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Enhancement of Power for Doubly Fed Induction Generator based Wind Energy Conversion System Using Artificial-Intelligence

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Abstract* – Energy demand and supply has always been a core issue in the world for decades. These days all the countries are trying to cope up with the rapidly growing energy demands due to high energy appliances and industrial machines. The renewable energy resources are a preferred area of interest for researchers as these resources are harmless to the environment. The aim is to contribute towards wind energy conversion systems based on doubly fed induction generator by designing an intelligent controller based on fuzzy systems to improve reference tracking and robustness. Two controllers, PI and Fuzzy Intelligence based controllers are designed for decoupled control of stator active and reactive power. The responses of the two controllers are compared using MATLAB Simulink.

***Keywords* – Active Power; DFIG; Fuzzy Logic; Membership Functions; Reactive Power; Rule Base; WECS**

I. INTRODUCTION

With the ongoing development in the field of science and technology there is a remarkable increase in the use of high power electric devices. Almost the whole world seems to have shifted to the use of electric machines, hence causing an increase in the demand of electric energy. Electricity can be produced using different techniques. Broadly speaking we have non-renewable and renewable resources of energy. Most of the non-renewable resources are not environment friendly unlike the renewable resources which have many advantages over non-renewable ones.

The renewable energy resources are the main focus of research nowadays. There are basically two main renewable i.e. wind and solar. A lot of research has been done on solar systems and it still continues on. Likewise there is a need to work on wind energy generation systems and many issues need to be addressed in this area. This is the main motive of our research on wind energy systems.

This study is mainly focused on improving the operation of doubly fed induction generator (DFIG) based wind energy conversion system (WECS) in such a way that the system can withstand and track desired power even if any of the machine parameters gets disturbed because of the environmental issues like temperature, moisture etc. Moreover, it also contributes towards the quick response of the system to certain changes in parameters.

There are two objectives that are successfully tackled using an Artificial-Intelligence based controller in comparison with a conventional PI controller. First is the perfect tracking of power references during normal operation of the machine and second is to maintain this improved tracking even if there is any change in machine parameters leading towards the enhanced robustness of the system.

Over the last few years, the world is focusing on how to reduce the carbon footprint which actually is a cause of emission of greenhouse gases damaging the ozone layer and assisting the global warming to increase as we move forward towards the modern era with a lot of development in science and technology, ultimately putting humans to use more electricity to run different technologically advanced machines.

The idea of generating power from renewable and specially the wind energy conversion systems has been very popular among people in power industry [1]. However, there is a need to improve the technical issues to control these huge systems. Basic wind energy conversion system consists of three main areas i.e. aerodynamic, mechanical and electrical parts. Figure-1 below shows the component level construction of a wind turbine. Figure-2 represents the block diagram which shows the bigger picture to understand its basics.

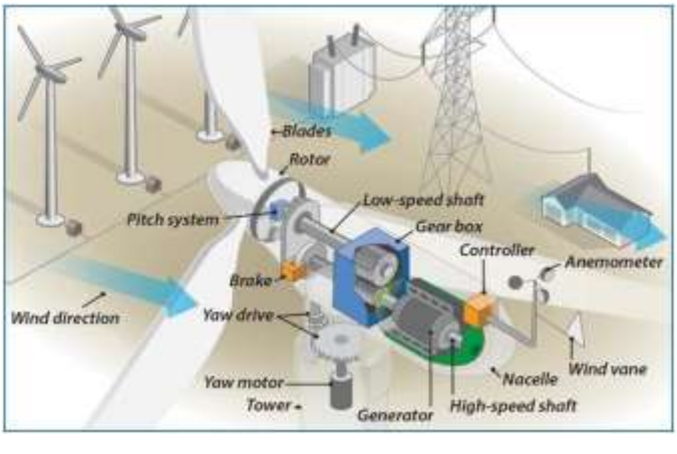


Figure- 1 Horizontal Axis Wind Turbine The first aerodynamic part consists of the rotor itself, rotor blades and hub and pitch system.

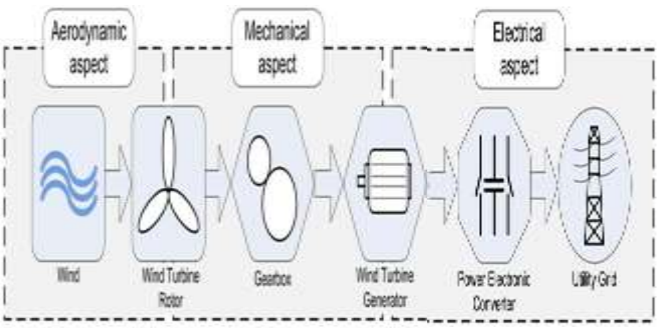


Figure- 2 WECS Block Diagram

The second mechanical part consists of low speed shaft, gear box, high speed shaft, brakes and yaw drive while the third electrical portion consists of a generator, power converters and control system. The step by step overall working of this system is such as when wind blows over the rotor blades, these blades forced the low speed shaft to move being connected to the rotor. With the presence of gearbox the slowly moving shaft ultimately turns the fast moving shaft of the generator and hence we can extract power from the generator as desired. But these lines are not so simple regarding its working instead a very efficient control system is always been a primary requirement without which desired result cannot be obtained. Moreover turbine itself can be damaged because of high wind speeds.

There are two main types of wind turbines used in wind energy conversion systems.

- Horizontal Axis Wind Turbines
- Vertical Axis Wind Turbines

Horizontal axis wind turbines have rotor rotating around a horizontal axis and able to collect maximum amount of energy from wind. The rotor blades can be pitched accordingly so that the damage is minimized during stronger winds in storms. Also the taller towers provide access to stronger wind sites with wind shear and placement on uneven land or in offshore locations.

While Vertical axis wind turbines have rotor rotating around a vertical axis, the rotor cannot be pitched accordingly so as to collect maximum amount from wind. This is an old technology wind turbine and cannot be placed on uneven land. Moreover, these turbines can be easily damaged because of stronger wind as guy wires are used to support the structure which can be broken down during stronger winds.

Therefore from the above discussion, it can be seen that horizontal axis turbines are better than vertical axis wind turbines, and is the point of focus throughout this study [2].

There is another classification of wind turbines i.e.

- Fixed speed wind turbines
- Variable speed wind turbines

Fixed speed wind turbines can extract power from the wind at some particular speed but variable speed wind turbines can operate on variable speed using variable pitch blades with application of doubly fed induction generator with power converters which enable operation at variable speed to extract maximum power at all wind speed range using some kind of control system.

Figure- 3 DFIG Based WECS

In this study the configuration that is used for mathematical modeling and control purposes is the DFIG based WECS [3] as given in above figure-3. It is clear in the figure that the stator is directly connected to the grid and rotor is fed via a back to back voltage source power converter.

As the stator is directly connected to the power grid so it is supplied with a constant voltage and constant frequency while the rotor is connected to the grid via power converters. So it can be supplied with variable voltage and frequency according to the requirement as shown in figure-3.

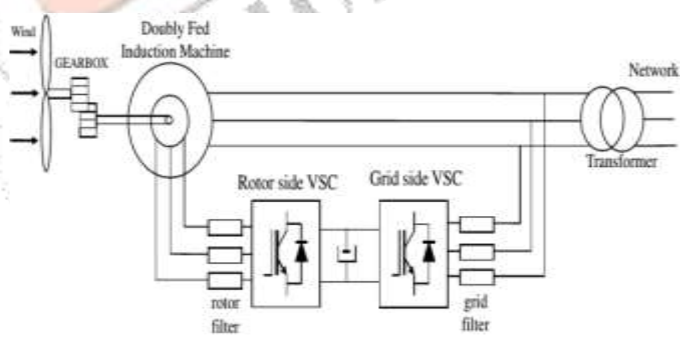
This topology is very much advantageous over the others because there is not any need of full scale power converters instead small scale converter that can handle approximately 30% of the total power as only this amount of total power is transferred between the grid and rotor [4]-[5].

In this paper an intelligent controller based on fuzzy logic [6] is designed to improve reference tracking and robustness of DFIG based WECS. Fuzzy controller is acting as a supervisory controller to tune PI controller [7] gains K_p and K_i by using method of gain scheduling to track stator active and reactive power references. The results show improvement in system response to certain parametric changes.

This paper is organized as follows: section-II contains mathematical Model, section-III contains controller design, section-IV contains simulation results and section-V contains conclusion and future work.

II. MATHEMATICAL MODEL

The power extraction by the rotor blades from the wind is based on the principle of aerodynamics. As the air strikes the wind turbine rotor blades the power extracted depends upon the size, shape and speed of wind etc. The relation between speed of wind and Kinetic Energy is given as below.



The Kinetic Energy is:

$$Kinetic\ Energy = KE = \frac{1}{2}(m).(v^2)$$

Where **m** is the mass of air and v is the speed of blowing wind. So the power extracted from wind given as under:

$$Power = P = \frac{1}{2}(Mass\ \ flow\ rate\ per\ second).(v^2)$$

But the actual power extracted by the rotor blades of wind turbine is the difference between upstream wind and downstream wind powers.

Therefore,

$$P = \frac{1}{2}(Mass\ \ flow\ rate\ per\ second).(v^2 - {v_0}^2)\ldots(1)$$

Where

P is the Mechanical Power extracted by the rotor blades (watts)

v is the upstream wind speed (m/s)

v_o is the downstream wind speed (m/s)

Let

ρ be the density of air (kg/ m^3)

A is the area covered/ spanned by the rotor blades (m^2)

Then the rate of mass flow through rotor blades of turbine:

$$Rate\ of\ mass\ flow = \ \rho.A.\frac{v+v_0}{2} \quad \ldots (2)$$

And finally the mechanical power which the rotor extracts is given by:

$$P = \frac{1}{2}\left[\rho.A.\left(\frac{v+v_0}{2}\right)\right](v^2 - {v_0}^2) \qquad \ldots(3)$$

After rearranging the term, we get:

$$P = \frac{1}{2}\rho.A.v^3C_p \qquad \ldots(4)$$

Where C_p is the coefficient of power of the rotor and given as:

$$C_p = \frac{\left(1+\frac{v_0}{v}\right)\left(1-\left(\frac{v_0}{v}\right)^2\right)}{2} \qquad \ldots(5)$$

The simplified and idealized model of this machine can be described using three stator and three rotor windings [8] according to the models developed by different researchers. Figure-4 shows this model which actually helps to develop an equivalent circuit of the machine which is shown in figure-5.

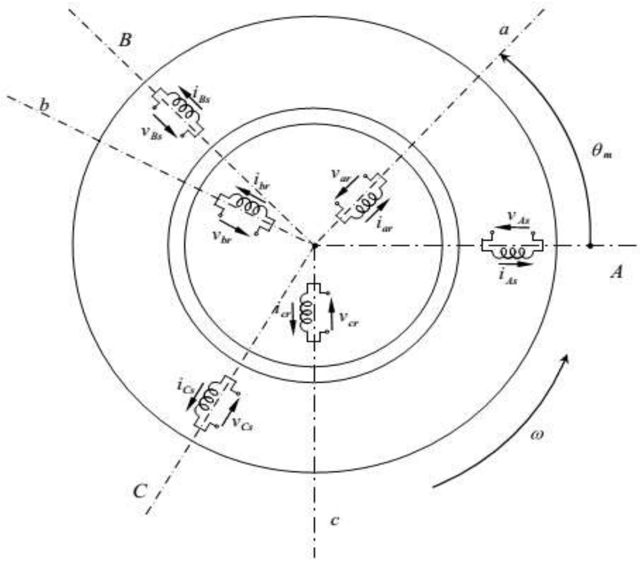


Figure- 4 WECS Block Diagram

Stator Voltage Equations

$$v_{as} = R_s i_{as} + \frac{d}{dt}\psi_{as}$$
$$v_{bs} = R_s i_{bs} + \frac{d}{dt}\psi_{bs}$$
$$v_{cs} = R_s i_{cs} + \frac{d}{dt}\psi_{cs}$$

Rotor Voltage Equations

But analysis and controller design by directly working on

$$v_{ar} = R_r i_{ar} + \frac{d}{dt}\psi_{ar}$$
$$v_{br} = R_r i_{br} + \frac{d}{dt}\psi_{br}$$
$$v_{cr} = R_r i_{cr} + \frac{d}{dt}\psi_{cr}$$

These above equations are very difficult. So space vector theory is used to transform these three phase quantities into dq reference frame i.e. dq components.

Where:

R_s: Stator Resistance

i_{as}, i_{bs}, i_{cs}: Stator currents of three phases a, b, c

v_{as}, v_{bs}, v_{cs}: Stator voltages of three phases a, b, c

Ψ_{as}, Ψ_{bs}, Ψ_{cs}: Stator fluxes of three phases a, b, c

R_r: Rotor Resistance

i_{ar}, i_{br}, i_{cr}: Rotor currents of three phases a, b, c

v_{ar}, v_{br}, v_{cr}: Rotor voltages of three phases a, b, c

Ψ_{ar}, Ψ_{br}, Ψ_{cr}: Rotor fluxes of three phases a, b, c

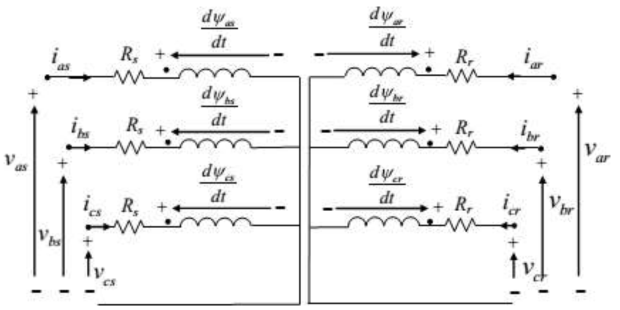


Figure- 5 Equivalent Circuit of Induction Machine

Different reference frames are shown in figure-6. Using Clarke and Park Transformations the αβ-model, the model in stationary reference frame i.e. stator reference frame, is given as follows.

Stator Voltage Equations

$$v_{as} = R_s i_{as} + \frac{d}{dt}\psi_{as}$$

$$v_{\beta s} = R_r i_{\beta s} + \frac{d}{dt}\psi_{\beta s}$$

Rotor Voltage Equations

$$v_{ar} = R_r i_{ar} + \frac{d}{dt}\psi_{ar} + \omega_m \psi_{\beta r}$$

$$v_{\beta r} = R_r i_{\beta r} + \frac{d}{dt}\psi_{\beta r} - \omega_m \psi_{ar}$$

Stator Flux Equations

$$\psi_{as} = L_s i_{as} + L_m i_{ar}$$

$$\psi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r}$$

Rotor Flux Equations

$$\psi_{ar} = L_m i_{as} + L_r i_{ar}$$

$$\psi_{\beta r} = L_m i_{\beta s} + L_r i_{\beta r}$$

Stator Active and Reactive Power Equations:

$$P_s = v_{as} i_{as} + v_{\beta s} i_{\beta s}$$

$$Q_s = v_{\beta s} i_{as} - v_{as} i_{\beta s}$$

Rotor Active and Reactive Power Equations:

$$P_r = v_{ar} i_{ar} + v_{\beta r} i_{\beta r}$$

$$Q_r = v_{\beta r} i_{ar} - v_{ar} i_{\beta r}$$

The dq-model; the model in synchronously rotating reference frame [9]-[11] is given as follows:

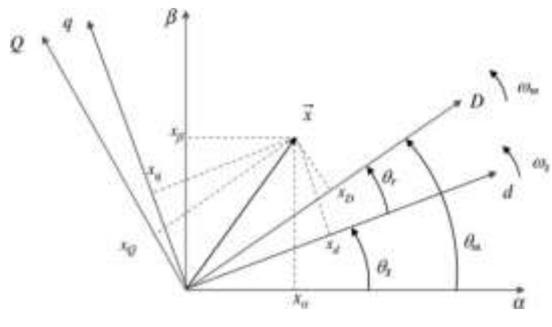


Figure- 6 Reference Frames Orientation

Stator Voltage Equations

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s \psi_{qs}$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s \psi_{ds}$$

Rotor Voltage Equations

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r \psi_{qr}$$

$$v_{qr} = R_s i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r \psi_{dr}$$

Stator Flux Equations

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr}$$

Rotor Flux Equations

$$\psi_{dr} = L_m i_{ds} + L_r i_{dr}$$

$$\psi_{qr} = L_m i_{qs} + L_r i_{qr}$$

Stator Active and Reactive Power Equations:

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs}$$

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs}$$

Rotor Active and Reactive Power Equations:

$$P_r = v_{dr} i_{dr} + v_{qr} i_{qr}$$

$$Q_r = v_{qr} i_{dr} - v_{dr} i_{qr}$$

The above mentioned ***dq-model*** is used to design the controller to improve the operation of DFIG.

III. CONTROLLER DESIGN

This section covers the complete details about the mathematical model used in the controller design process. It also describes details for the selections of reference frame orientation in order to obtain decouple control of active and reactive power of DFIG [4]-[5]. The doubly fed induction generator is very popular in wind energy conversion systems because it provides variable speed operation and the power converters used in this system enables control of stator active and reactive power by controlling the currents of the rotor.

Wind energy conversion system is not very simple to control it easily because if we closely monitor the mathematical equations then one can notice that firstly these equations are cross coupled differential equations and to solve these equations is really very difficult task. So for controller design purposes these differential equations are not directly used instead vector control theory is used to design a controller for induction machine. So for making the model of the machine simple usually different reference frames are used to transform the three phase quantities to two phase dc quantities, so that, controller can be designed efficiently.

Using stator flux orientation technique we can achieve decoupled control of the stator active power and reactive power. Stator flux orientation well described by figure-7 below:

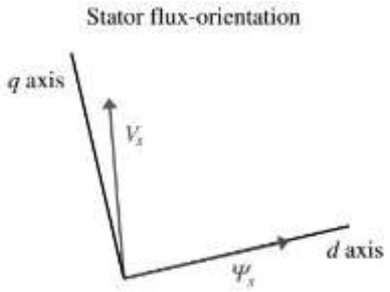


Figure- 7 Stator Flux Orientation

In the figure above we can see stator flux aligned with the d-axis [9]-[11]. So there is no component along q-axis of stator flux.

$$i.e \qquad \psi_{ds} = \psi_s; \qquad \psi_{qs} = 0$$

So dq-Model equations simplifies to

$$\psi_{ds} = \psi_s = L_s i_{ds} + L_m i_{dr} \qquad \text{....(6)}$$
$$\psi_{qs} = 0 = L_s i_{qs} + L_m i_{qr} \qquad \text{....(7)}$$

So from equation 6 and 7

$$v_{ds} = 0 \qquad \text{...(8)}$$
$$v_{qs} = v_s = \omega_s \psi_{ds} \qquad \text{...(9)}$$

Using equations 6, 7, 8, 9 in equations, we get

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} = -V_s \frac{L_m}{L_s} i_{qr} \qquad \text{...(10)}$$
$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} = -V_s \frac{L_m}{L_s} i_{dr} + V_s \frac{\psi_m}{L_s} \qquad \text{...(11)}$$
$$v_{dr} = R_r i_{dr} + L_r \sigma \frac{d}{dt} i_{dr} - g\omega_s L_r \sigma i_{qr} \qquad \text{...(12)}$$
$$v_{qr} = R_r i_{qr} + L_r \sigma \frac{d}{dt} i_{qr} - g\omega_s L_r \sigma i_{dr} \qquad \text{...(13)}$$

Note that equations (10) and (11) show that P_s and Q_s can be controlled by controlling the rotor currents. So if we control the rotor currents then it means to have a complete control over stator active power and reactive power control.

By taking into account the equations involving stator active P_s and reactive powers Q_s and taking the Laplace of V_{dr} and V_{qr} equations, We get the following transfer function to control the rotor current to get required stator active and reactive power:

$$G(S) = \frac{L_m V_s / L_r L_s \sigma}{s + L_s R_r / L_r L_s \sigma}$$

Where

$$\sigma = 1 - \left(\frac{L_m^2}{L_r L_s}\right)$$

And when using PI controller, suitable values of K_p and K_i, we can get the desired results. See Result section for simulation results.

The results of PI controller based system show that for certain variation in machine parameters the PI controller cannot perfectly tracks the desired power references because for every parameter value change there must be some mechanism to update the PI gains K_p and K_i according to the requirement. So in this thesis an intelligent controller is designed using fuzzy systems and the method of gain scheduling is used to update the values of K_p and K_i continuously according to the situation i.e. the fuzzy controller acts as a supervisory controller which updates the gain values for PI controller [12] used as first level controller in this case.

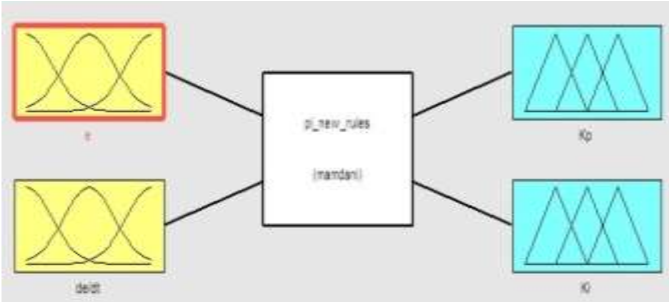


Figure- 8 Fuzzy Controller Schematic Diagram

The inputs to the fuzzy supervisory controller being e the error plus the term de/dt the derivative, while normalized values of K_p and K_i are outputs as shown in figure-8.

Figure-9 shows the membership functions for error e, derivative of error de/dt , K_p and K_i are given below.

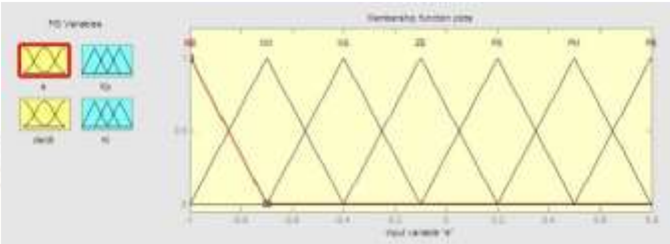


Figure- 9(a) Membership Functions for Error e

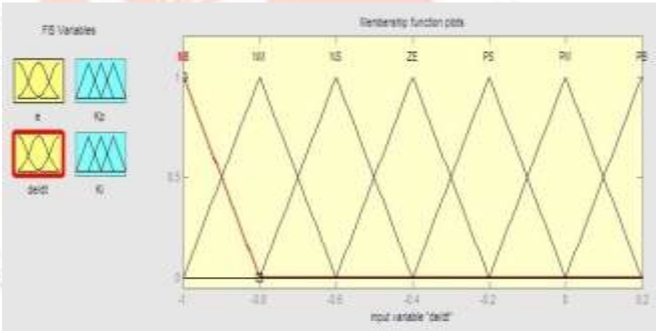
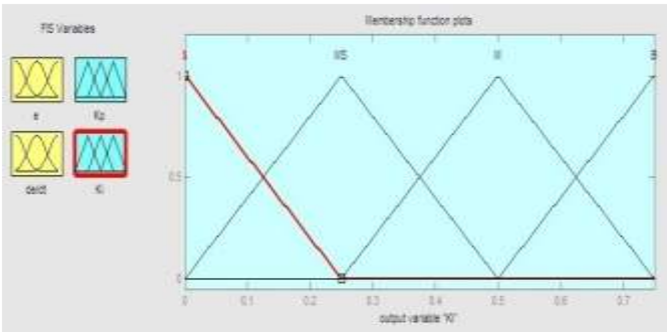


Figure- 9(b) Membership Functions for de/dt

Figure- 9(c) Membership Functions for K_p



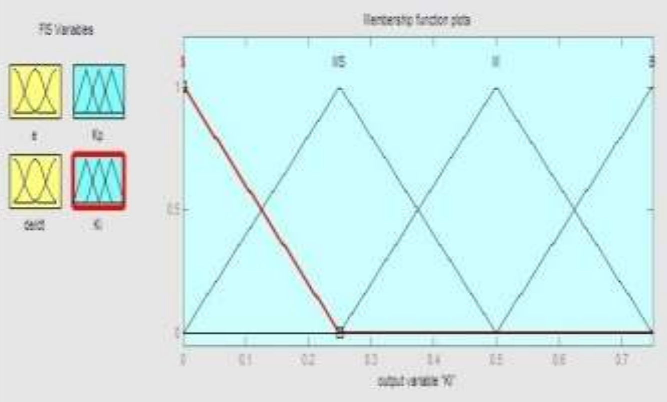


Figure- 9(d) Membership Functions for K_i

IV. SIMULATION RESULTS & DISCUSSION

The simulation is done by changing different parameters of the machine [13]. The parameter that are changed while checking system response are rotor resistance R_r, rotor inductance L_r, stator inductance L_s, Mutual inductance L_m. Machine Parameters are: Vs= 398/690V, R_s= 0.012Ω, R_r= 0.021Ω, L_s= 0.0137H, L_r= 0.0136H, L_m= 0.0135H

Matlab Simulink model for stator active power is given below.

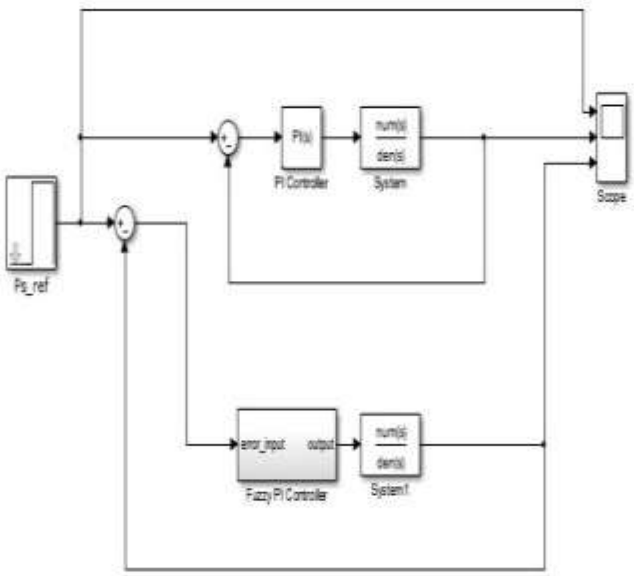


Figure- 10(a) Simulink Model for Stator Active Power

Matlab Simulink model for stator reactive power is given below.

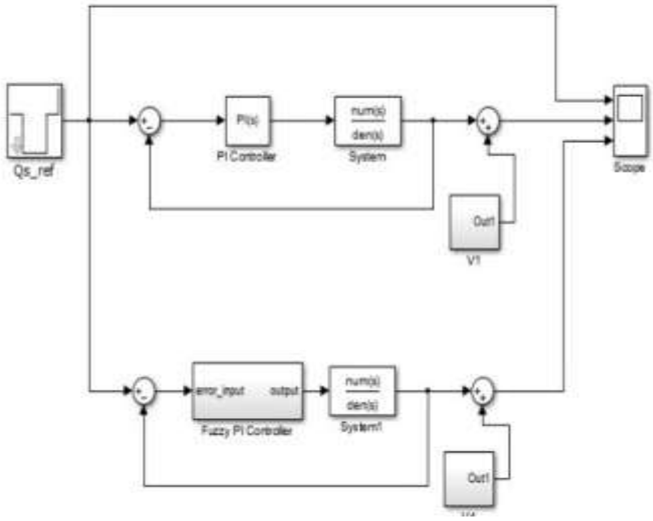


Figure- 10(b) Simulink Model for Stator Reactive Power

By varying different parameters of machine the responses of both the controller are given in diagrams given. Figure-11(a & b) shows the response when varying rotor resistance R_r, Figure-11(c & d) shows the response when varying stator inductance L_s, Figure-11(e & f) shows response when varying rotor inductance L_r and Figure-11(g & h) represents the system response when varying all the parameters simultaneously.

These results show that the system with conventional PI controller having fixed values of gains K_p and K_i, it is not possible to perfectly track the stator active and reactive power references when varying different parameters of the machines. The system with a fuzzy controller acting as a supervisory controller for online tuning of PI controller gains enhanced the system's reference tracking capability, hence improving robustness of the system.

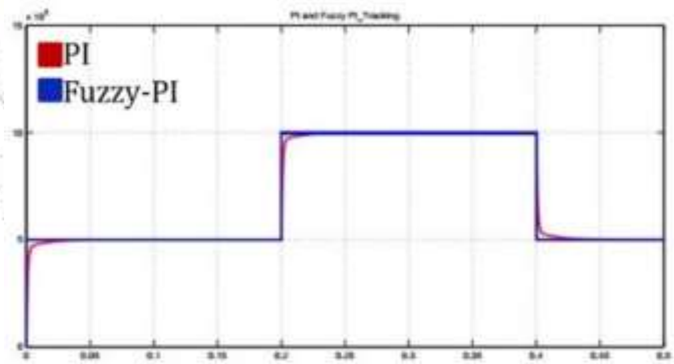


Figure-11(a) Stator Active Power with R_r variation

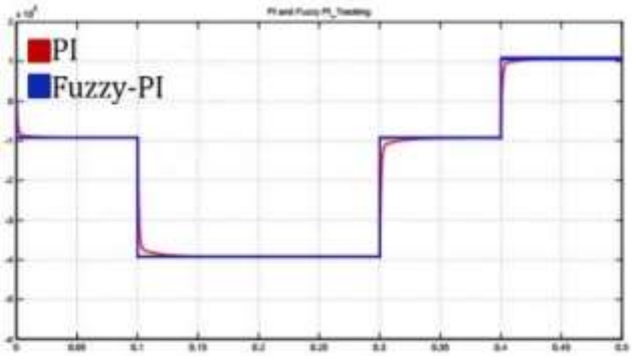


Figure-11(b) Stator Reactive Power with R_r variation

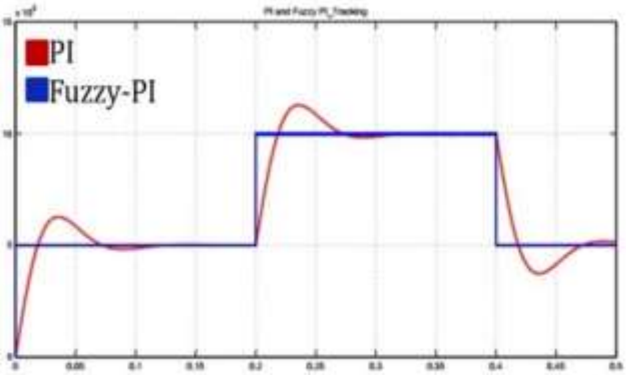


Figure-11(c) Stator Active Power with L_s variation

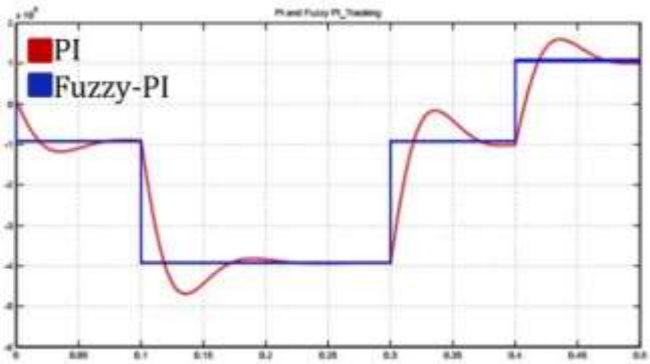


Figure-11(d) Stator Reactive Power with L_s variation

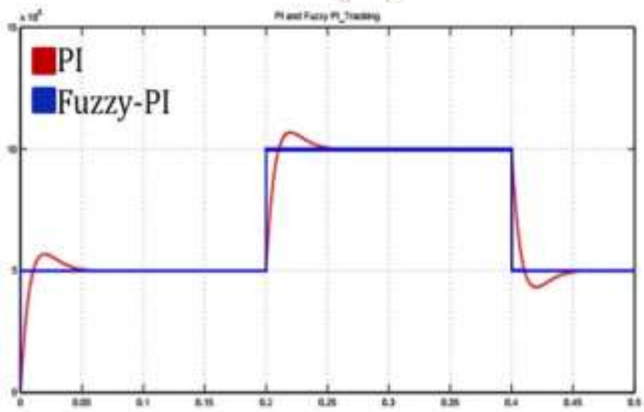
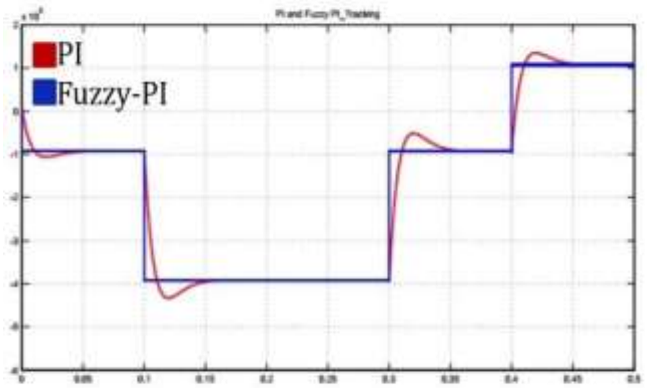


Figure-11(e) Stator Active Power with L_r variation

Figure-11(f) Stator Reactive Power with L_r variation
Figure-11(g) Stator Active Power with R_r, L_s, L_r, L_m variation



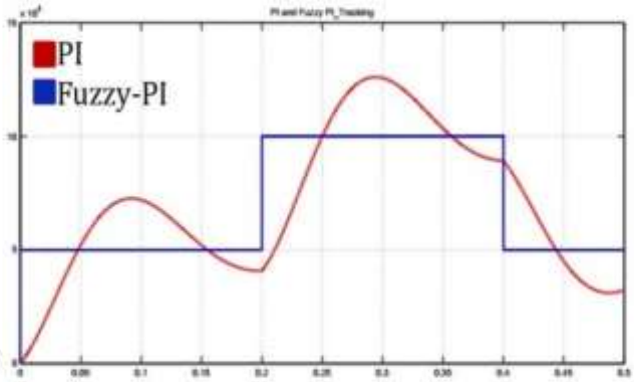
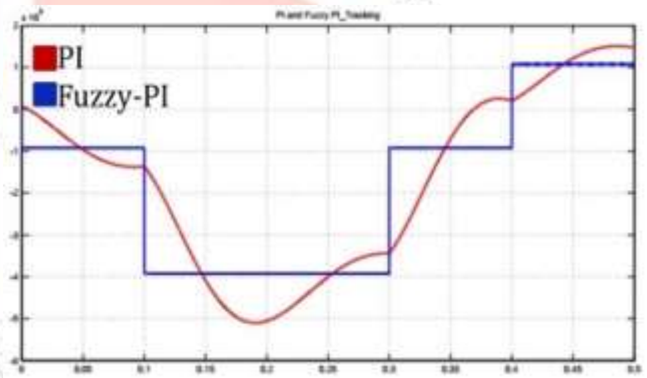


Figure-11(h) Stator Reactive Power with R_r, L_s, L_r, L_m variation



V. CONCLUSION AND FUTURE WORK

The wind energy conversion system is a combination of aerodynamic, mechanical and electrical portions reflecting its complex nature in order to control it. Moreover, its mathematical model involves cross differential equations and analysis with these equations is difficult so vector control technique proves good for simplification of mathematical model facilitating intelligent controller design process for decouple control of active and reactive power. The intelligent controller based on fuzzy logic improved the reference tracking by online tuning of PI controller gains. So instead of only using a PI controller it is better to have an intelligent controller so that the system can cater for expected variation in machine parameters.

While designing the intelligent controller based on fuzzy logic, the key step is to design a rule base which consists of different number of IF-THEN rules depending on the number of membership functions defined for each input for the controller. And as the number of rules increases the response gets improve but with increase in the computational time. So there is still a room to design and analyze the response of different controllers like neural networks or some hybrid controller e.g. neuro-fuzzy or fuzzy-neuro controller. There is definitely a need to look for a controller which is less complex in design but computationally more efficient.

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