



Speed Control of Wind Turbine through Pitch Control using Different Control Techniques

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A B S T R A C T

Pitch control is one of the major aspects of wind turbine control, particularly over high wind speed and oscillations. General Electric (GE) model of wind turbine is practically compatible with the structure of the wind turbines. It has been proved that simulation results using this model are closer to the actual case, compared to other available models. Therefore, in this paper the GE model is used to evaluate the effectiveness of three different controllers including Fuzzy controller, self-organized Fuzzy controller (SOFC) and PI controller in pitch control of the wind turbine. Afterward, the results of the controller applications as well as the no controller case in the pitch control are compared. The results show a better performance of SOFC in damping the oscillations and overshoot of the wind turbine shaft speed. Finally, electrical power limit and converter cost, the economic analysis of pitch controller application are carried out. It is shown that the application of the SOFC results are around \$142,646 saving.

1. INTRODUCTION

More attention has been paid to conversion of wind energy into electrical energy in the last two decades; therefore, this industry needs development of efficient generation equipment [1]. The efficiency of the equipment may be improved by controlling the rotor speed. Rotor distortions and oscillations lead to a higher cost of the system. The aim of pitch control is to achieve an optimal angle of wind incident to the pitch. When the wind speed is higher than the permissible level, pitch rotates in an appropriate direction with respect to the wind speed in order to decrease the wind effect [2]. Pitch control prevents imposing the wind power that is higher than the tolerability of the equipments. By controlling the pitch angle in high wind speeds, aerodynamic load and generated power by the rotor are adjusted. This also minimizes the wind turbine mechanical loads fatigue [3].

2. LITERATURE SURVERY

In modern power control techniques, power is kept at the rated value by controlling pitch angle β . Angle β is defined as the angle between the pitch rope and its rotating shaft. The normal rate of the pitch angle variation is $5^\circ/s$ and it can increase to $10^\circ/s$ in the emergency cases. When the wind speed is high, the pitch torque is asymmetrical and to reduce this asymmetry in the modern turbines an attempt has been made. This system has many advantages and thanks to the power electronics converters for making it possible to introduce this system to the industry. Simultaneous application of this system and pitch angle control provide two-degree of freedom for power control in the system which is considered as an advantage. The pitch angle variation time constant versus speed variation may be longer. At this end, to decrease the noise comes from the pitch variations, turbine wheel speed is reduced [4]. Fig. 1 shows the advantages of pitch angle control.

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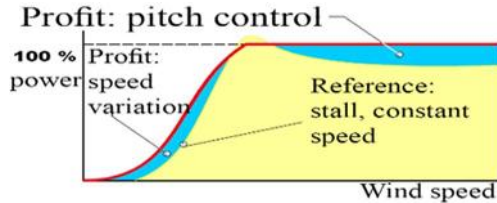


Figure 1. Advantages of pitch angle control [4].

Variable speed wind generators have some advantages [5]. It introduces a saddle type model generator and pitch angle control. When the wind speed is low or medium, generator and power converter fix the rotor speed at its pre-defined optimal value; therefore, the generator captures the maximum energy of the wind.

In high speed wind, the wind turbine absorbs aerodynamic power from the wind and therefore controls the pitch angle and generator load. It is noted that the generator load control technique gets in to some problems such as raising the stator current over its permissible limit over a wide range of wind speeds. Precise available models of MW power wind turbine with pitch angle control have been given in [6, 7]. These models are based on a set of non-linear equations showing the relationships between the pitch angles, rate of angle variations and power factor. In addition, a PI controller is employed to control the pitch angle in order to limit the wind turbine output at high speed wind. Further work has been reported in [8], which is efficient in power system network for dynamic analysis of different variable speed generators. In this model, the wind turbine efficiency drops over high speeds wind by controlling the pitch angle. An energy wasting resistance on DC link can be used to control the pitch angle [9].

To decrease the amount of the wasting energy in the resistance, simultaneous application of pitch angle controlling and inserting the resistance has been recommended. Pitch angle control has slow response. The rate of pitch angles in urgent case is considered 10° to 20° . If after the fault detection with one cycle delay, the voltage dip is quickly diagnosed and reference of the pitch angle control system is put equal to the peak value of $\beta_{\max}=30^\circ$, the maximum DC link voltage will be 1.9 pu for pitch angle rate of $10^\circ/s$. If the higher rate of $20^\circ/s$ is considered, the DC link voltage will be 1.6 pu. It is seen that even for $20^\circ/s$ rate, the capacitor voltage will be unacceptable. So, the use of pitch control angle to balance the power at LVRT conditions will not be enough. A combination of a DC braking resistance, turbine pitch angle and converters makes it possible to protect the power electronics devices and mechanical tools; this allows to keep the turbine connected to the network for a long time.

In this paper the GE wind turbine model is reviewed and simulation results are obtained by applying different

controllers. The results of application of Fuzzy controller, SOFC and PI controllers are presented and compared to the no controller case with the pitch control process. To show the efficiency and effectiveness of the proposed controllers, economic saving of their applications in the wind turbine is discussed.

3. WIND TURBINE MODEL AND CONTROLLERS APPLICATION

To study the wind turbine response to the applied pitch control, simulation results using Fuzzy SOFC and PI controller are obtained and compared. The controllers are applied to the general model of GE wind turbine. In addition to investigate the results of wind turbine speed control, a case with a proportional controller ($k_p=1$) is proposed. Because of simplification, this is called "no controller" case. Speed error (W_{err}) is the input of the turbine pitch controller. The output of the controller is the command to the actuator (for example hydraulic) of the wind turbine which is simulated in the form $1/(0.01s+1)$ and moves the pitch angle fixed at the commanded point. The pitch varies considering an appropriate pitch angles against wind incident surface. This leads to the variation of the force and applied wind speed with the pitch. Consequently, shaft speed of wind turbine tends to the base speed. Fig. 2 shows the simulation block diagram of GE model wind turbine in which pitch controller is a proportional controller with a $k_p=1$ (no controller). Since it has no impact on the process, it has not been shown in Fig. 2.

The pitch limiter in Fig. 2 is used to limit changes in the pitch angle to $\pm 10^\circ/s$ [10]. The torque controller could be described by $(3s+0.6)/s$. The limiters separate the positive values from input values. The filter functions are $1/(0.01s+1)$, $1/(0.05s+1)$ and $1/(0.02s+1)$. The wind turbine model in Fig. 2 consists of the wind power and wind speed sub-models [11]. The mechanical power applied to the turbine shaft depends on the wind speed, pitch angle and shaft speed. It is noted that severe variations of the wind power are important. Wind power model function used to estimate the wind turbine mechanical power is as follows:

$$P = \frac{\rho A_r V_w^3}{2} C_p(\lambda, \theta) \quad (1)$$

where P is the extracted mechanical power from the wind, ρ is the air density in kg/m^3 , A_r is the swept area of the rotor pitch in m^2 , V_w is the wind speed in m/s , C_p is the power factor, depending on λ and θ (pitch angle). λ is the ratio of rotor pitch tip and wind speed as follows:

$$\lambda = K_b(\omega / V_w) \quad (2)$$

where ω is the rotor speed and K_b is a constant.

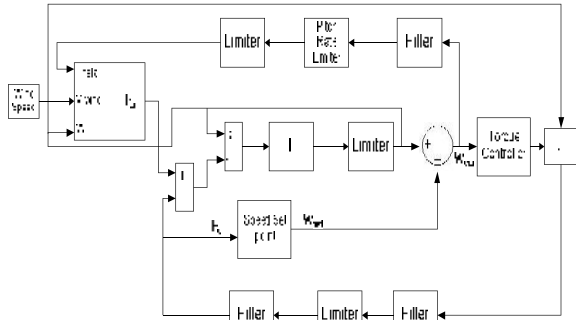


Figure 2. Simulation block diagram of GE model wind turbine with no pitch controller

Generally, a set of C_p versus λ curves (Fig. 3) for different values of θ is given as follows:

$$C_p(\lambda, \theta) = \sum_{i=0}^4 \sum_{j=0}^4 \alpha_{i,j} \theta^i \lambda^j \quad (3)$$

Fig. 4a shows a simulation block diagram with a PI controller for pitch control. Fig. 4b shows the block diagram for pitch control using a Fuzzy controller. This controller generates an appropriate signal to apply to the hydraulic system based on the error and rotor speed error changes using Fuzzy deduction. Fig. 4c shows the block diagram for the pitch control using SOFC

4. WIND TURBINE PITCH CONTROLLERS

In the GE model of wind turbine, a PI controller is used.

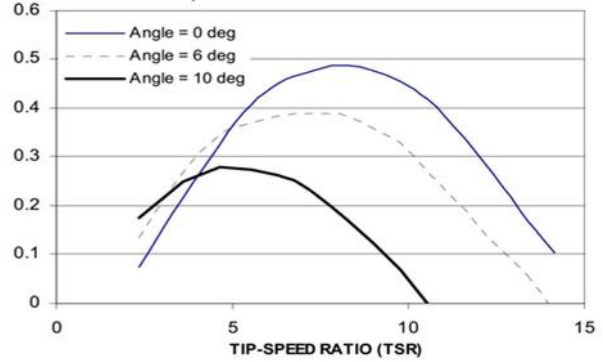
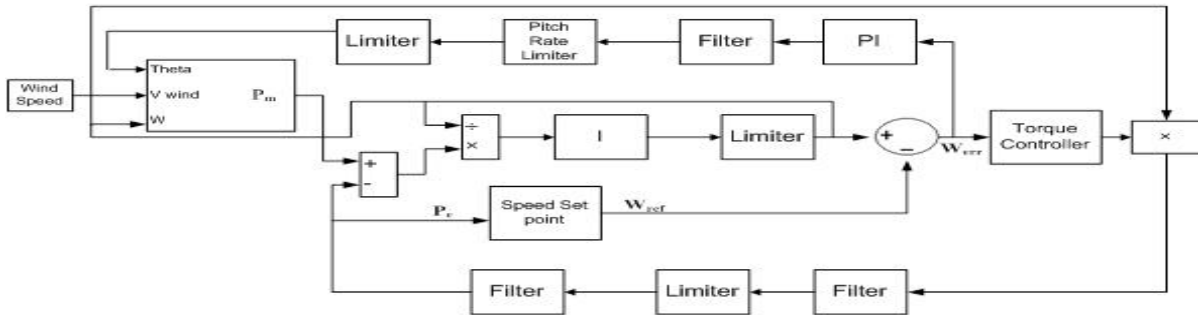


Figure 3. C_p curves for wind power [14].

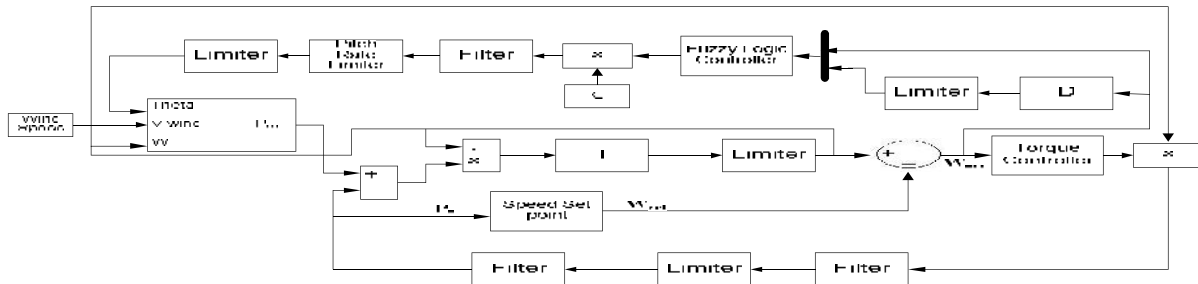
for pitch control. The values of the constant factor (KPP) and Integrator factor (KIP) of PI controller are 150 and 25 respectively, which have been calculated using manufacture data [11]. Here, Fuzzy controller and SOFC are used for pitch control in order to damp oscillations and overshoot of the speed.

4.1. Fuzzy Controller

Fig. 4b shows the simulation block diagram of wind turbine rotor speed control using Fuzzy method in 49 rules cases. Fig. 5a and Fig. 5b show the membership functions of input error and its variations respectively. Fig. 6 expresses the output variables of Fuzzy controller membership function and Fig. 7 indicates the Fuzzy rules versus input and output membership functions values. Table I summarizes the used Fuzzy rules in the Fuzzy controller with 49 Fuzzy rules for Fuzzy deduction.



(a)



(b)

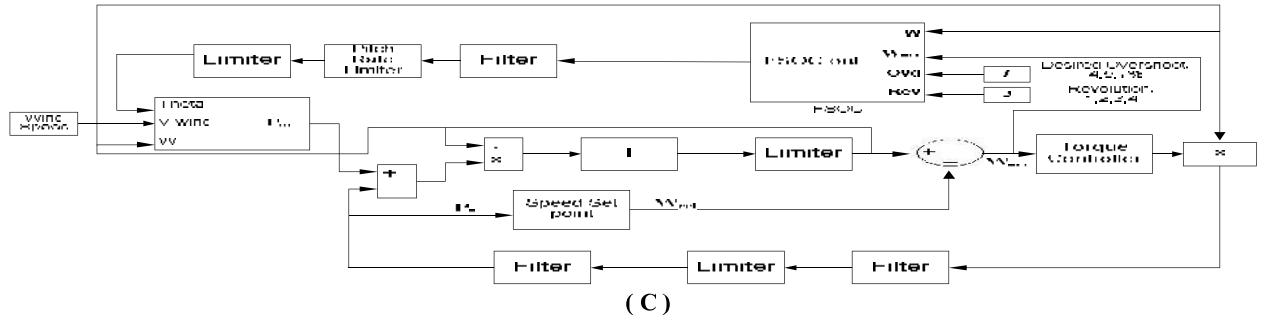


Figure 4. Simulation block diagram of GE model wind turbine with: (a) PI controller, (b) Fuzzypitch controller and (c) Self-organized Fuzzy pitch controller

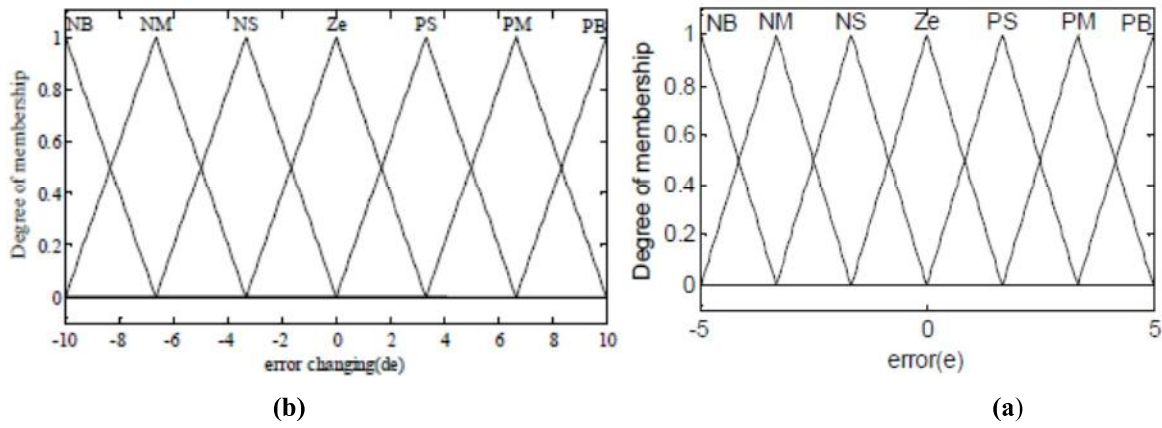


Figure 5. Membership functions in Fuzzy controller: (a) input error and (b) input error variations

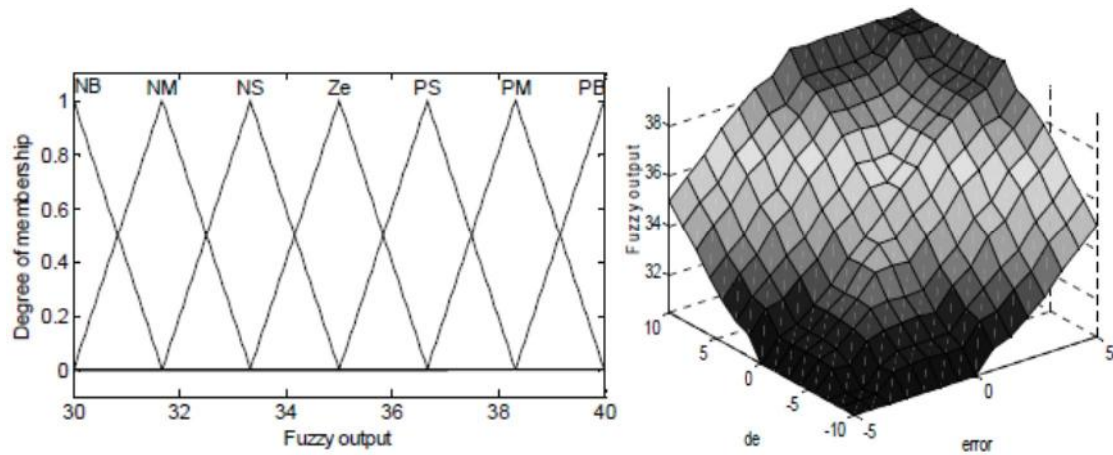


Figure 6. Seven memberships for output variable of Fuzzy controller membership function

Figure 7. A block diagram connecting error and error variations membership functions with Fuzzy controller output in 49 rules state

TABLE 1. Rules used in Fuzzy controller with 49 rules

e \ d	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4.2. Self - organized Fuzzy Controller

Fig. 4c shows the block diagram of SOFC for the pitch control and Fig. 8 exhibits its internal structure. Fig. 9 presents the controller part of SOFC in which the input is Fuzzified by Fuzzifying unit and then the existing knowledge is modified using an adaptive control method. The proposed output is calculated using the modified chosen rule. After passing through the Fuzzification unit, it is defuzzified and applied to the actuator of the wind turbine and controls the pitch. In the empirical Table 2, there are the initial values of 49 rules to use in the knowledge base of SOFC controller. By entering the error of the desirable speed and measured speed of the system, and after Fuzzification [12], one of the 49 existing rules in the knowledge base is chosen based on the proposed deduction. Then, after Fuzzification, it is applied to the actuator. Then the Fuzzy decision table in the knowledge base is modified self-organizing using an adaptive control method as follows:

$$E = \frac{1}{2} [y(t) - y_{sp}]^2 \tag{4}$$

$$\bar{c}_l(k+1) = \bar{c}_l(k) - \alpha \frac{\partial E}{\partial c_l} \tag{5}$$

where $c_l(k)$ is the membership function rule l in training course of k , $c_l(k+1)$ is the membership function rule l in training rule of $k+1$, α is the training rate and $(\neq E/\neq c_l)$ is the derivative function with respect to c_l as follows:

$$\frac{\partial E}{\partial c_l} = \frac{\mu_l(e) \times \mu_l(ce) \times [y(t) - y_{sp}]}{\sum_{l=1}^n (\mu_l(e) \times \mu_l(ce))} \tag{6}$$

where $\mu_l(e)$ is the membership error level due to l^{th} rule, $\mu_l(ce)$ is the membership level of variations of l^{th}

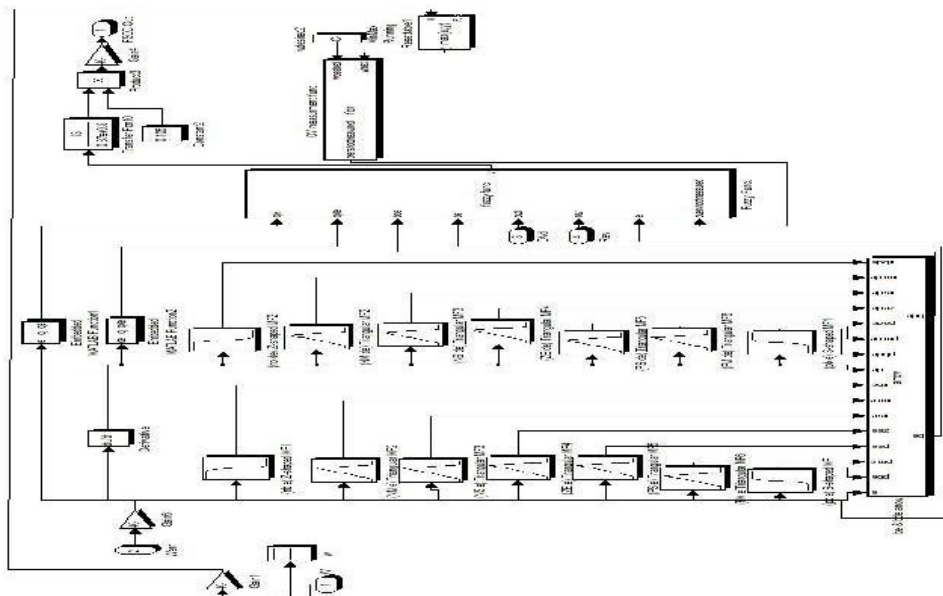


Figure 8. Internal structure of SOFC

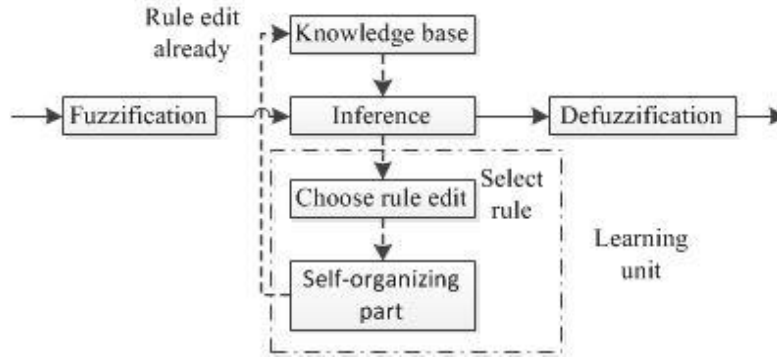


Figure 9. Controller part of SOFC

rule, y_{sp} is the required periodical value and $y(t)$ is the measured periodical value. The training rate is calculated as follows:

$$\alpha = weight \times |e(nT) - \bar{c}_i(nT)| \quad (7)$$

where *weight* is the loading value, $e(nT)$ is the error at time nT , and $c_i(nT)$ is the output singleton Fuzzy of the I^{th} rule at time nT .

The operational value which is the difference between the value of the specific operation and the value of desirable operation is obtained as follows:

$$\Delta OV = OV_{desierd} - OV \quad (8)$$

The weight value is determined as follows [13,14-18]:

If $\Delta OV < 0.3$ then *weight*=0.

If $\Delta OV \geq 0.3$ and $\Delta OV \leq 1$ then *weight*=1.

If $\Delta OV \geq 1$ and $\Delta OV \leq 3$ then *weight*=3.

If $\Delta OV \geq 3$ then *weight*=3.

5. HARDWARE OF FUZZY CONTROLLER, SOFC AND PI CONTROLLER

this section discusses implementation of the software, for different hardwares in various controllers. It is shown that Fuzzy and SOFC are not very expensive compared to PI controller.

Nowadays, one of the tools that can play the role of hardware controller of the wind energy is Field Programmable Gate Array (FPGA). The developed computer program for the controller can cover PI, PID, Fuzzy, SOFC or other controlling methods [19]. For instance, the FPGA has been used in wind turbine controller to control signals due to the sensor which expresses the operating conditions of the wind turbine. The FPGA can quickly make decision based on the received operating conditions from the sensors and its control program. It is common to apply FPGA to wind turbine control [20, 21]. Other control methods that are used in the wind turbines is PC based control (PC) [22] and supervisory control and data acquisition (SCADA) in which controllers such as programmable logic controllers (PLC) are applied [23].

TABLE 2. Knowledge base and existing rules at time n in training course of K

	De	NB	NM	NS	ZE	PS	PM	PB
e	Center	-0.6	-0.4	-0.2	0	0.2	0.4	0.6
NB	-0.6	-0.6	-0.6	-0.6	-0.6	-0.4	-0.2	0
NM	-0.4	-0.6	-0.6	-0.6	-0.4	-0.2	0	0.2
NS	-0.2	-0.6	-0.6	-0.4	-0.2	0	0.2	0.4
ZE	0	-0.6	-0.4	-0.2	0	0.2	0.4	0.6
PS	0.2	-0.4	-0.2	0	0.2	0.4	0.6	0.6
PM	0.4	-0.2	0	0.2	0.4	0.6	0.6	0.6
PB	0.6	0	0.2	0.4	0.6	0.6	0.6	0.6

A typical application of SCADA controllers is 1.5 MW GE turbine model GE's 1.5-77 [24].

If hardwares such as FPGA and PLC are used then PI, PID, Fuzzy, adaptive and SOFC controllers can be applied to the system [20]. The main difference of these controllers using the controlling hardwares is the developed controlling program for loading these tools. Therefore, the use of SOFC and Fuzzy control system is not more expensive than that of the PI and PID controllers.

6. SIMULATION RESULTS

Fig. 10 shows the random function with large oscillations and average speed of 6.7 m/s applied to the wind turbine.

The Fig. 11 describes the pitch angle variations of described controllers. The SFOC and fuzzy controller change the pitch angle more quickly compared with other described controllers. It is normally a Gaussian distribution random signal. The parameters of this function include the mean, variance, initial seed having values of 64, 1 and 2.6. The results of simulation with this input function using FSOC, Fuzzy, PI controllers and with no controller have been presented in Fig. 12. The base values in this simulation are speed of 45 rpm and power of 12 MVA. Although, the overshoot of the simulation with PI control is very large in Fig. 12, the used parameters have been taken from [5]. On the other

hand, if PI controller is optimized at this wind speed, probably its parameters will not be optimal anymore by wind speed variations and it needs to be optimized again. So, different parameters must be applied for different speeds, while, the two other proposed methods (SOFC, Fuzzy) in this paper can automatically adapt themselves with the conditions.

It is clear that usually the wind turbine should be under the maximum power point tracking (MPPT) control at rated wind speed, and in other cases, it turns to pitch control.

Speed oscillations of the wind turbine cause oscillation of the generated electrical power, and this oscillation must be controlled. At this end, a special converter should be used for controlling purposes. However, it will be shown that compensating the wind turbine speed oscillations using converter is more expensive.

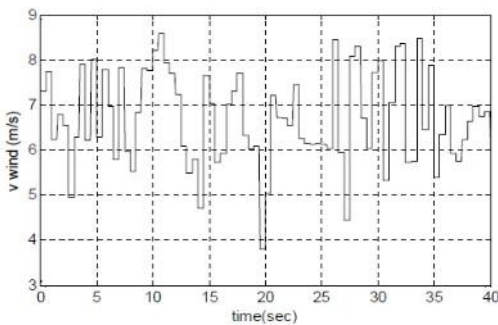


Figure 10. A random function with large oscillations and average speed of 6.7m/s applied to wind turbine

Using the GE model of a wind turbine and comparison of the results indicate that SOFC gives the best performance and damps the oscillations and overshoot of the wind turbine shaft speed. Also, Fuzzy controller operates better than that of PI controller and PI controller better than the no controller case. Fig. 12b shows the electrical power using different controllers and the merit of Fuzzy controller and SOFC.

7. ECONOMIC COMPARISON OF OSCILLATIONS AND OVER-SHOOT CONTROLLERS DESIGN IN WIND TURBINE

Power converter can be used to damp the frequency fluctuations of the wind electrical power. This is an expensive method and cost will be increased by enhancing the power level. To show the saving of the controllers, first the converter power cost is estimated and then controllers application are saved, afterwards the connection between the converter power and its cost, will be determined. The economic analysis is based on [10] and the converter power required in a wind turbine is as follows:

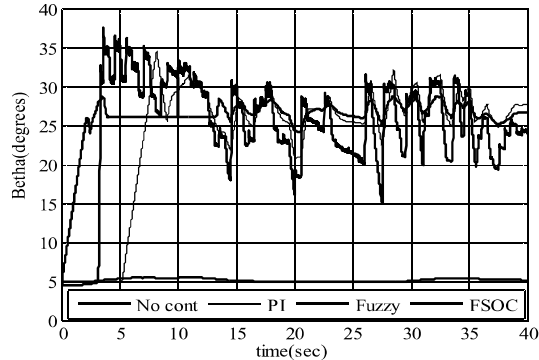
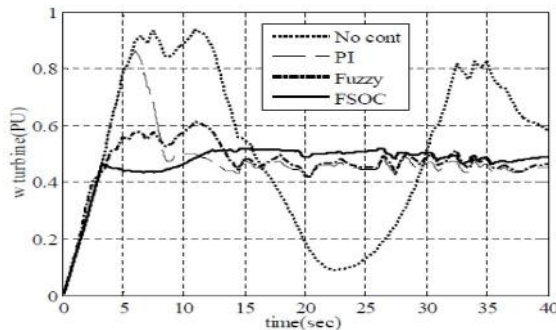
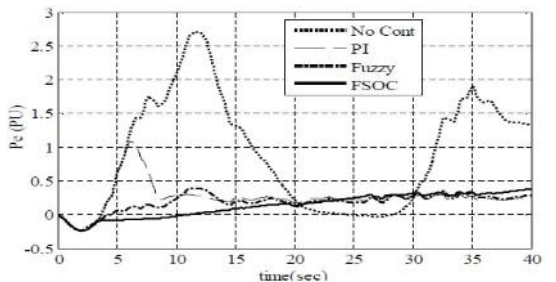


Figure 11. Pitch angle variations diagram of different controllers



(a)



(b)

Figure 12. Wind turbine shaft speed (a) and electrical power (b) using Fuzzy, SOFC, PI controllers and with no controller by applying a random wind speed with average speed of 6.7 m/s

$$P_s = S_r P_e \tag{9}$$

where P_s is the slip power, approximately equal to converter power and P_e is the electrical power, S_r is the slip as follows:

$$S_r = \frac{\omega_s - \omega_r}{\omega_s} \tag{10}$$

where ω_r and ω_s is the rotor angular speed and stator angular synchronous speed respectively. Converter cost has approximately linear relationship with the power level. By slip reduction, the converter power and its cost is dramatically reduced. As shown in Fig. 12a, application of SOFC leads to a lower slip compared to the other controllers. Based on (9), the

converter power curve (P_s) is obtained and shown in Fig. 13b. As seen in Fig. 13, the required peak power of the converter is accessible using different controllers. In PI control, P_s is 0.97 pu and overshoot of the electrical power is 1.1 pu. Therefore, it is necessary to choose a converter that supports the power of 0.97 pu while in the case of using SOFC, the converter power reduces to 0.11 pu. So, if SOFC is used, the cost of the new converter is $X=0.1134$ times of that of the PI controller. X is the ratio of the power of the PI controller converter and that of SOFC converter. The saving cost is:

$$B=(1-X)(\text{cost of PI controller converter}) \quad (11)$$

Table 3 summarizes the saving cost using SOFC and Fuzzy controller in comparison with the PI controller. The wind turbine cost in 2011 was about 900-1400 \$/kW and the labor payment around 103 \$/kW [25]. So, the cost of wind turbine equipment is 797-1297. Therefore, 3.6 MW wind turbine equipment is between 2869200 to 4669200 \$. Since the converter cost is 6.4% to 12.5% of the wind turbine equipment, the converter cost is between \$22954 and \$298829 and its average cost is \$160891 [26].

TABLE 3. Cost saving of using different controllers

Controller type	P_s (p.u)	X	Economical Benefit
PI	0.97	1	0
Fuzzy	0.13	0.1340	\$139329
SOFC	0.11	0.1134	\$142646

8. CONCLUSIONS

In this paper the general model of General Electric (GE) wind turbine was used for simulation purposes. This model is adaptive with the typical practical case. A PI controller had been (ready) used for pitch control of wind turbine. A novel SOFC and Fuzzy controller were introduced in this paper for pitch control. The results of application of the above-mentioned controllers were compared to that of the PI controller and no controller case. It was shown that the use of SOFC and Fuzzy controller damps oscillations, and overshoot of speed and electrical power. Also economic analysis of the above-mentioned controllers applications was done and the advantages of each controller were emphasized. Future work will concentrate on the comparison of distributed power flow controller (DPFC) results for GE model with the described controllers results and the comparison of different pitch controllers application for other wind turbine models.

9. ACKNOWLEDGEMENT

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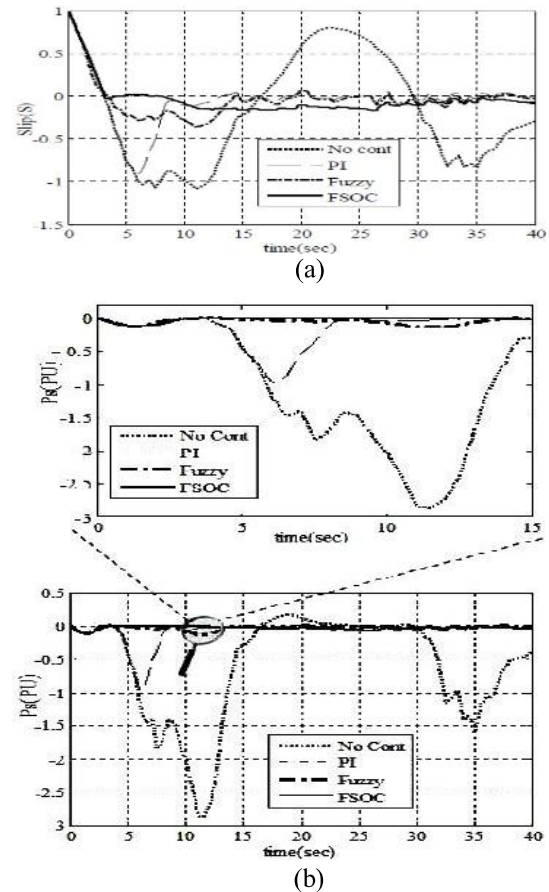


Figure 13. Slip (a) and power converter wind turbine (b) using different controllers

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