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Pitch Angle Control of Wind Turbine Using Adaptive Fuzzy-PID Controller

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Abstract

The control strategy for wind turbine is very important an equipage that diverts the kinetic energy of the wind to electrical power. The rotation speed control of wind turbine is necessary for highest degree energy capture and pitch angle advanced control planning depending on traditional PID controller and fuzzy logic adaptive PID controller. Input variables of fuzzy logic controller (FLC) are selected to give smooth control of pitch angle which in turns will adjust the speed of wind turbine at reference level. A very small adaptation in pitch angle has influence on the ancestry of obtainable energy, torque and output power of the grid. A modeling of self-excitation induction generator (SEIG) 1KW wind turbine is achieved by Matlab/Simulink package and all modeling equations are studied. The effect of pitch angle on speed of the wind turbine is studied and a comparison between traditional PID controller and fuzzy logic adaptive PID controller was made.

Keywords: Small wind turbine, PID controller, fuzzy logic controller, wind linearization parameters.

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1. Introduction

The renewable energy sources are needed in order to overcome the problem of increasing the energy demand. The global energy demand may be arrived to triple times in 2050. Renewable energy coverage around (15% to 20%) of total energy demand in the word [1]. Under changing operating conditions, wind turbine equipped with (SEIG) has on offer impressive efficiency in addition to the rugged construction. Induction machines are relatively required little maintenance and minimum care. The properties of this generator have the capability to bear the exceeded speed which make it occasion for wind turbine enforcement [2]. The advanced applications that using with power electronics make it practicable to adjustment the SEIG in different methods, which lead to use SEIG in small wind turbine [3]. The capacity of wind turbine to deliver power is depending on the speed and direction variations. Small scale wind turbine has some form of control strategy in order to enhancement their power production and longevity.

The main objects of a control unit in the wind turbine are:

- In habit damage of wind turbine.
- In habit damage to the load.
- Optimum power production.

The operation of wind turbine control unit variable along the speed range of the wind turbine. A typical curve represents

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power -speed is shown in figure 1. Zone I called low –wind speed area/partial-load area (energy capture maximization). Zone II illustrate the transition between low wind speed area and high wind speed area. Zone III represents high speed area/full-load area.

A pitch angle control method based fuzzy logic under various wind speed conditions is represented [4].

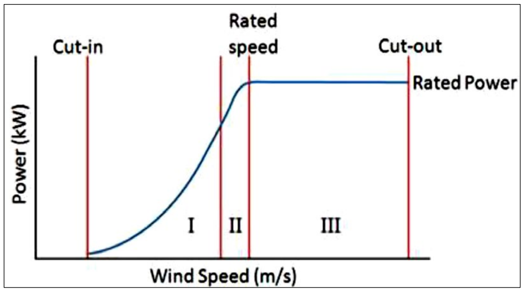


Figure 1. Power vs wind speed curve

Wind turbine is considered within dynamic system including turbine, power electronics, generator, transformer and grid [5].

2. Wind Turbine

Wind turbine is divided according to the type into three scales: small scale (1 Watts to 5KW), medium scale (5KW to 5MW) and large scale (5MW to 50MW) [6]. In this work, a small scale is chosen as shown in figure 2.

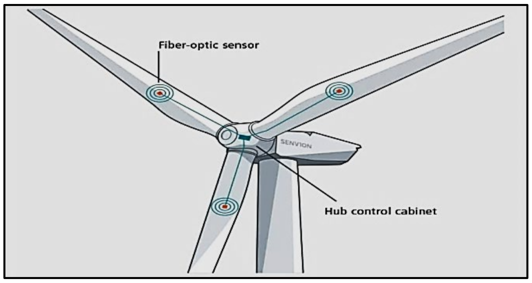


Figure 2. Wind turbine unit.

3. Wind Turbine Characteristics

The mechanical equations of wind turbine are given below:

$$P_m = \frac{1}{2}\,\rho\, A\, C_p(\lambda,\beta)\, v^3 \qquad (1)$$

where,
P_m : mechanical power (W).
ρ : air density (kg/m^3).
A: swept area (m^2).
C_P : power coefficient.
β: blades pitch angle (degree).
v: wind speed (m/s)
λ: tip speed ratio

Tip speed ratio is given as:

$$\lambda = \frac{R\omega_t}{v} \qquad (2)$$

where,
ω_t : rotor speed of turbine (rad/s).
R: blade radius (m)

Power coefficient is an indication to the turbine efficiency which obtained from converting the kinetic energy to the mechanical energy [7]. Equation 3 represents the power coefficient variable:

$$C_P(\lambda, \beta) = C1(C2K - C3\beta - C4\beta^X - C5)\exp(-C6K) \qquad (3)$$

where,

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

The values of C1 to C6 are 0.5, 0.4, 0, 5, 21 respectively and x = 0.

Figure 3 illustrates the relevance between tip speed ratio and power coefficient at different wind speeds [8].

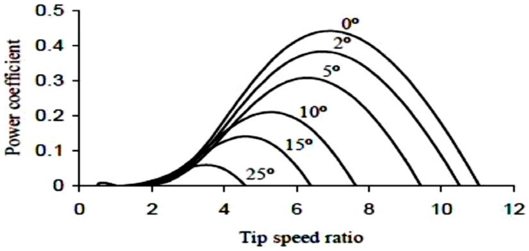


Figure 3. Power coefficient vs tip speed ratio at variable wind speed.

The upper limit of power coefficient value is approximately 0.59. According to Beta limit, the torque obtainable from the wind turbine can be given as [9]:

$$T = \tfrac{1}{2}\,\rho\, A R C_T\, v^2 \qquad (4)$$

$$C_T = \frac{C_P(\lambda,\beta)}{\lambda}$$

where,
C_T : torque coefficient.
then,

$$T = \tfrac{1}{2}\frac{C_P(\lambda,\beta)}{\lambda}\,\rho A R v^2 \qquad (5)$$

$C_P(\lambda,\beta)$ It contained the exponential term that mentioned above therefore, this term is reparation by sine term as mathematical convert terms list and obtained on the equation below:

$$T = 0.5\rho A\left[(0.44 - 0.0167\beta)\sin\left[\frac{\pi\left(\frac{\omega_t R}{\upsilon}\right)}{15-0.3\beta}\right] - 0.00184\left(\frac{\omega_t\ R}{\upsilon} - 3\right)\beta\right]\upsilon^2 \qquad (6)$$

4. Modeling of Wind Turbine

The fundamental equation that describe the dynamic behavior of the wind turbine is given in equation (6).
ω_t : is referred to the rotor speed where t is abbreviated to the turbine word

$$J_t\dot{\omega_t} = T\omega - T_m \qquad (7)$$

where,
J_t: moment of inertia (Constant value).
T_m: mechanical torque.

This model is called one-mass model, due to the liberal drive train is admired as a single mass. This model is much unadorned in the simulation procedures. The system of wind turbine is highly non-liner one, when using PID controller [10]. The non-linear behavior of the wind turbine should be work around a specific operating point in order to remain within a linearization area .The linearized equation is given as:

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

where,
γ, ξ.and δ represent the linearization parameters.

$$\gamma = \frac{\partial T_\omega}{\partial\,\omega_t}|op$$

$$\xi = \frac{\partial T_\omega}{\partial V_\omega}|op$$

$$\delta = \frac{\partial T_\omega}{\partial\beta}|op$$

Δω, ΔV and Δβ represent the deviation from the selected operating point. By taking Laplace transform of equation (8):

$$J_t S\Delta\omega_t = \gamma\Delta\,\omega_t + \xi\Delta\ V_\omega\quad(S) + \delta\Delta\beta(S) \qquad (9)$$

Also, the change of turbine rotor shaft is:

$$\Delta\omega_t = \left[\frac{\xi}{Jt}\Delta V_\omega(s) + \frac{\delta}{Jt}\Delta\beta(s)\right]\frac{1}{S-D} \qquad (10)$$

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

Figure 4 represents the block diagram of linearization model.

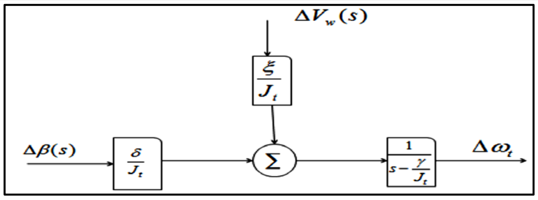


Figure 4. Block diagram of a linearized unit.

5. Proposal Algorithm

Figure 5 represents an algorithm pitch angle control of a wind turbine based PID and Fuzzy tuning PID controller. The proposed fuzzy logic incorporated PID controller is adopted in order to keep on actual speed nearly the reference speed [11].

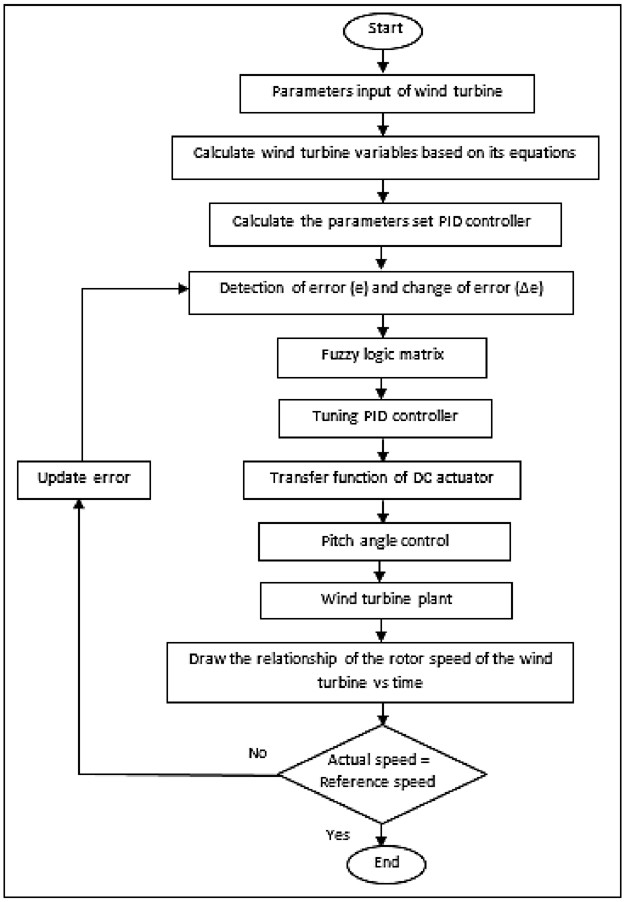


Figure 5. Flow chart of wind turbine based adaptive fuzzy-PID controller

6. PID Controller

The rotor speed of wind turbine can be controlled by PID controller, Such PID controller is given in figure 6.

where,
Δωt(s): *is* the variance between actual rotor speed and reference rotor speed.

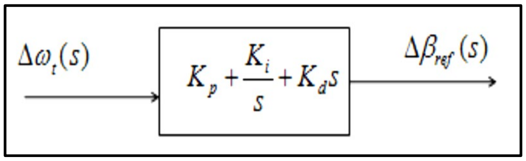


Figure 6. Block diagram of PID controller.

The consummate control system is illustrated in figure 7.

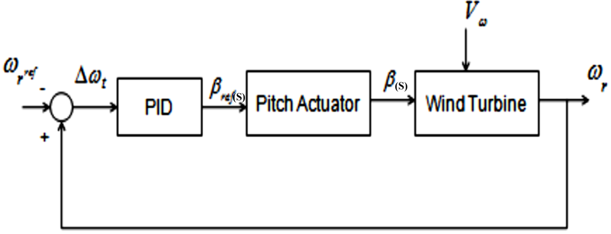


Figure 7. Block diagram of control system.

7. Pitch Actuator

In a small-scale wind turbine, the control strategy that used with pitch angle is utilize to limit the output power of the turbine. The rotation of the blades along its horizontal axes is adjusted by a pitch actuator [12]. The electromechanical and hydraulic devices are utilized as a pitch actuators. The pitch servo modeling equation is given as:

$$\frac{d\beta}{dt} = -\frac{1}{\tau_c}\beta + \frac{1}{\tau_c}\beta_{ref} \qquad (11)$$

where,

τ_c: is the time constant.

The range of pitch actuator is (0.2s–0.25s) by taking Laplace transformation of equation (11) would yield:

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

$$\beta(s) = \frac{1}{1+\tau_c s}\beta_{ref}(s) \qquad (12)$$

Equation (12) can be expressed as a block diagram depicted in figure 8.

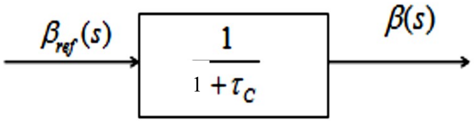


Figure 8. Pitch actuator gain.

The output variable $\beta_{ref}(s)$ of PID controller in Fig.7 is similar to that in Fig.8, but in Fig.8, $\beta_{ref}(s)$ represents the input of the actuator block $\left(\frac{1}{1+\tau_c s}\right)$ after PID controller unit.

8. Fuzzy Logic Controller (FLC)

Rules based FLC are the best way for blade pitch angle control. Fuzzy logic is a very good selection with the system has parameters fluctuated from its expected value. FLC is considered the modern control strategy with wind turbine applications [13]. The structure of FLC is shown in figure 9.

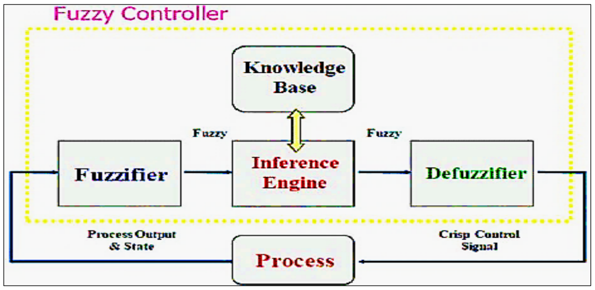


Figure 9. Block diagram of FLC.

9. Wind turbine based FLC

Figure 10 represents the control strategy for pitch angle of the wind turbine blades based FLC. Fuzzy logic is the best selection in this applications because it has linguistic variables rather than the numeric variables [14].

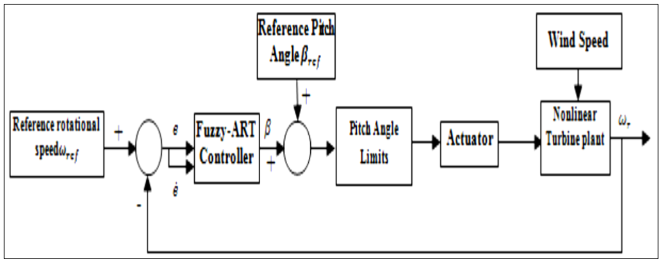


Figure 10. Structure of proposed controller

10. Modeling of Pitch Angle Control at a Wind Turbine

10.1. Modeling of wind turbine system based PID controller.

The circuit diagram of wind turbine based PID controller is given in figure 11. This modeling is designed in order to control the pitch angle depending on traditional controller (PID-type).

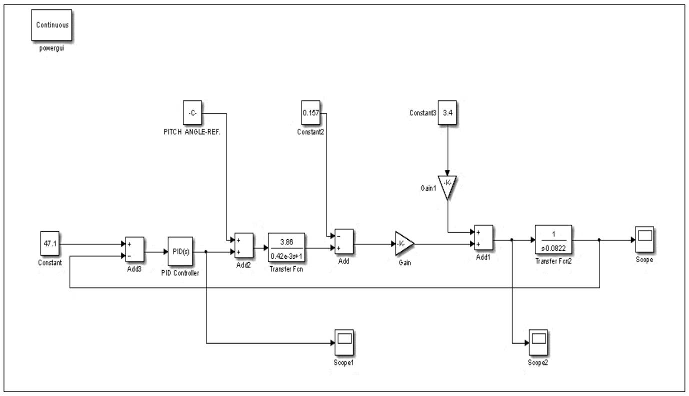
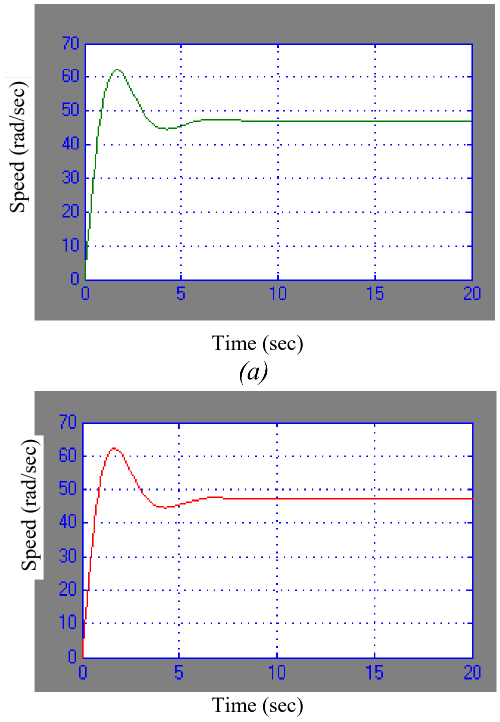


Figure 11. Pitch angle control of wind turbine based PID controller.

The relationship between wind turbine speed versus time is given in figure 12. Below.



(a)

(b)

Figure 12. Wind turbine speed response vs time.
(a) *at pich angle* 15^o
(b) *at pitch angle* 30^o

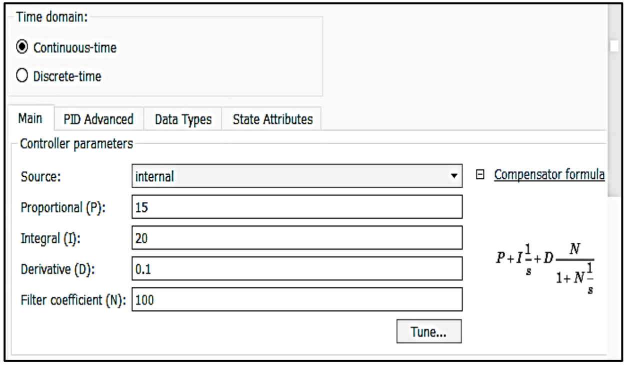
The dynamic behaviuor of rotor speed based PID controller is illustrated in table 1.

Table 1. Dynamic behaviour of rotor speed based PID controller.

P.O.S (%)	Max. time (sec)	Rise time (Sec)	Settling time (sec)
32.02	1.687	1.02	5.245

The PID-controller parameters is given in table 2.

Table 2. PID controller parameters



Time domain:
● Continuous-time
○ Discrete-time

Controller parameters
Source: internal
Proportional (P): 15
Integral (I): 20
Derivative (D): 0.1
Filter coefficient (N): 100

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

10.2. Modeling of wind turbine system based FLC.

The modeling circuit of control system based smart fuzzy logic adaptive PID controller for pitch angle control is given in figure 13.

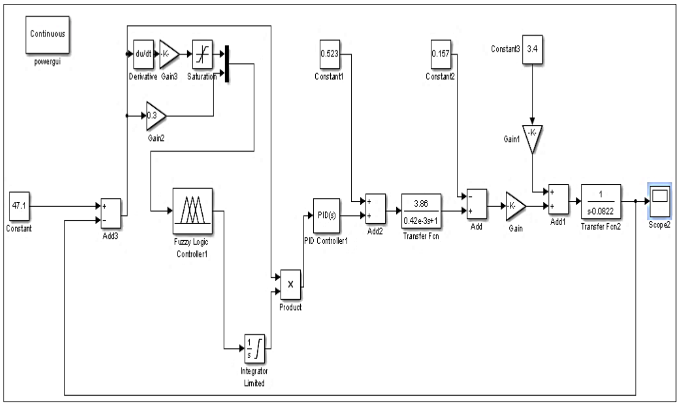
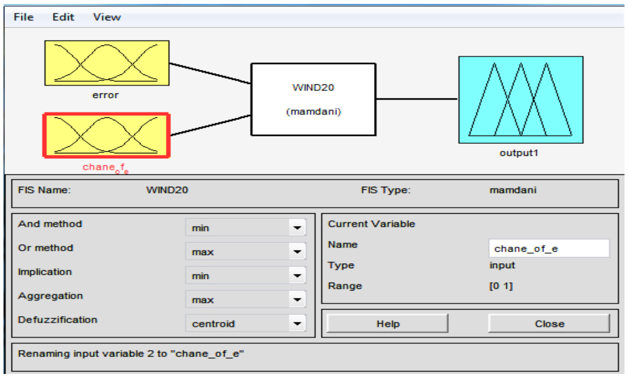


Figure 13. Pitch angle control of wind turbine based fuzzy controller.

11. FLC Construction

Fuzzy logic can be represented by the manner of the human language. A FLC diverts a linguistic variables to automatic control strategy. Fuzzy logic rules is constructed by knowledge data base [15]. Set error (e) and change of error (Δe) to be the input variables of the FLC and output 1 represents the output variable of this controller as show in figure 14.



FIS Name: WIND20
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: chane_of_e
Type: input
Range: [0 1]
Renaming input variable 2 to "chane_of_e"

Figure 14. Internal construction of FLC.

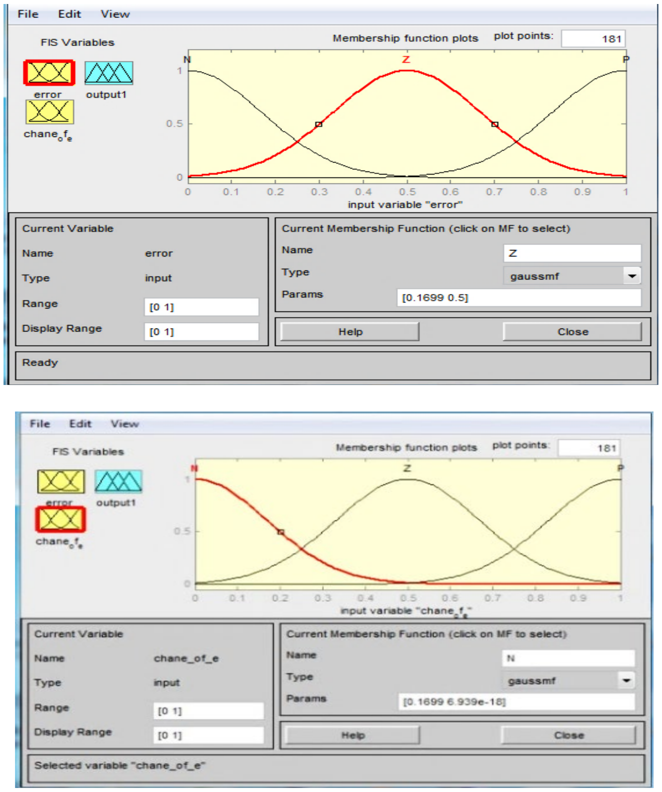
The linguistic variables are:
NB: negative big
NS: negative small
Z: zero
PS: positive small
PB: positive big

The dimensions of fuzzy rules matrix are [5X5] which shown in table 3.

Table 3. Rules of FLC

e/Δe	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NS	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PS	PB
PB	Z	PS	PB	PB	PB

The input variables of FLC is selected as gauss waveform in order to coverage all points in the domains as shown in figure 15.



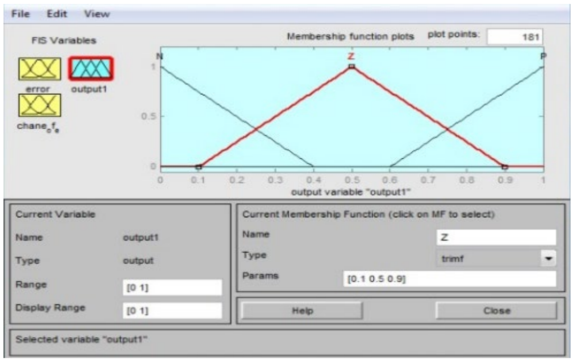
Current Variable
Name: error
Type: input
Range: [0 1]
Display Range: [0 1]
Current Membership Function (click on MF to select)
Name: Z
Type: gaussmf
Params: [0.1699 0.5]
Ready

Current Variable
Name: chane_of_e
Type: input
Range: [0 1]
Display Range: [0 1]
Current Membership Function (click on MF to select)
Name: N
Type: gaussmf
Params: [0.1699 6.939e-18]
Selected variable "chane_of_e"

(a)
(b)

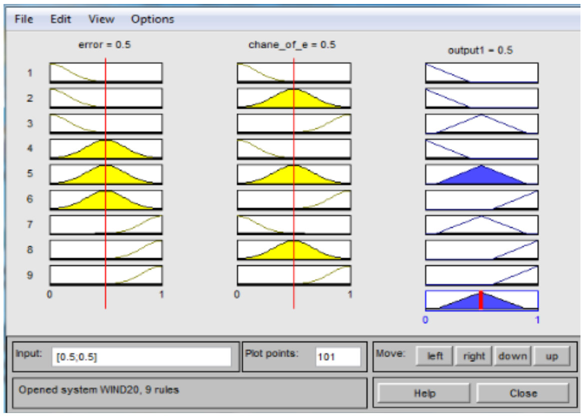
Figure 15. Input variables of FLC
(a) error (e)
(b) change of error (Δe)

The output variable is selected as trams waveform in order to keep the output signal lies within linear region as shown in figure16. The rules which applied on FLC can be viewed as given in figure 17.



Current Variable
Name: output1
Type: output
Range: [0 1]
Display Range: [0 1]
Current Membership Function (click on MF to select)
Name: Z
Type: trimf
Params: [0.1 0.5 0.9]
Selected variable "output1"

Figure 16. Output variable of FLC



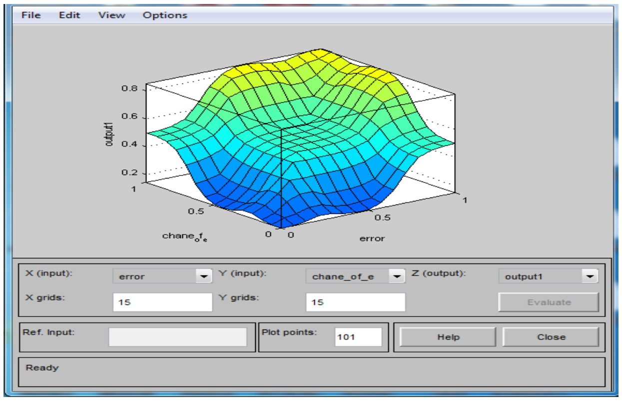
Input: [0.5;0.5]

Plot points: 101

Opened system WIND20, 9 rules

Figure 17. Wave shapes of fuzzy logic rules

The 3D – surface of the above rules can be seen in figure 18.



X (input): error

Y (input): chane_of_e

Z (output): output1

X grids: 15

Y grids: 15

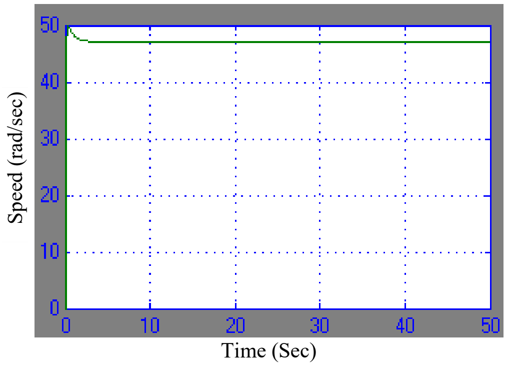
Ref. Input:

Plot points: 101

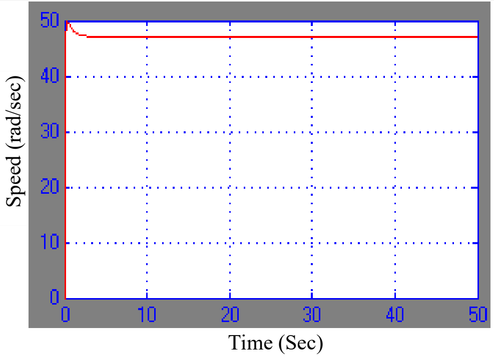
Ready

Figure 18. 3D-Surface of FLC.

The relationship between rotor speed response vs time based on fuzzy tuning PID parameters is given in figure 19.



(a)



(b)

Figure 19. Speed response of wind turbine based adaptive fuzzy-PID controller.
(a) at pich angle 15^o
(b) at pitch angle 30^o

The dynamic behavior of wind turbine speed based fuzzy controller is illustrated in table 5.

Table 5. Dynamic behaviuor of wind turbine speed based fuzzy-tuning PID controller.

P.O.S (%)	Max. time (sec)	Rise time (Sec)	Settling time (sec)
4.9	0.438	0.211	0.891

12. Conclusions

Adaptive fuzzy-PID controller gives smoothly motion for pitch angle of the turbine blades as compared with traditional PID method. Fuzzy tuning PID parameters gives an enhancement in the speed response of the wind turbine as compared with using PID controller only. Also, this intelligent method is suppressed the oscillation. PID controller emits to give lower rise time and delay time but with overshoot equal to 32.02% which lead to defect in the system performance. Fuzzy tuning PID controller made an enhancement in the transient response parameters as compared with conventional PID controller where, the reading ratio as a percentage for P.O.S, max time, rise time and settling time was 84.69%, 74.03%, 79.3% and 83% when using adaptive fuzzy-PID controller.

The intelligent techniques are better than that of traditional control method where, these techniques are used to attain the control process of pitch angle and to ensure the stabilization to the wind turbine output power. Pitch angle control based fuzzy Turing PID parameters improved the rendition of the system.

Appendix: Parameters of wind turbine and SEIG

Table 4. Parameters of wind turbine and SEIG

Wind turbine		SEIG	
Parameters	Value	Parameters	Value
Rated output power	1000W	Rated power	1kw
Rated speed	450 rpm	Rated frequency	50Hz
Equator radius	1 m	Rated voltage	400V
Height	4 m	Rated current	3.8A
Swept area	4 m^2	No. of poles	2
Air density	1.25 kg/m^2	R_s	3.62Ω
Cut-in speed	3 m/s	$R_{\acute{r}}$	5.6Ω
Cut-out speed	15 m/s	$L1s$	9.23mH
		$L\acute{1}\mathrm{r}$	9.23mH

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