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Modeling and Control of Wind Energy Conversion Systems under High Wind Turbulence using Conventional, Fuzzy Logic and H-Infinity Controllers

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Abstract: ***Electricity generated from wind power can be highly variable at several different timescales- hourly, daily or seasonally. Annual variation also exists, but is not as significant because instantaneous electrical generation and consumption must remain in balance to maintain grid stability. The conventional PI controller may not be ideal and robust during high wind turbulence. The robust design is to find a controller for a given system. Hence the H_∞ controller is used in order to reduce the fluctuations due to high turbulence in wind velocities and a fuzzy logic controller is implemented such that maximum power is delivered to the load.***

Keywords: Wind energy Conversion Systems, Doubly Fed-induction Generator, Fuzzy Logic Control, H- infinity Controller.

1. Introduction

Wind power is the conversion of wind energy into a useful form of energy. Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, produces no green house emissions during operation and uses little land. Wind power capacity has expanded rapidly and wind energy production was around 4% of total world-wide electricity usage. Wind power is very consistent from year to year but has significant variation over shorter time scales[1]. Hence in order to reduce the fluctuations occurred due to variations in wind speed above or below the rated speed, H-∞ controller is designed. Also a fuzzy logic controller is used in order to extract maximum power output. Based on the generated power and power output, the fuzzy logic controller adjusts the torque output on the shaft to drive the turbine to the desired speed. Fuzzy logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It helps us model difficult, even intractable problems. Advantages of fuzzy control are that it is parameter insensitive, provides fast convergence and accepts noise and inaccurate signals. The fuzzy algorithms are universal and can be applied retroactively in any system. H_∞ methods are used in control theory to synthesize controllers achieving stabilization with guaranteed performance. To use H_∞ methods, a control designer expresses the control problem and then finds the control problem as a mathematical optimization problem and then finds the controller that solves this optimization. H_∞ techniques have the advantage over classical control techniques as they are readily applicable to problems involving multivariate systems.

2. Wind Energy Systems

Wind energy conversion systems are very different in nature from conventional generators, and therefore dynamic studies must be addressed in order to integrate wind power into the power system. Models utilized for steady-state analysis are extremely simple, while the dynamic models for wind energy conversion systems are not easy to develop. Dynamic modeling is needed for various types of analysis related to system dynamics: stability, control system and optimization. Modern wind turbine generator systems are constructed mainly as systems with horizontal axis of rotation, a wind wheel consisting of three blades, a high speed asynchronous generator (also known as induction generator) and a gear box. Asynchronous generators are used because of their advantages, such as simplicity of construction, possibilities of operating at various operational conditions, and low investment and operating costs.

1. Modeling of wind turbine: the wind turbine blades extract the kinetic energy in the wind and transform it into mechanical energy. The power coefficient C_P can be defined as a function of the tip –speed ratio and the blade pitch angle as follows

$$C_P(\lambda,\beta) = c_1.\left(c_2.\frac{1}{\gamma} - c_3.\beta - c_4.\beta^x - c_5\right)e^{-c_6\frac{1}{\gamma}} \quad (1)$$

The power extracted from the wind is given by

$$P_{BLADE} = C_P(\lambda,\beta).\frac{1}{2}.\rho.A.v^3 \quad (2)$$

The rotor torque T_w can be computed as

$$T_w = \frac{P_{BLADE}}{w_m} = \frac{C_P(\lambda,\beta).\frac{1}{2}.\rho.A.v^3}{w_m} \quad (3)$$

with γ defined as

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \quad (4)$$

while the coefficients c1-c6 are proposed as equal to: C_1=0.5, C_2=116, C_3=0.4, C_4=0, C_5=5, C_6=21.

2. Doubly fed induction generator: Wind turbines usually employ DFIG having wound rotor induction generator. The DFIG is one of the machines which employ the principle of variable speed[2]. Unlike other generators, the DFIG delivers power to the grid through both stator and rotor terminals. The stator is directly connected to the grid while the rotor is connected to the grid via power electronic converters[3].

Rotor circuit equation in d-q frame:

$$v_{qr} = R_r i_{qr} + p\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (5)$$

$$v_{dr} = R_r i_{dr} + p\psi_{dr} + (\omega_e - \omega_r)\psi_{qr} \quad (6)$$

Flux Linkage expressions:

$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr}$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr}$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m (i_{qr} + i_{qs}) = L_r i_{qr} + L_m i_{qs}$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{dr} + i_{ds}) = L_r i_{dr} + L_m i_{ds} \quad \ldots (7)$$

$$L_s = L_m + L_{ls} \text{ and } L_r = L_m + L_{lr}$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr})$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr})$$

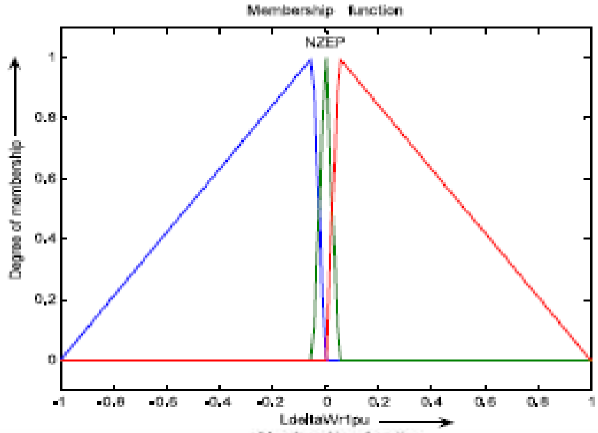
3. Controller Implementation

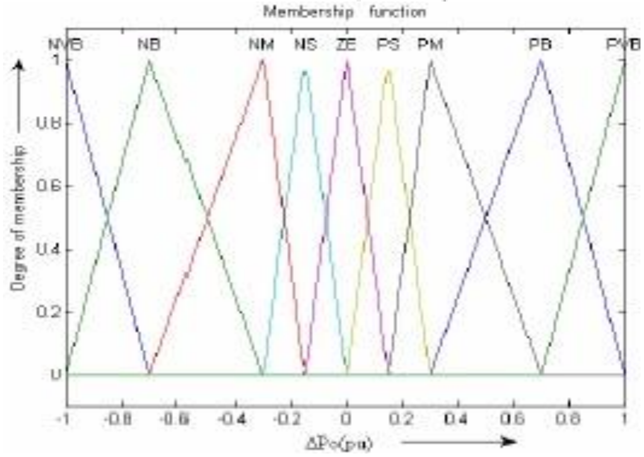
Fuzzy logic controller: An induction generator require controller which will track wind speed in order to achieve w_{opt} and thus extract maximum power. An MPPT control for each wind speed increases the output power in variable speed wind turbine system. A fuzzy logic controller is used to implement MPPT control[5]. The heuristic way of searching the maximum could be based on a rule based as "Fuzzy Meta rule", given as "If the last change in the input variable (X) has caused the output variable (Y) to increase, keep moving the input variable in the same direction: if it has caused the output variable to drop, move it in the opposite direction." In Fuzzy logic controller, there are two inputs ΔP_0 and $L\Delta w_r^*$ and one output Δw_r^*. In the implementation of fuzzy control, the input variables are fuzzified, the valid control rules are evaluated and combined and finally the output is defuzzified to convert to the crispy value[6]. The rule matrix for the fuzzy logic control is

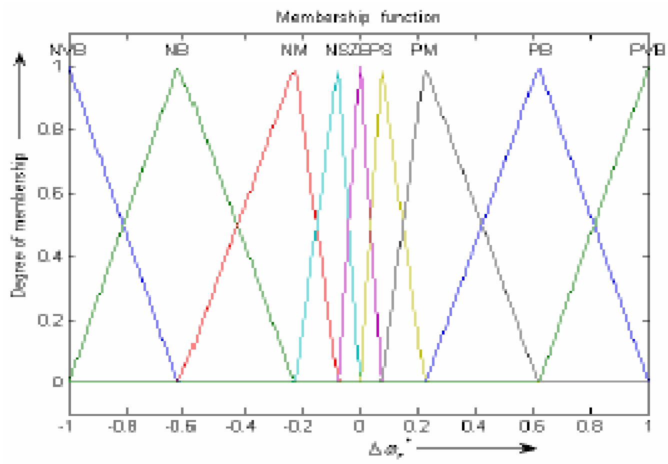
$L\Delta\omega_r^*$ / ΔP_0	P	ZE	N
NVB	NVB	NVB	PVB
NB	NB	NVB	PB
NM	NM	NB	PM
NS	NS	NM	PS
ZE	ZE	ZE	ZE
PS	PS	PM	NS
PM	PM	PB	NM
PB	PB	PVB	NB
PVB	PVB	PVB	NVB

Table 1: Rule matrix for FLC-1

A typical rule can be read as follows:
"If ΔP_0 is PM (Positive Medium) AND $L\Delta w_r^*$ is P (Positive), THEN Δw_r^* is PM (Positive Medium)."



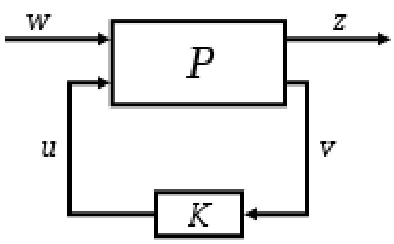




The fuzzy algorithms are universal and adaptive and can be applied in other systems.

H_∞ Controller Problem formulation:

Initially, the process has to be represented according to the following standard configuration



The plant P has two inputs W, that includes reference signal and disturbances, and the manipulated variables u. there are two outputs, the error signals z that we want to minimize, and the measured variables v, that we use to control the system. V is used in K to calculate the manipulated variable u. In formulae, the system is[8]

$$\begin{bmatrix} z \\ v \end{bmatrix} = P(s)\begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix}\begin{bmatrix} w \\ u \end{bmatrix} \quad (8)$$

$$u = K(s)u \quad (9)$$

It is therefore possible to express the dependency of z on w as:

$$z = F_l(P,K)w \quad (10)$$

$$F_l(P,K) = P_{11} + P_{12}K\left(I - P_{22}K\right)^{-1}P_{21} \quad (11)$$

Therefore, the objective of H_∞ control design is to find a controller K such that $F_l(P,K)$ is minimized. The infinity norm of the transfer function matrix $F_l(P,K)$ is defined as

$$\|F_l(P,K)\|_\infty = \gamma \quad (12)$$

Where γ is the maximum singular value of the matrix $F_l(P,K)$ *(jw).*

H_∞ control implementation:

1. Generator side controller:

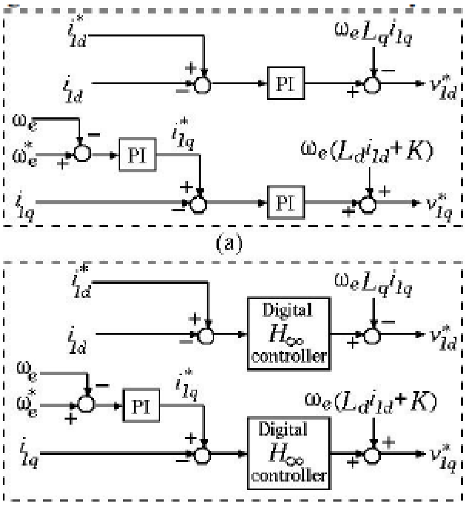


Figure (a): Generator side converter

The generator side converter controls the rotational speed of the induction generator. The rotational speed error is used as the input of the speed(PI) controller from which q-axis stator current command is produced i_{1q}^*. The errors between the dq-axis current commands and the actual dq-axis currents are used as inputs to the current controllers which produces the dq-axis voltage commands V_{1d}^* and V_{1q}^*[9].

Rewriting the generator equations we obtain the following equations

$$\frac{d}{dt}i_{1d} = \frac{1}{L_d}(-R_a i_{1d} + w_e L_q i_{1q} + v_{1d}) \quad (13)$$

$$\frac{d}{dt}i_{1q} = \frac{1}{L_q}(-R_a i_{1q} - w_e(L_d i_{1d} + K) + v_{1q}) \quad (14)$$

$$\frac{d}{dt}\psi_d = (-R_a i_{1d} + w_e \psi_q + v_{1d}) \quad (15)$$

$$\frac{d}{dt}\psi_q = (-R_a i_{1q} - w_e \psi_d + v_{1q}) \quad (16) \quad \psi_q = L_q i_{1q}$$

Expressing the above equations in the matrix form, the plant matrix is given below

$$\begin{bmatrix} \dot{i}_{1d} \\ \dot{i}_{1q} \\ \dot{\psi}_d \\ \dot{\psi}_q \end{bmatrix} = \begin{bmatrix} -(R_a/L_d) & 0 & 0 & 0 \\ 0 & -(R_a/L_q) & 0 & 0 \\ -R_a & 0 & 0 & w_e \\ 0 & -R_a & -w_e & 0 \end{bmatrix}\begin{bmatrix} i_{1d} \\ i_{1q} \\ \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} 0 & 0 & (1/L_d) & 0 \\ 0 & 0 & 0 & -(1/L_q) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{1d}^* \\ i_{1q}^* \\ d_1 \\ d_2 \end{bmatrix} + \begin{bmatrix} (1/L_d) & 0 \\ 0 & (1/L_q) \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{1d} \\ v_{1q} \end{bmatrix} \quad (17)$$

The error signal 'z' is as follows

$$z = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}\begin{bmatrix} \dot{i}_{1d} \\ \dot{i}_{1q} \\ \dot{\psi}_d \\ \dot{\psi}_q \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{1d}^* \\ i_{1q}^* \\ d_1 \\ d_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{1d} \\ v_{1q} \end{bmatrix}$$

. ... (18)

The output signal 'y' is

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{i}_{1d} \\ \dot{i}_{1q} \\ \dot{\psi}_d \\ \dot{\psi}_q \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{1d}^* \\ i_{1q}^* \\ d_1 \\ d_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} v_{1d} \\ v_{1q} \end{bmatrix}$$

... (19)

$$d_1 = w_e L_q i_{1q}$$

$$d_2 = w_e(L_d i_{1d} + K)$$

The values d_1 and d_2 are considered as disturbances

2. Grid side Inverter:

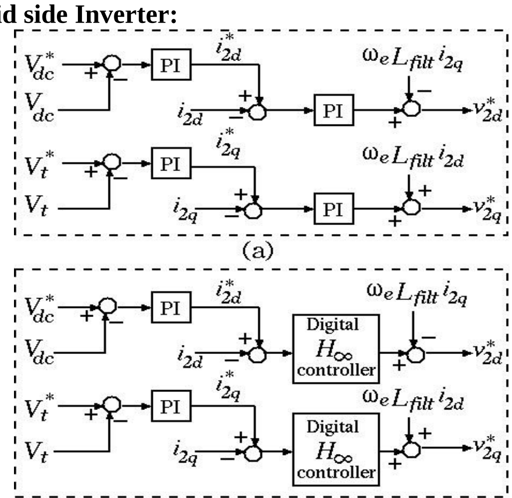


Figure (b): Grid side converter

In order to maintain the DC bus voltage V_{dc} and the grid voltage V_t constant we use grid-side inverter. The d-axis current can control the DC bus voltage and to control the grid voltage we use q-axis current as shown in figure.
From the following equations we can develop the grid side inverter state space matrix.

$$\frac{L_f}{w_e}\frac{d}{dt}i_{2d} = v_{2d} - R_f i_{2d} + w_e L_f i_{2q} \quad (20)$$

$$\frac{L_f}{w_e}\frac{d}{dt}i_{2q} = v_{2q} - R_f i_{2q} + w_e L_f i_{2d} \quad (21)$$

$$\begin{bmatrix} \dot{i}_{2d} \\ \dot{i}_{2q} \end{bmatrix} = \begin{bmatrix} -(R_f w_b / L_f) & 0 \\ 0 & -(R_f w_b / L_f) \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix}$$

$$+\begin{bmatrix} 0 & 0 & w_b / L_f & 0 \\ 0 & 0 & 0 & w_b / L_f \end{bmatrix} \begin{bmatrix} i^*_{2d} \\ i^*_{2q} \\ d_3 \\ d_4 \end{bmatrix} + \begin{bmatrix} w_b / L_f & 0 \\ 0 & w_b / L_f \end{bmatrix} \begin{bmatrix} v_{2d} \\ v_{2q} \end{bmatrix} \quad \ldots (22)$$

The error signal 'z' is given as

$$z = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i^*_{2d} \\ i^*_{2q} \\ d_3 \\ d_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{2d} \\ v_{2q} \end{bmatrix} \quad \ldots (23)$$

The output 'y' is

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i^*_{2d} \\ i^*_{2q} \\ d_3 \\ d_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{2d} \\ v_{2q} \end{bmatrix}. \quad \ldots (24)$$

$$d_3 = w_e L_f i_{2q}$$

$$d_4 = w_e L_f i_{2d}$$

d_3,d_4 are considered as disturbances.

System Parameters

Blade radius	R_o=39m
Air Density	ρ=1.205kg/m^2
Stator Resistance	0.02Ω
Rotor Resistance	0.015Ω
Stator Reactance	0.18Ω
Rotor Reactance	0.15Ω
Mutual Inductance	3Ω

3. Simulation Results

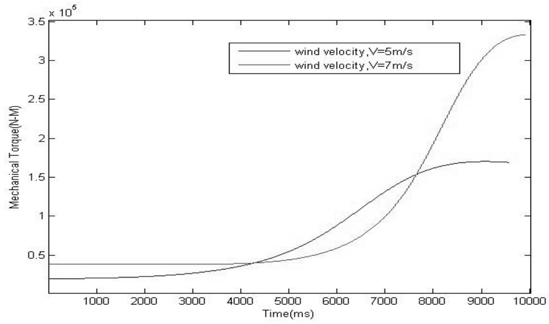


Figure (a): Torque output of the wind turbine for different wind speeds.

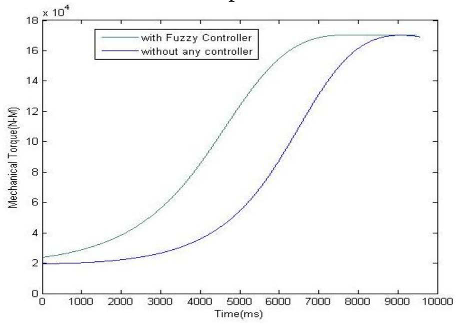


Figure (b): Torque output of wind turbine with and without Fuzzy logic controller

Fig:(a) shows the mechanical torque output of wind turbine for two different speeds i.e., at w=5m/s and w=7m/s. From Fig:(b) we can see that when Fuzzy logic controller is connected to the system, the constant mechanical torque is obtained at a faster rate when the machine is loaded for a particular wind speed, w=5m/s which is used as input to the induction generator.

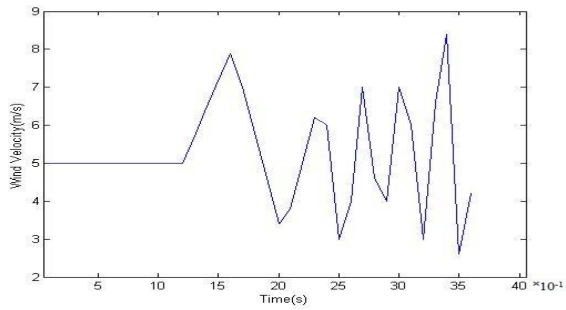


Figure (c): Different wind velocities at different times

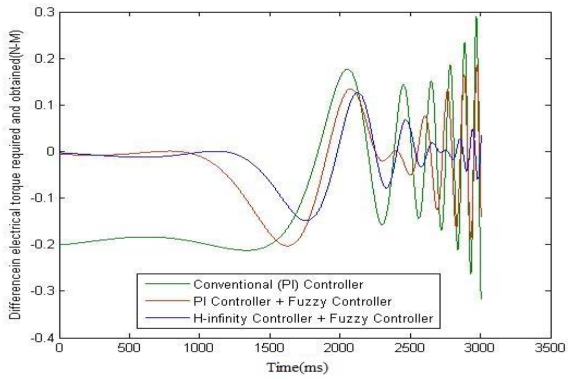


Figure (d): Difference between electrical torque generated and the required value of induction generator with controllers.

The following are the graphs corresponding to the outputs of generator side controller and grid side inverter during changes in the wind velocity. We can observe that during the time between 2s to 3s the H-infinity controller works efficiently.

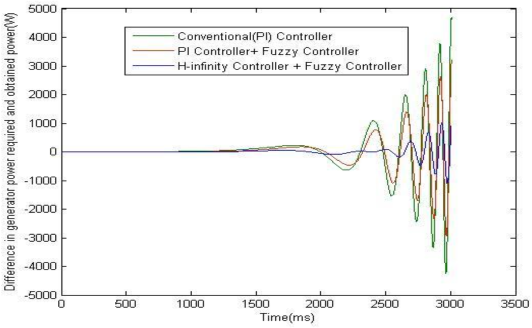


Figure (e): Difference between electrical power output and the required value of induction generator with controllers.

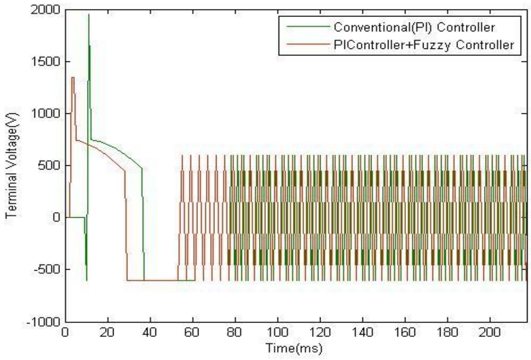


Figure (f): Terminal Voltage at the Grid side Controller with PI (Conventional) and Fuzzy Controller.

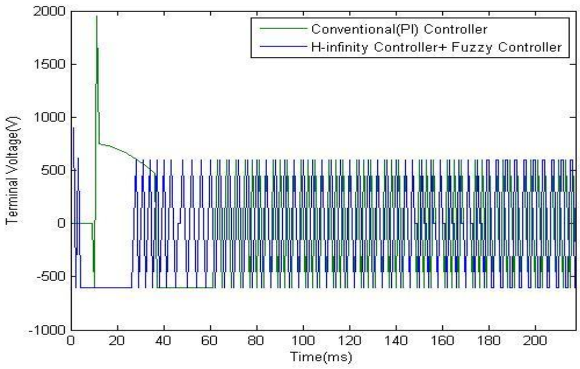


Figure (g): Terminal Voltage at the Grid side converter with PI and H-infinity controller.

From Fig:(f) and Fig:(g) we can observe that the disturbances in the terminal voltage are reduced with H-infinity controller when compared to PI controller.

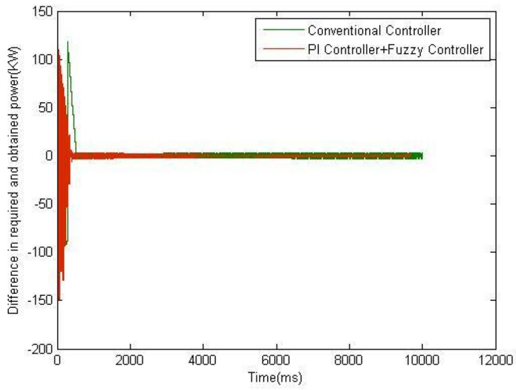


Figure (h): Output power at the grid side converter with PI (Conventional) Controller.

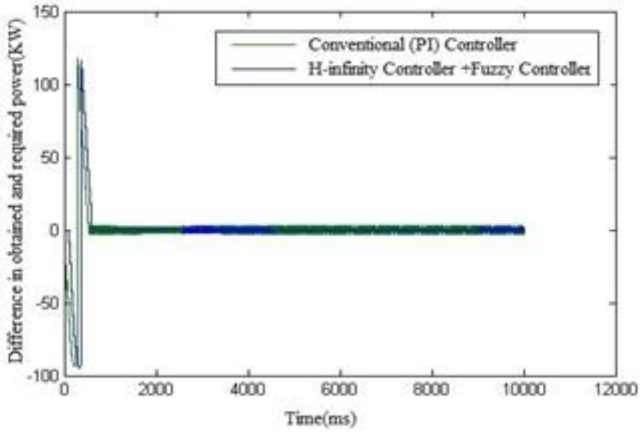


Figure I: Output power at the grid side converter with H-infinity controller

From Fig: (h) and Fig:(i) shows the difference between the generated power and the required power. We can observe that the output power is stable with the proposed method when compared to the PI controller method.

4. Conclusion

In this paper, a fuzzy logic controller was studied and analyzed such that maximum power is generated for a particular wind speed and a robust control method has been presented in order to reduce the fluctuations occurred due to high wind turbulence in the wind energy conversion systems i.e., to reduce the mechanical stress on the generator, improve the stability in the output power delivered to the load.

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