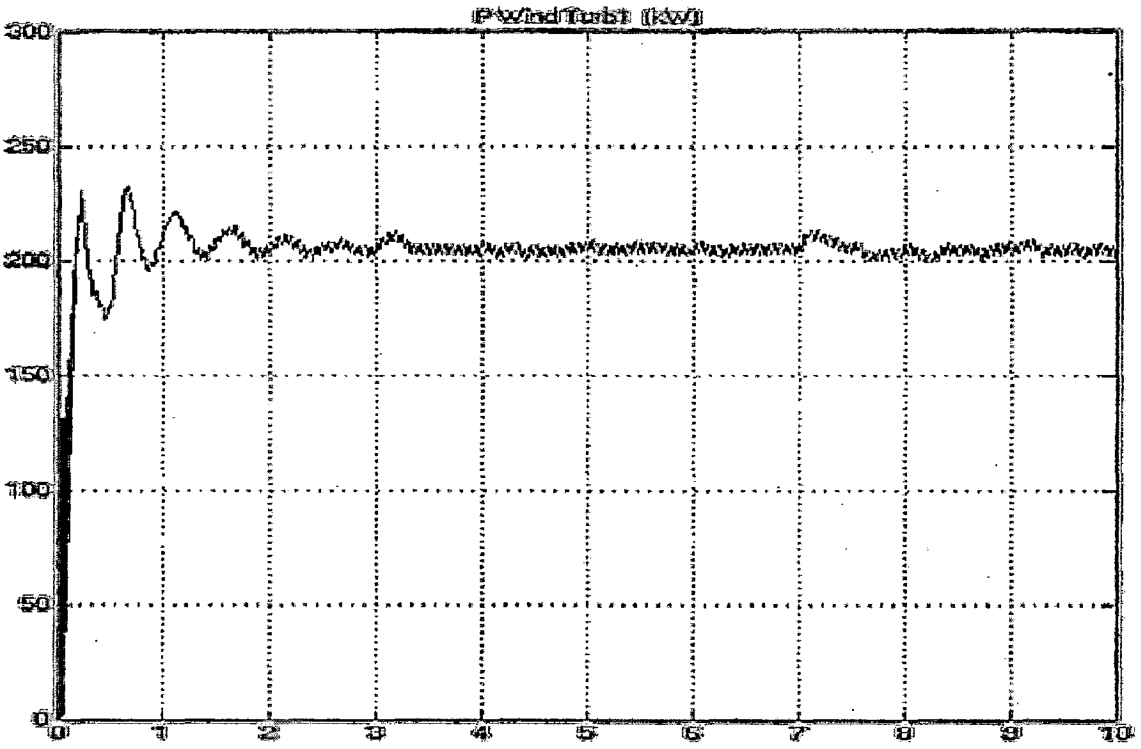


Fig.5.12 Power output of wind turbine-1(kW) (case-2)

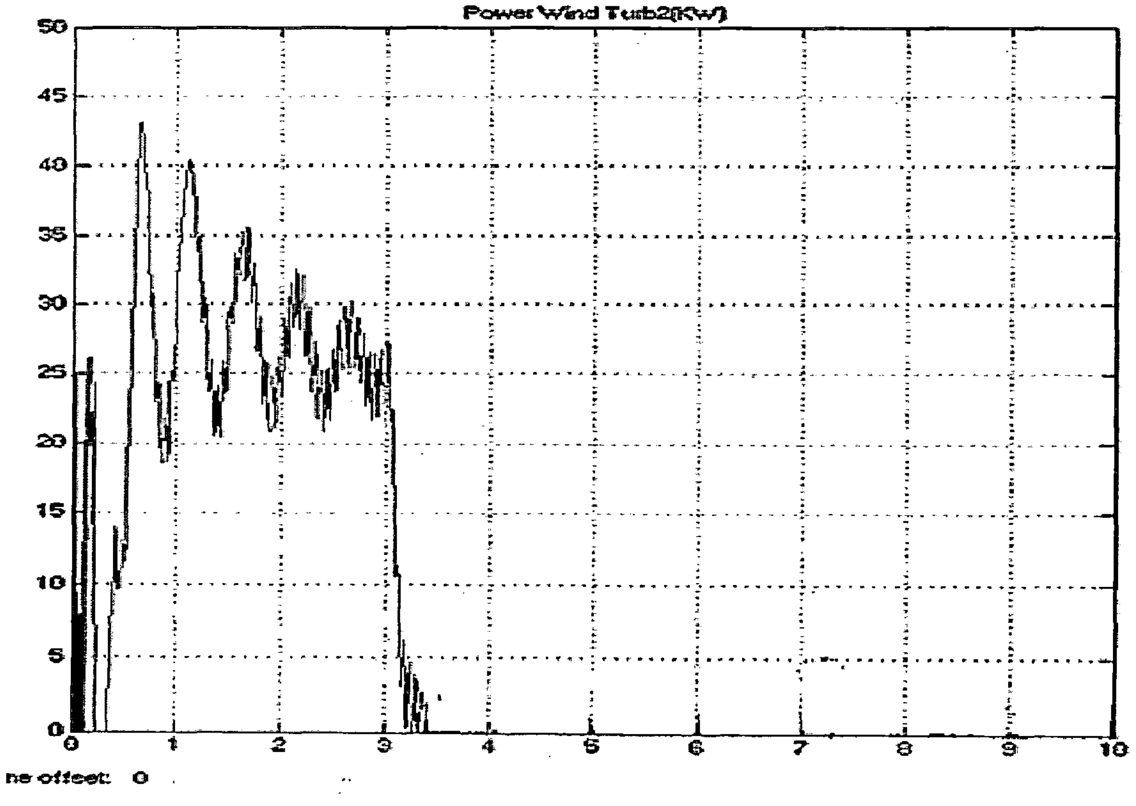


Fig.5.13 Power output of wind turbine-2(kW) (case-2)

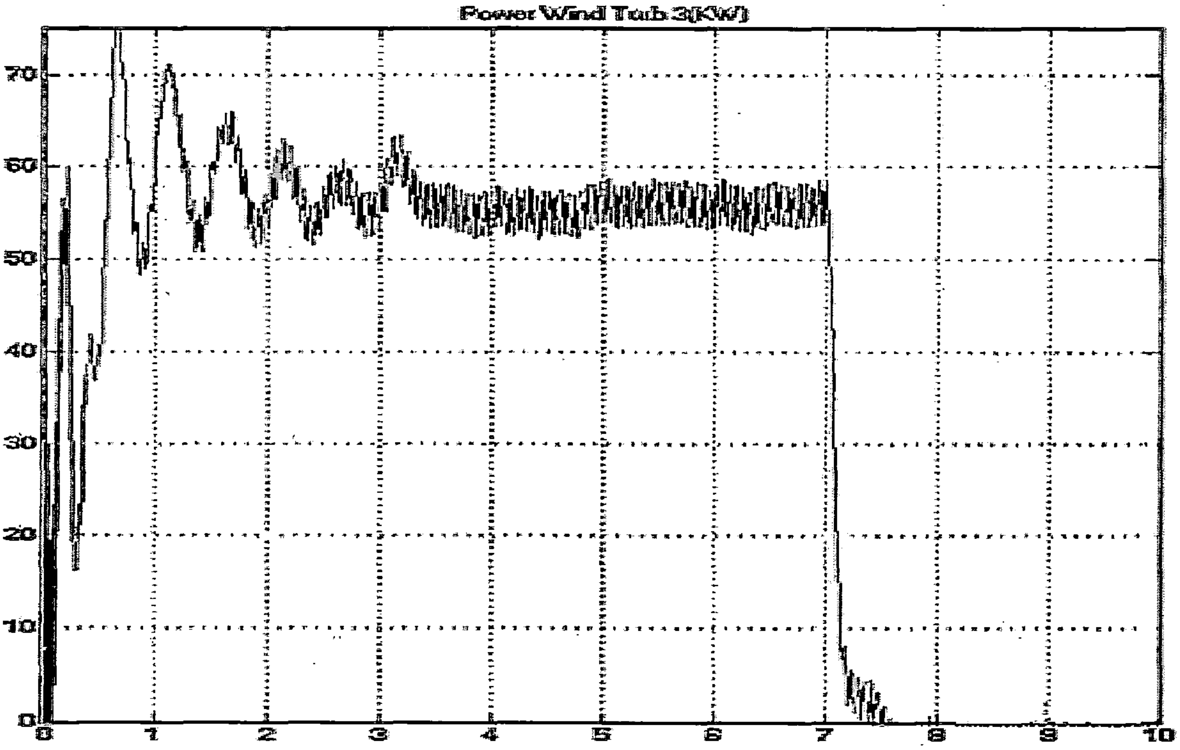


Fig.5.14 Power output of wind turbine-3(kW) (case-2)

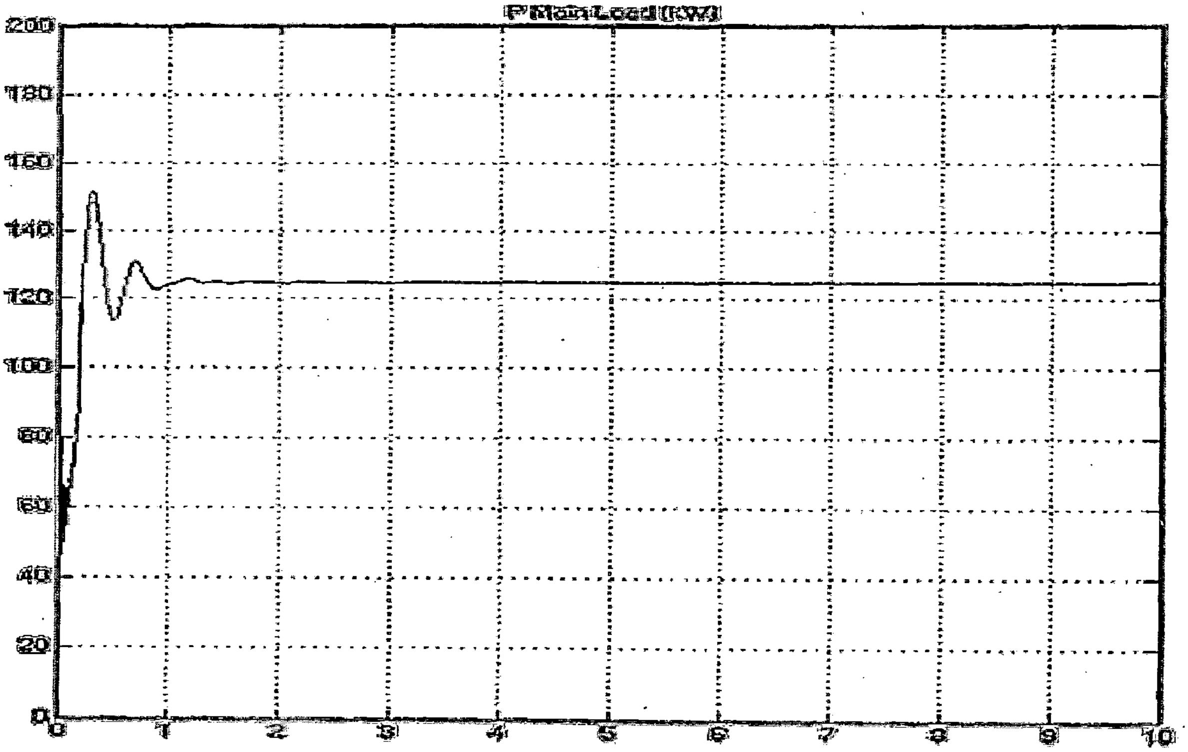


Fig.5.15 Main Load Power (kW) (case-2)

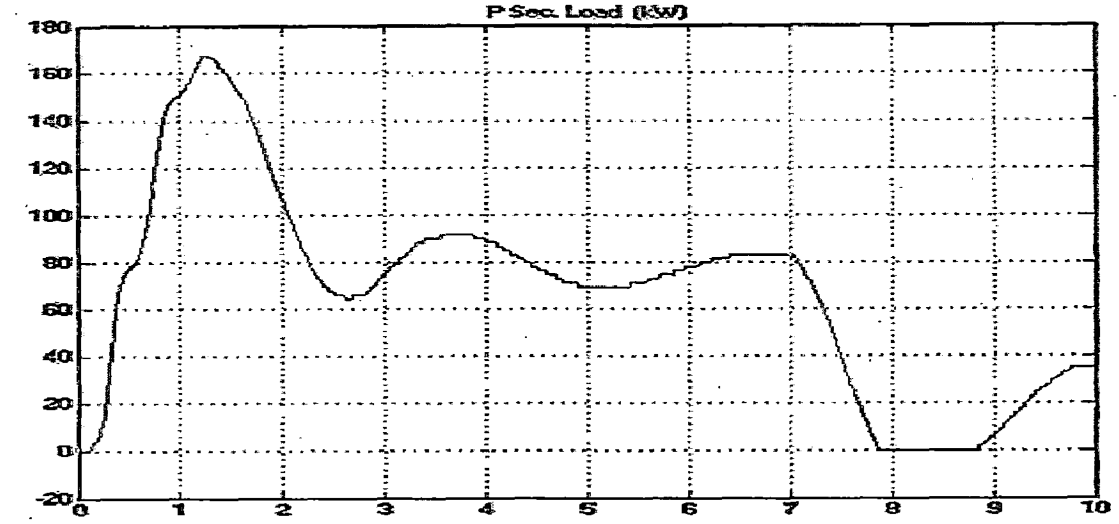


Fig.5.16 Secondary Load Power with PID controller (kW) (case-2)

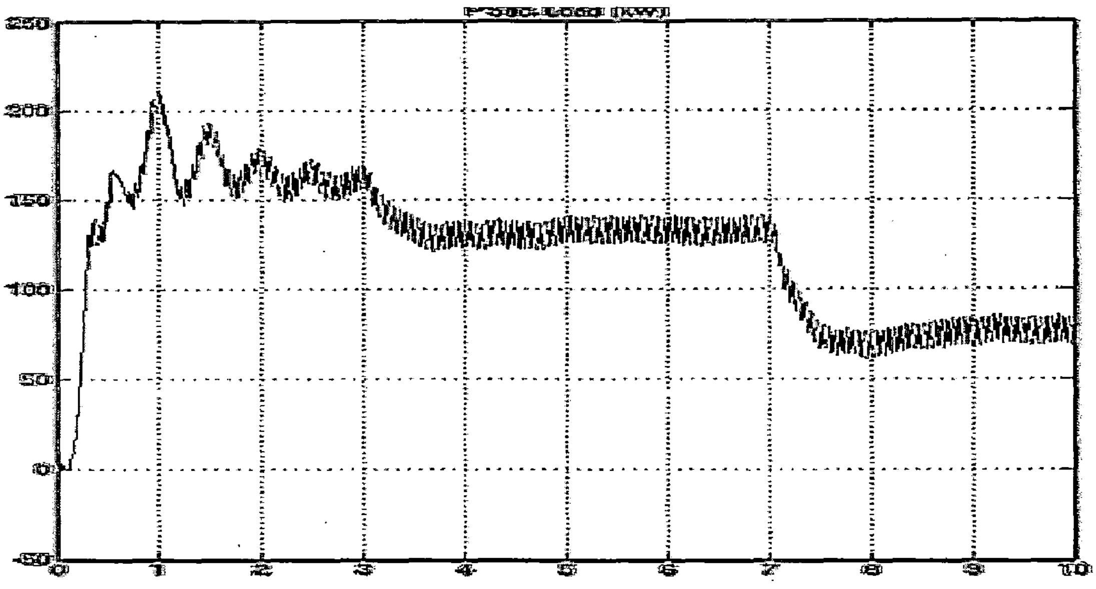


Fig 5.17 Secondary Load Power With Fuzzy Controller (kW) (case-2)

Table5.3: Comparison of Time taken by PID and Fuzzy controllers for change in secondary load (case-2)

Time	Required change in secondary load	Time taken by PID controller	Time taken by Fuzzy controller
3 sec	-25 kW	not stable	0.5 sec
7 sec	-60 kW	not stable	0.5 sec

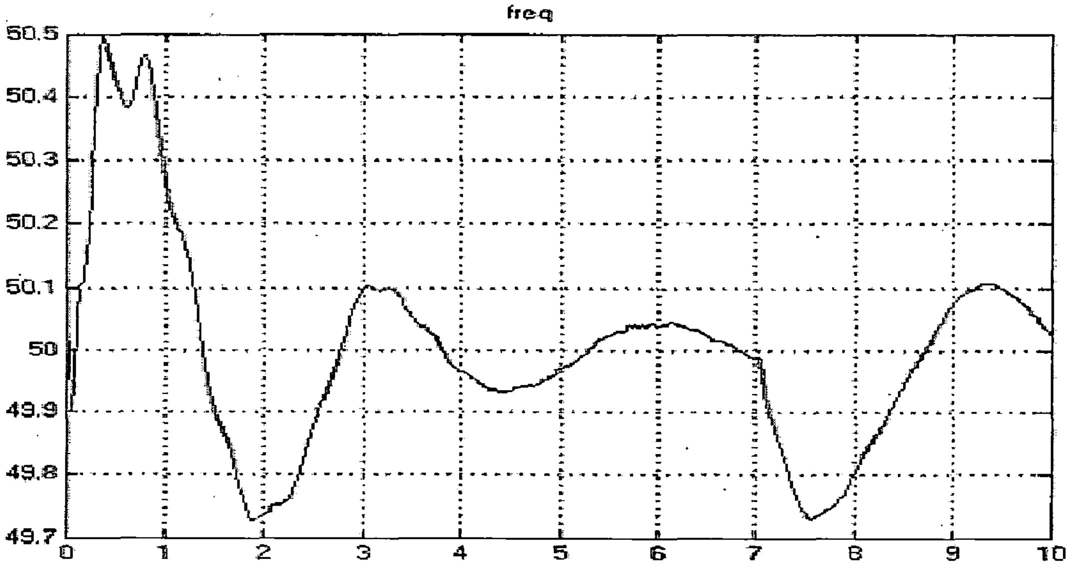


Fig.5.18 Frequency with PID controller (Hz) (case-2)

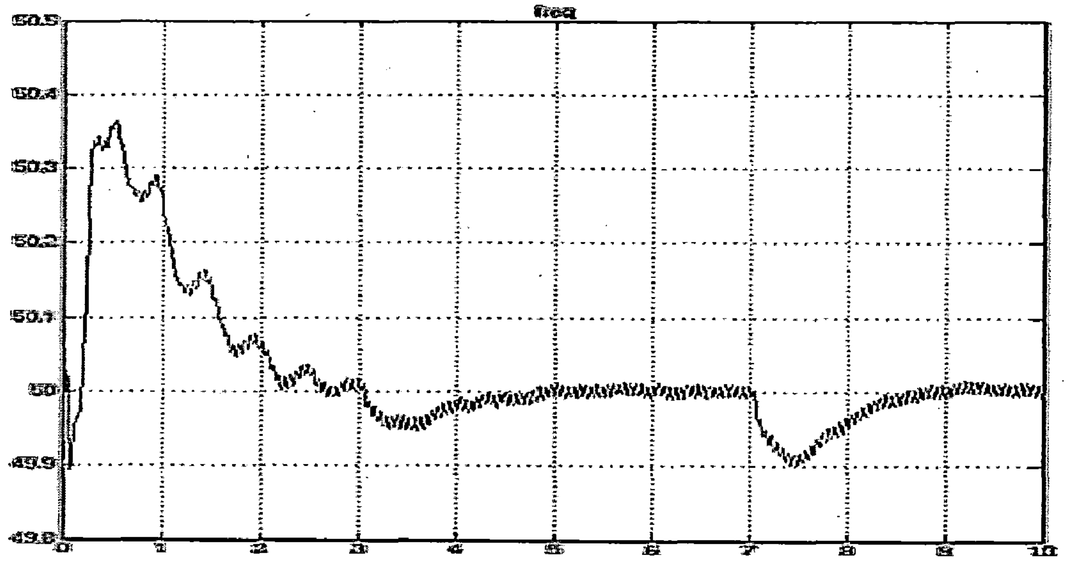


Fig.5.19 Frequency with Fuzzy controller (Hz) (case-2)

Table 5.4: Comparison of Frequency with PID and Fuzzy controllers (Case-2)

Input power change at	PID controller		Fuzzy controller	
	Max change in frequency	Frequency settling time	Max change in frequency	Frequency settling time
3sec	-0.18 Hz	4 sec.	-0.05Hz	1 sec
7sec	-0.25 Hz	not stable	-0.1 Hz	1.3 sec

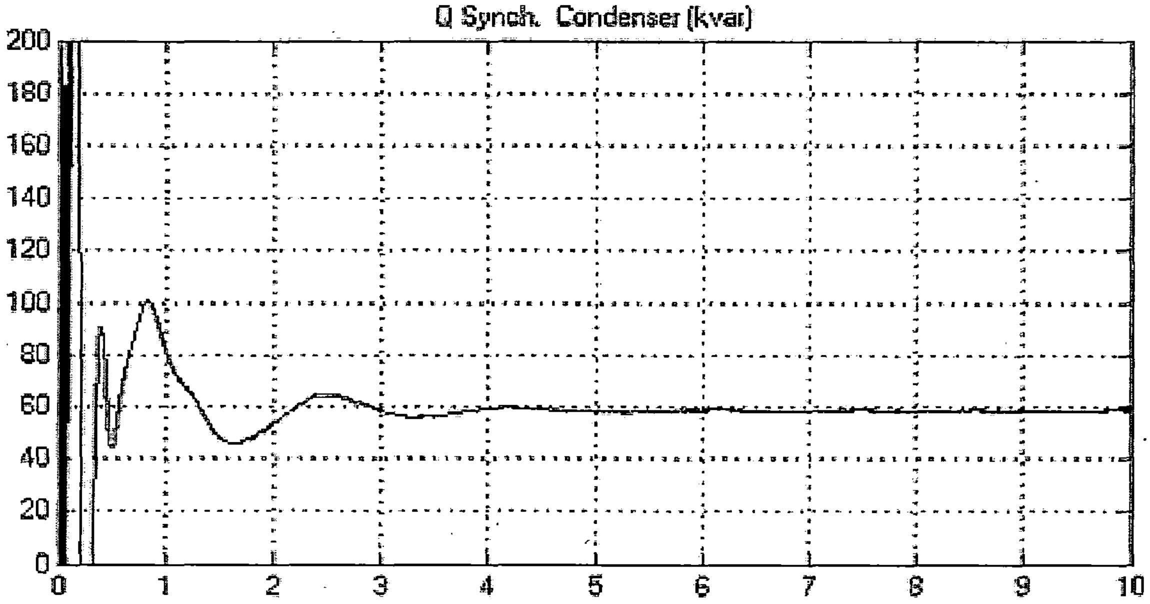


Fig.5.20 Synchronous condenser reactive power (kVAr) (case-2)

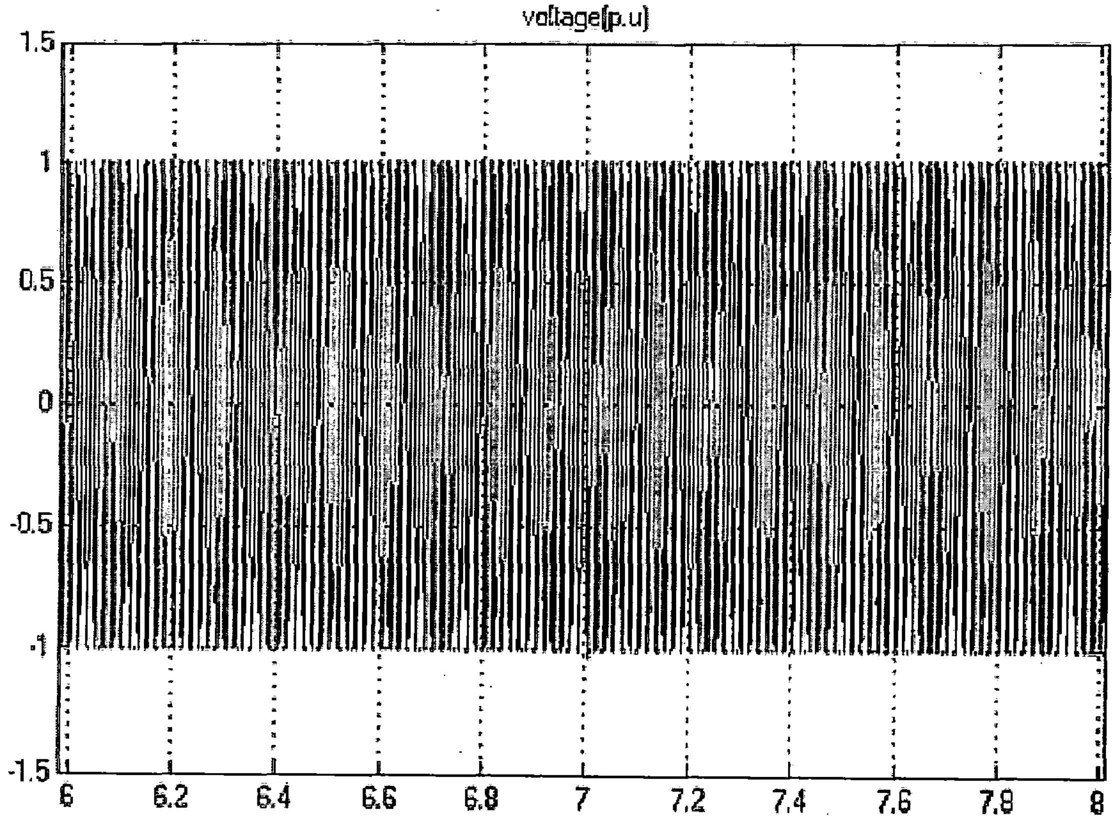


Fig.5.21 System Voltage (p.u) (case-2)

CHAPTER 6

CONCLUSION

6.1 Conclusion:

In this dissertation, a fuzzy based control scheme has been presented for improving the performance of wind energy conversion system. For controlling the frequency a fuzzy controller is used which changes the secondary load power to keep the active power balance in the system. The fuzzy controller uses two real time measurements, namely the error in frequency and its rate of change. These input signals are fuzzified and represented in fuzzy set notations using linguistic labels characterized by membership grades. Using a set of 49 rules, fuzzy set theory and associated fuzzy operations, the controller's output is obtained. The fuzzy set describing the controller's output (in terms of linguistic labels) is defuzzified to obtain an analog signal which is used to control the secondary load power, so the frequency in the system.

In this system, the synchronous generator is used as a synchronous condenser. By controlling the field excitation, the synchronous generator can be made to either generate or absorb reactive power to maintain its terminal voltage at its rated value. The performance of the fuzzy controller along with synchronous condenser has been tested using simulation. The proposed control scheme provides more effective control for the system to achieve good power quality, which is demonstrated by smooth transition of frequency and the voltage is maintained constant by the synchronous condenser.

The fuzzy based control scheme improves the system frequency performance compared to the PID controller. The maximum frequency deviation with fuzzy controller is less than 1% in all conditions and the frequency is settled faster with fuzzy controller compared to the PI controller. With the proposed controller, all performances are smooth and damped, while the PID controller shows undamped frequency response. With the proposed scheme, the improvement in frequency deviation during startup with respect to the PID controller is 61.53% for a 25% change in the load.

Thus, an alternative controller based on fuzzy set theory is presented. Unlike its counterpart, the PID controller no detailed mathematical model or linearization about an operating point is required by the fuzzy logic controller. Also, each rule addresses a wider scenario of operating conditions and ensures the same performance even with, variation in system parameter with aging or with change in operating conditions.

6.2 Future Scope:

In present work a fuzzy controller has been used for improving the performance of wind energy conversion system by controlling the frequency. The proposed controller can also control the voltage but only if the voltage changes are due to the active power changes in the system. Since the voltage in the system is a function of the field excitation as well as angular speed of the generators. In future a non linear fuzzy controller can be developed taking the detailed mathematical model of the wind energy conversion system into account and for controlling the voltage the controlled capacitors and inductors can be switched on with the help of the fuzzy controller.

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Appendix-1

Asynchronous machine model:

The asynchronous machine is modeled in a synchronously rotating reference frame with the d-axis oriented along the rotor-flux vector position. In this way, a decoupled relation between the electromagnetic torque and the rotor excitation current is obtained. The mathematical model of the asynchronous generator presents two subcomponents: the electrical system and the mechanical system. The equations (1)-(9) represent the Park dq - asynchronous machine model:

Electrical system equations:

$$U_{qs}=R_s i_{qs}+\frac{d}{dt}(L_s i_{qs}+L_m i_{qr})+\omega(L_s i_{ds}+L_m i_{dr}) \qquad (1)$$

$$U_{ds}=R_s i_{ds}+\frac{d}{dt}(L_s i_{ds}+L_m i_{dr})-\omega(L_s i_{qs}+L_m i_{qr}) \qquad (2)$$

$$U_{qr}=R_r i_{qr}+\frac{d}{dt}(L_r i_{qr}+L_m i_{qs})+(\omega\text{-}\omega_r)(L_r i_{dr}+L_m i_{ds}) \qquad (3)$$

$$U_{dr}=R_r i_{dr}+\frac{d}{dt}(L_r i_{dr}+L_m i_{ds})-(\omega\text{-}\omega_r)(L_r i_{qr}+L_m i_{qs}) \qquad (4)$$

$$T_e=\frac{3}{2}p\big((L_s i_{ds}+L_m i_{dr})i_{qs}-(L_s i_{qs}+L_m i_{qr})i_{ds}\big) \qquad (5)$$

Where

$$L_s=L_{ls}+L_m \qquad (6)$$

$$L_r=L_{lr}+L_m \qquad (7)$$

Mechanical system equations:

$$\frac{d}{dt}(\omega_m)=\frac{1}{2J}(T_e-T_m) \qquad (8)$$

$$\frac{d}{dt}(\theta_m)=\omega_m \qquad (9)$$

R_s L_{ls}=Stator resistance and leakage inductance,

R_r , L_{lr} =Rotor resistance and leakage inductance,

L_m = Magnetizing inductance,

L_s, L_r = Total stator and rotor inductances.

U_{qs}, i_{qs} = q axis stator voltage and current,

U_{qr}, i_{qr} = q axis rotor voltage and current,

U_{ds}, i_{ds} =d axis stator voltage and current,

U_{dr}, i_{dr} =d axis rotor voltage and current,

ω_m = Angular velocity of the rotor,

θ_m =Rotor angular position,

p =Number of pole pairs,

ω_r =Electrical angular velocity,

T_e =Electromagnetic torque,

T_m =Shaft mechanical torque,

J =Combined rotor and load inertia constant.

Appendix-2

Specifications

Asynchronous Generator:

Voltage (L-L) : 400 Volt

Nominal Power : 275 kW

Frequency : 50Hz

Stator Resistance : 0.016 p.u

Stator Inductance : 0.06 p.u

Rotor Resistance : 0.015 p.u

Rotor Inductance : 0.06 p.u

Mutual Inductance : 3.5 p.u

Inertia Constant : 2

Friction Factor : 0

Pole Pairs : 2

Synchronous condenser:

Voltage (L-L) : 400 Volt

Nominal Power : 300 kW

Frequency : 50Hz

D-axis steady state reactance (X_d) : 3.23p.u

D-axis transient reactance (X_d') : 0.21 p.u

D-axis sub transient reactance (X_d'') : 0.15

Q-axis steady state reactance (X_q) : 2.79 p.u

Q-axis sub transient reactance (X_q'') : 0.37 p.u

Leakage reactance (X_l) : 0.09 p.u

Stator Resistance : 0.017 p.u

Inertia Constant : 1

Friction Factor : 0

Pole Pairs : 2

Controlled Secondary load:

Nominal Voltage (L-L) : 400 V

Nominal Frequency :50 Hz

Power per step :1.75 kW

Initial Power :0 kW

Conventional PID controller:

Proportional gain : 255

Derivative gain : 30

Integral gain : 1

Upper dead zone for PID controller: +0.005 Hz

Lower dead zone for PID controller: -0.005 Hz