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Pitch Angle Control of Wind Turbine using Fuzzy Logic

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***Abstract*— A wind turbine is a device that converts kinetic energy from the wind into electrical power. The speed control of wind turbine rotation is necessary for maximum energy capture and to keep the turbine components within designed speed and torque limits. In this paper, an advanced pitch angle control strategy based on fuzzy logic is proposed. The control input variables for the fuzzy logic controller are generator output power and wind speed and the output is pitch angle reference. A small change in pitch has effect on the extraction of available energy, reduction of torque and output power variation to the grid. The effectiveness of the proposed method is verified by simulation results for a 1.5MW induction generator wind turbine system.**

Index terms- Fuzzy logic controller ; Pitch angle controller ; Wind turbine.

I. INTRODUCTION

In recent years, wind energy has become one of the important renewable energy sources all over the world, since it is non-polluting and economically viable. Now-a-days, wind power is reported as the fastest growing renewable energy source. Energy from wind is captured using wind turbines, for this there are fixed and variable speed turbines. In the early years, the researchers were concentrated on fixed speed wind turbines. Recently variable speed wind turbines are the most used one since they optimize power generation along a wide range of variation of wind speed, which is having a stochastic nature.

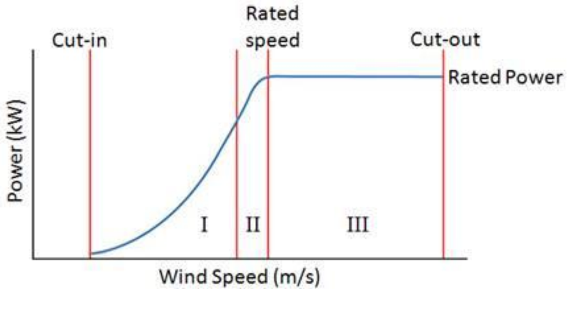

Fig.1. Power-wind speed curve.

The operation and control of wind turbine varies along the wind speed range. Fig. 1 shows a typical power-wind speed curve. Region 1 is called low-wind speed region / partial-load region, where the main objective is energy capture maximization. Region 3 is called high-wind speed region / full-load region, where the objective is to regulate the turbine at its rated power and to keep the turbine components within safety limits. The transition between high-wind speed region and low-wind speed region is shown by region 2.

At high-wind speed for limiting the aerodynamic power captured by the wind turbine, different pitch angle control methods can be suggested. Continuous rotation of turbine higher than the rated speed will produce high aerodynamic torque such that the mechanical structure of turbine may get damaged. For the power regulation, proportional-integral (PI) or proportional-integral-derivative (PID) based pitch angle controllers are often used.

In this paper a fuzzy logic based pitch control system is modelled and realized under various wind speed conditions.

II. WIND TURBINE CHARACTERISTICS

The mechanical power extracted from the wind is given by equation (1)

$$P_m = \frac{1}{2}\rho A_r C_P(\lambda,\beta) v_w^3 \tag{1}$$

Where:

P_m = mechanical power (W)

ρ = air density (kg/m^3)

A_r = blades swept area (m^2)

C_P = power coefficient

β = pitch angle of blade (degree)

v_w = wind speed (m/s)

λ = tip speed ratio

The power coefficient is a function of the tip-speed ratio (λ) and the pitch angle (β). The turbine power is determined by the power coefficient. The tip-speed ratio is calculated as

$$\lambda = \frac{R\omega_t}{v_\omega} \tag{2}$$

Where :

ω_t = turbine rotor speed (rad/s)

R = radius of the blade (m)

So the power coefficient depends on the blade pitch angle and the linear relationship between the turbine rotor speed and the wind speed.

This power coefficient determines the efficiency of the wind turbine to transform the kinetic energy contained in the wind to mechanical energy.

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The power coefficient is expressed as follows:

$$C_p(\lambda, \beta) = c_1\left(c_2 \frac{1}{\Lambda} - c_3\beta - c_4\beta^x - c_5\right)\exp\left(-c_6\frac{1}{\Lambda}\right) \quad (3)$$

Where

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3}$$

and $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21$, and $x = 0$.

Fig. 2 shows the power coefficient curves of the wind turbine as a function of the tip speed ratio and pitch angle.

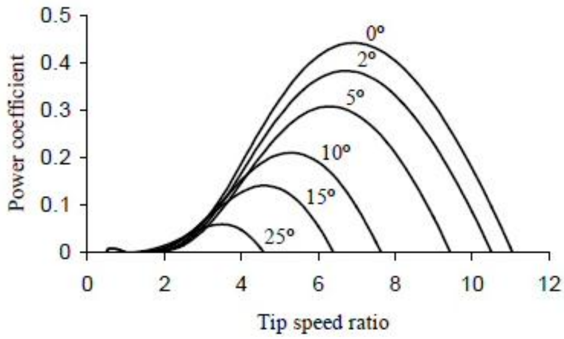


Fig.2. Power coefficient

According to the Betz limit, for horizontal axis turbines having three blades, the maximum possible value of power coefficient is approximately 0.59.

The torque available from the wind turbine can be expressed as (4)

$$T_w = \frac{1}{2}\rho A R C_T V_\omega^2 \quad (4)$$

C_T is the torque coefficient, $C_T = \frac{C_P}{\lambda}$

Therefore,

$$T_w = 0.5\rho A\left[(0.44 - 0.0167\beta)\sin\left(\frac{\pi\left(\frac{\omega_t R}{V_\omega} - 3\right)}{15 - 0.3\beta}\right) - 0.00184\left(\frac{\omega_t R}{V_\omega} - 3\right)\beta\right]\frac{V_\omega^3}{\omega_t} \quad (5)$$

III. MODELING OF WIND TURBINES

The fundamental dynamics of the variable-speed wind turbine is expressed by the following simple mathematical model.

$$J_t \dot{\omega}_t = T_\omega - T_m \quad (6)$$

Where :

J_t = moment of inertia.

T_m = mechanical torque necessary to turn the generator (constant).

This model is also called one-mass model. Here the whole drive train is considered as a single mass. One mass model is very simple and can be used in simulation. According to the complexity of the problem, two mass or three mass models are considered.

The most commonly used linear controller is proportional –integral – derivative (PID) controller. The wind turbine system is a highly non-linear one, to use PID controller the non-linear turbine dynamics is to be linearized about a specific operating point.

Linearized turbine equation (6) will give as follows:

$$J_t \Delta\dot{\omega}_t = \gamma\Delta\omega_t + \xi\Delta V_\omega + \delta\Delta\beta \quad (7)$$

Where γ , ξ , δ are linearization coefficients which are given by

$$\gamma = \left.\frac{\partial T_w}{\partial \omega_t}\right|_{op}$$

$$\xi = \left.\frac{\partial T_w}{\partial V_\omega}\right|_{op}$$

$$\delta = \left.\frac{\partial T_w}{\partial \beta}\right|_{op}$$

Here $\Delta\omega_t$, ΔV_ω , $\Delta\beta$ represents deviations from the selected operating conditions $\omega_{top}, V_{\omega op}, \beta_{op}$. Selecting the operating point is very critical to preserve aerodynamic stability in this system.

Laplace transformation of equation (7) is as follows:

$$J_t s\Delta\omega_t = \gamma\Delta\omega_t + \xi\Delta V_\omega(s) + \delta\Delta\beta(s) \quad (8)$$

From equation (8), the turbine rotor shaft can be expressed as

$$\Delta\omega_t = \left[\frac{\xi}{J_t}\Delta V_\omega(s) + \frac{\delta}{J_t}\Delta\beta(s)\right]\frac{1}{s - D} \quad (9)$$

where $D = \frac{\gamma}{J_t}$

Equation (9) shows the linearized model of a wind turbine, it can be represented by block diagram as follows:

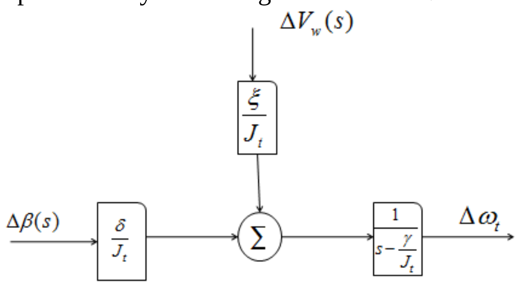


Fig.3. Block diagram of a linearized wind turbine model

IV. PITCH SERVO

In large wind turbines the pitch angle control is used to limit the turbine output power. The pitch actuator will adjust the rotation of the blades along its longitudinal axes. The hydraulic or electromechanical devices are used as pitch actuators. The pitch servo is expressed as

$$\frac{d\beta}{dt} = -\frac{1}{\tau_C}\beta + \frac{1}{\tau_C}\beta_{ref} \quad (10)$$

where τ_C is the time constant of the pitch actuator which is normally in range of 0.2 – 0.25 s.
Laplace transformation of equation (10) would yield

$$s\beta(s) = -\frac{1}{\tau_C}\beta(s) + \frac{1}{\tau_C}\beta_{ref}(s)$$

$$\beta(s) = \frac{1}{s+\tau_C}\beta_{ref}(s) \qquad (11)$$

Equation (11) can be represented by block diagram as follows.

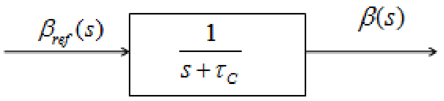


Fig.4. Block diagram of pitch actuator

V. PID CONTROLLER FOR SPEED CONTROL

To control the rotor speed of the wind turbine a PID controller can be used. Such a PID controller is illustrated in Fig. 5.where $\Delta\omega_t(s)$ represents the error signal (difference between the reference rotor speed and actual rotor speed).

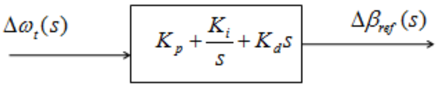


Fig.5. PID controller

The complete speed control system is shown in Fig. 6.

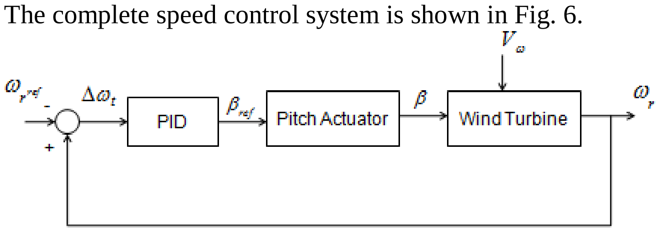


Fig.5. Block diagram of speed controller

The wind-turbine speed control is simulated using Matlab-Simulink. The reference speed is given as 62.83 m/s. The wind speed input was given using a random generator block in Simulink with a mean value of 10m/s and a deviation of 3 m/s, which is shown in Fig. 6.

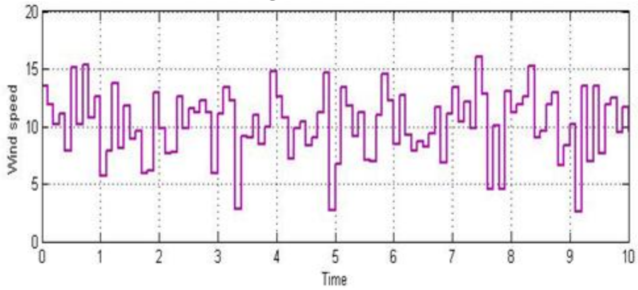


Fig.6. Wind speed input

The optimum value for PID controller parameters are K_p = 43.4186, K_i= - 0.2895 and K_d=30.5946. The output response obtained is as shown in Fig. 7.

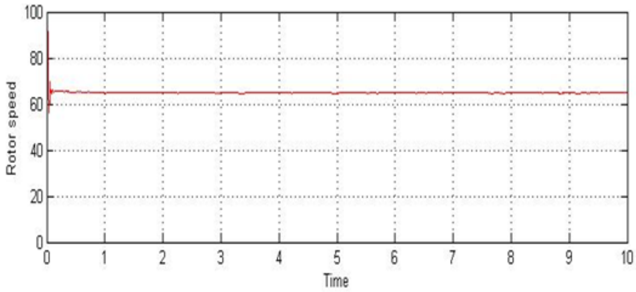


Fig.7. Rotor speed output.

VI. PROPOSED PITCH CONTROL SCHEME USING FUZZY LOGIC CONTROL

The most convenient way for blade pitch angle control is to use rule based fuzzy logic controllers. Fuzziness means vagueness. Fuzzy logic is very good to deal with uncertainty, which means that such controllers are well suited where the system parameters are not well known or the parameters have a fluctuating tendency from its expected value. In case of wind turbines the parameter wind speed is a fluctuating quantity. The main advantage of fuzzy logic is that it does not require an accurate description of the model. This paper proposes a fuzzy logic controller (FLC) for controlling the blade pitch angle of a wind turbine which is connected to a grid.

The main block diagram of a fuzzy logic controller is shown in Fig. 8.

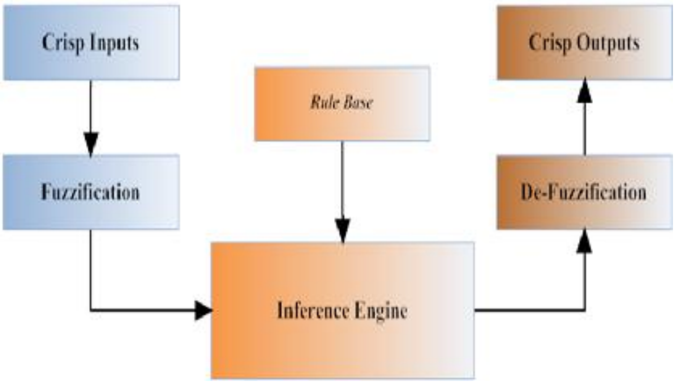


Fig.8. Block diagram of fuzzy logic controller

Mainly there are three steps for designing a rule based fuzzy logic controller. a. determining the membership functions for the control and convert the crisp values to fuzzy values and this process is called fuzzification. b. setting the rules for fuzzy reasoning and c. de-fuzzification i.e. to convert the fuzzy values to crisp system output. Centre of area, centre of sums are some methods used for de-fuzzification. Fig. 9. shows the flowchart of fuzzy logic operation. The block diagram of fuzzy logic based pitch control is shown in Fig. 10.

The proposed fuzzy logic system has two inputs a. the error signal from generated power and nominal power. b. wind speed. The output of fuzzy logic controller is pitch angle.

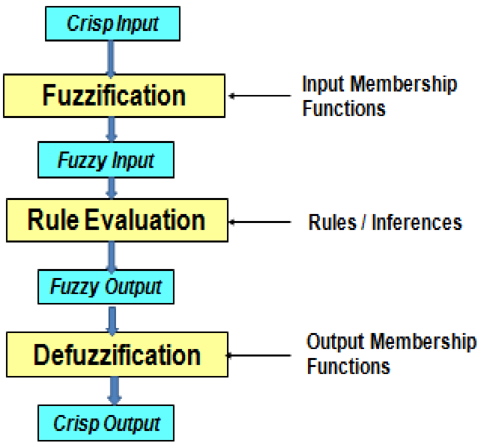


Fig.9. Fuzzy logic controller operation.

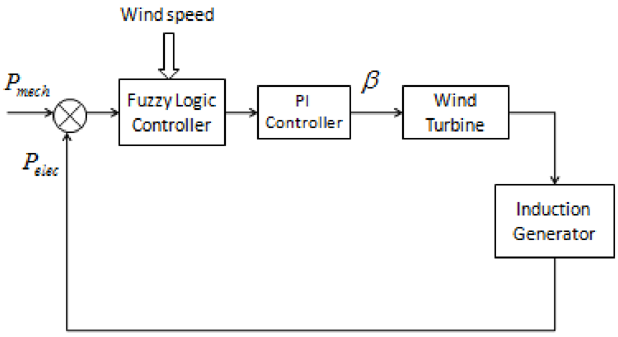
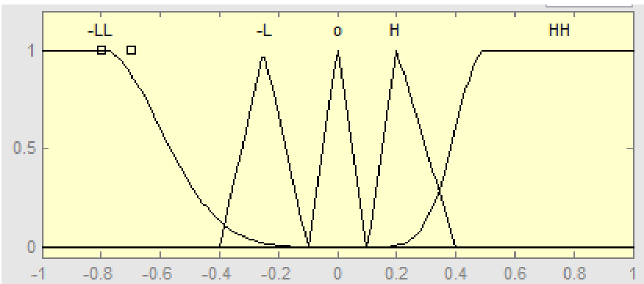
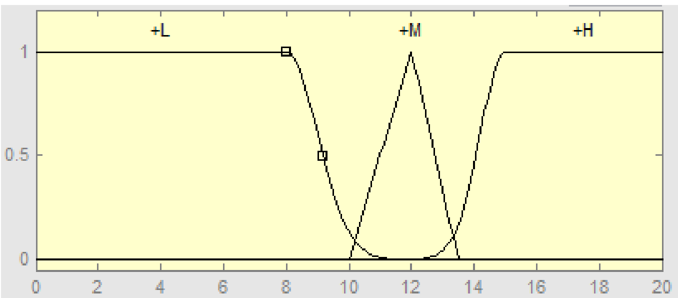


Fig.10. Block diagram of fuzzy logic based pitch control system

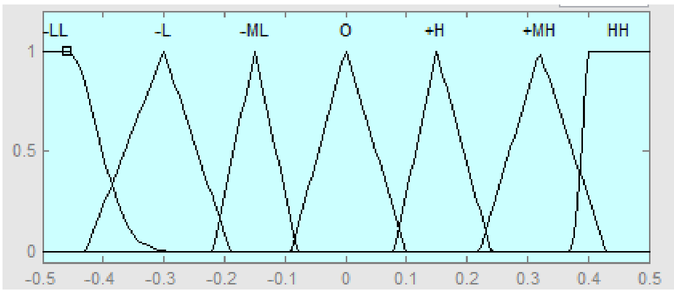
The input and output fuzzy variables used to describe Wind energy converstion System is as shown in Fig. 11.



(a)



(b)



(c)

Fig.11. Membership functions for (a) wind speed (b) error signal of power (c) output pitch angle.

The control rules are derived from the experience and knowledge of the control system. In this paper the fuzzy with mamdani model is applied for the inference mechanism.

1. If error is –L and wind speed is +M then the output pitch is –LL.
2. If error is –L and wind speed is +H then the output pitch is –H.
3. If error is H and wind speed is +H then the output pitch is O.
4. If error is –LL and wind speed is +H then the output pitch is HH.
5. If error is –L and wind speed is +H then the output pitch is HH.
6. If error is O and wind speed is +H then the output pitch is HH.
7. If error is H and wind speed is +H then the output pitch is HH.
8. If error is HH and wind speed is +H then the output pitch is HH.

The surface view of the fuzzy logic rule set is shown in Fig. 12. It shows the relationship between the preset input variables and output variations.

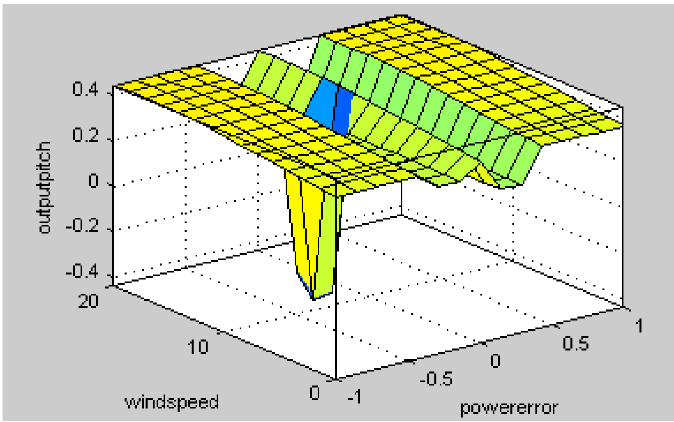


Fig.12 Surface view of the fuzzy rules.

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V. SIMULATION RESULTS

The proposed control system is modeled using SIMULINK and analyzed for grid performance evaluation. Here induction machine is used as generator. Here a 25 Km short transmission line is used as the supply grid. The wind speed is varied from 8 m/s to 11 m/s for 10 seconds and the increasing slope is assumed to be one, which is shown in Fig. 13. The turbine rated power is 1.5MW.

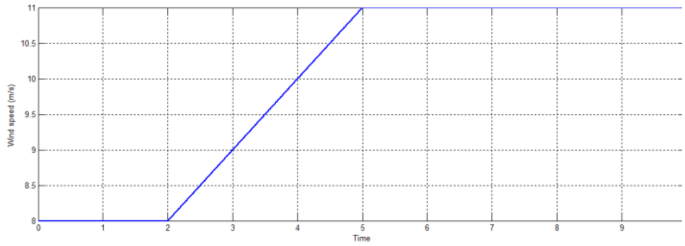

Fig.13. Wind Speed Input

First a PI controller is modeled using power error signal. The result is shown in Fig. 14.

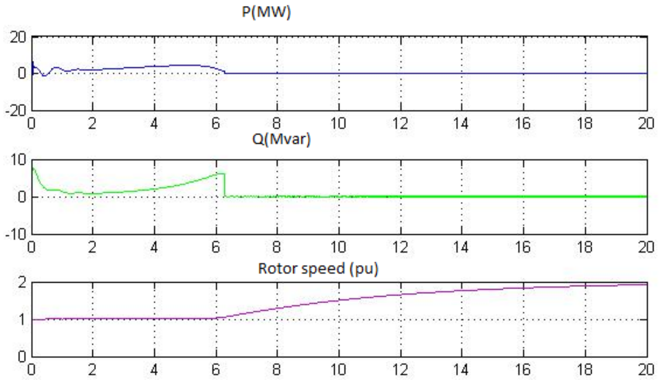

Fig.14. Generator Output using PI

With this control it is seen that when the turbine starts to rotate at a speed above rated speed at high wind condition, the PI control system tries to stop the turbine immediately, which is shown in Fig. 15.

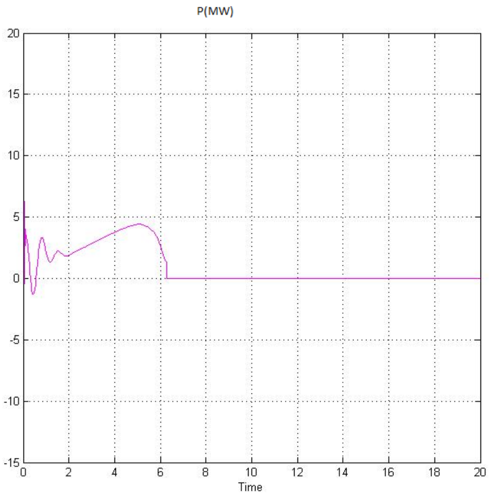

Fig.15. Generator Output Power

The grid voltage, active power, reactive power and positive sequence voltage for PI control system is shown in Fig. 16.

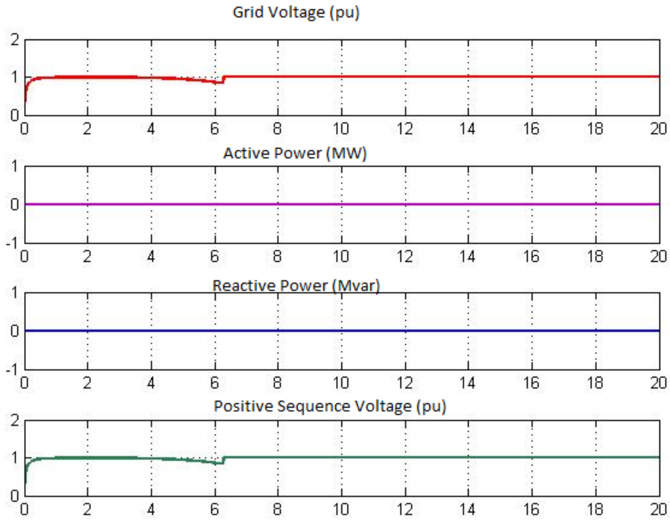

Fig.16.Grid positive sequence components for PI

When the wind speed increases to a higher limit the fuzzy logic controller will change the pitch angle gradually so as to limit the output power. The generator output while using Fuzzy PI is shown in Fig. 17.

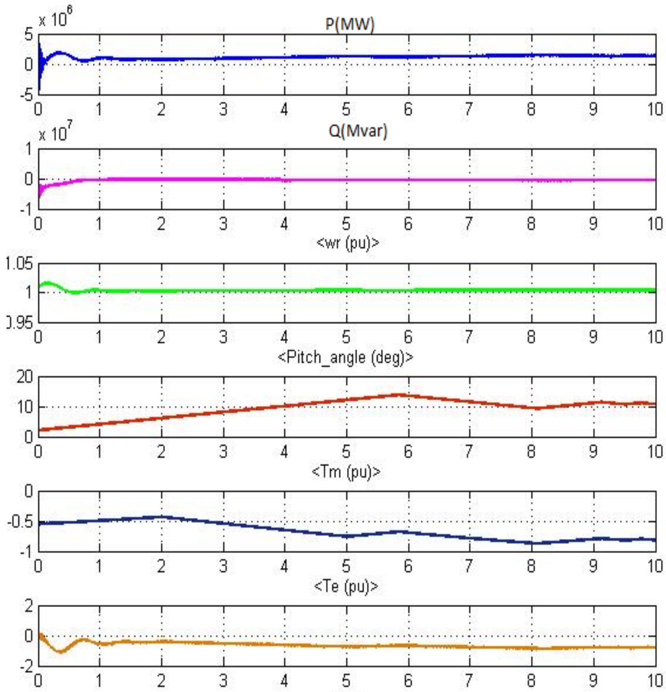

Fig.17. Active power, reactive power, Rotor Speed, Pitch angle, Mechanical torque, Electromechanical Torque of generator

With this Fuzzy PI control it is seen that when the turbine starts to rotate at a speed above rated speed at high wind condition, the control system tries to limit the output power to its rated value. The grid voltage, active power, reactive power and positive sequence voltage for Fuzzy PI control system is shown in Fig. 18.

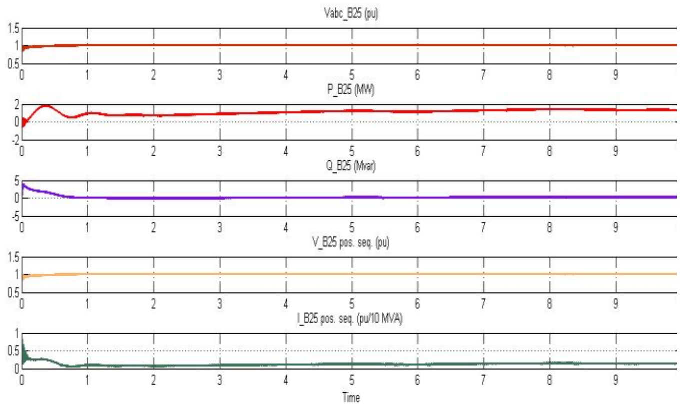

Fig.18.Grid positive sequence components for Fuzzy PI

VI. CONCLUSION

In this one mass modeling of wind turbine is done first and a PID controller is incorporated in the system for speed control. Later a novel pitch control scheme employing fuzzy logic control for the induction generator wind turbine has been proposed to limit the turbine output power and the turbine speed at their ratings during high wind speed conditions. The result of fuzzy PI is compared with classical PI controller and it is found that fuzzy PI provides better result than classical PI controller.

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