Comparative Study of Different Pitch Angle Control Strategies for DFIG Based on Wind Energy Conversion System

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Abstract- This paper presents an advanced pitch-angle control for large scale Wind Energy Conversion System (WECS) based on a Doubly-Fed Induction Generator (DFIG). Blade pitch-angle control technique is implemented for regulating the aerodynamic power of the wind turbine and minimize aerodynamic fatigue when the wind-speed is higher than its rated value. The traditional control techniques require proper system modelling and analytical analysis of the transfer function of the system which is not always available. Moreover, nonlinearity of the system increases the complexity of the system. To overcome the issues in the traditional control, adaptive fuzzy-PID control is proposed in this work. The process of the blade pitch control using adaptive fuzzy-PID control strategy is featured with nonlinearity, multi-variable, time variation and time delay. The developed control strategy is applied to a WECS of 1.5 MW based Doubly-fed induction generator wind turbine. System modelling and analysis are performed using MATLAB/Simulink software. The simulation results verify the effectiveness of the auto-tuning adaptive fuzzy-PID (AF-PID) controller in improving the dynamic performance of the wind turbine (WT).

Keywords Doubly-Fed Induction Generator (DFIG), Wind Energy Conversion System (WECS). wind turbine (WT), adaptive fuzzy-PID (AF-PID), Fuzzy Logic Controller (FLC).

1. Introduction

Recently, wind energy has been possessed an increasingly significant position in the field of electric power generation. Factors such as growing demand of electricity globally, tendency towards clean and inexhaustible energy sources, have motivated the development of WECSs [1-5]. Moreover, the wind energy is considered the most applicable energy source to satisfy the world's future energy needs/ desires [6, 7].

A wind turbine (WT) is classified into fixed and variable speed turbine. The variable speed wind turbine (VSWT) can extract additional energy compared to fixed speed type [8].Most of the WT manufacturers are improving a novel megawatt-scale WTs with variable-speed operation based on pitch control utilizing a doubly fed induction generator (DFIG) or a permanent magnet synchronous generator (PMSG) [9].DFIG has a widespread implementation in wind power plants due to high control capacities [10, 11].

For efficient operation of WECS, maximum power must be extracted from the wind power. To achieve this objective, the tip speed ratio (TSR) of the WT is regulated to its optimal value with varying of wind-speed [12]. Therefore, it is essential to improve more developed control methods for WECS. Various control strategies have been proposed by several authors to control the blade pitch-angle of the WT

[13-15]. The pitch-angle control in DFIG has an important function to limit the destructive effects bring by a high wind-speed [16].

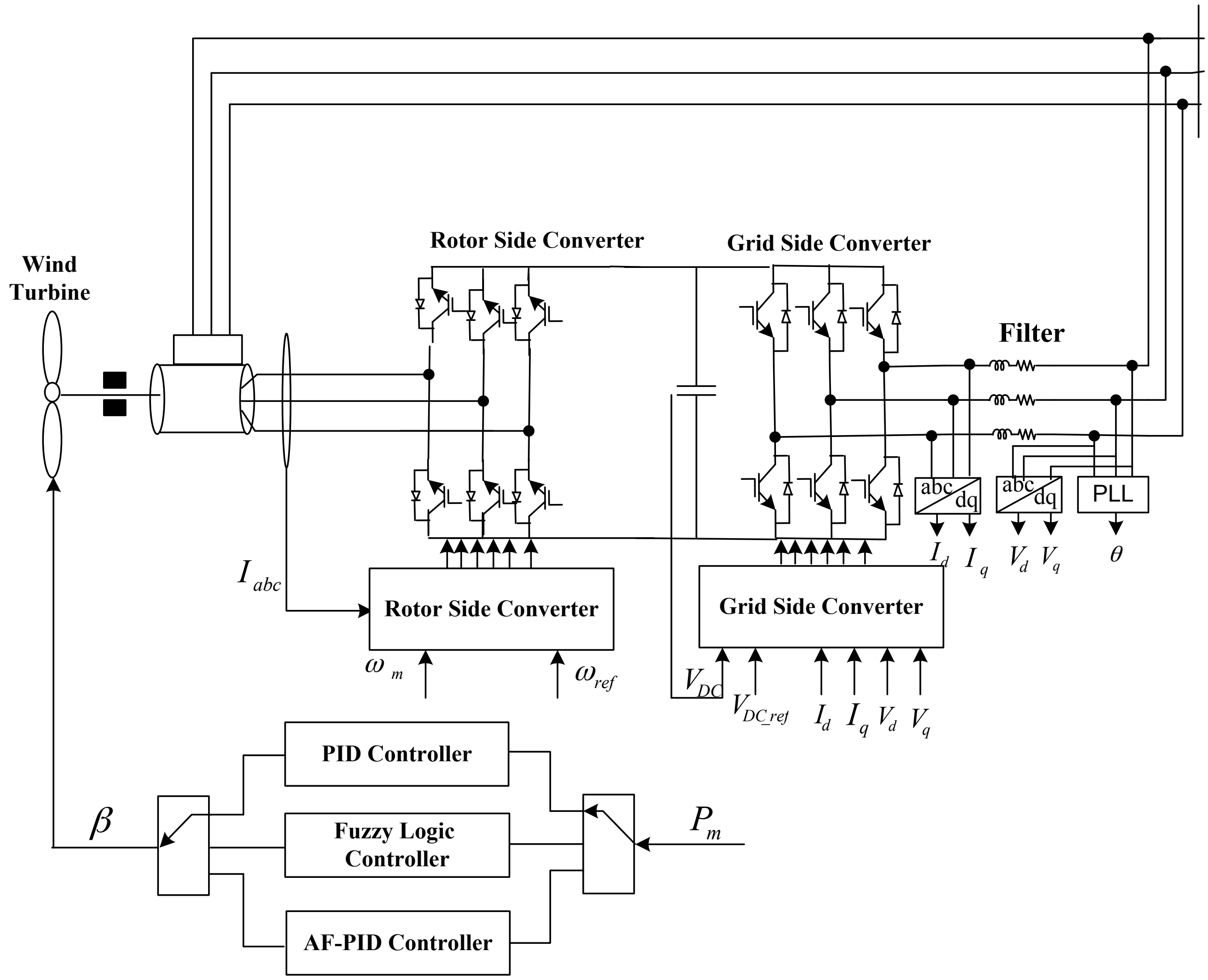


Fig. 1. A Composition of wind conversion system with DFIG.

Large-scale wind turbines are characterized with non-linearity which adversely affect the performance of traditional controllers. Due to the non-linearity among the wind-speed and the pitch-angle, the pitch-angle is generated by the fuzzy logic controller (FLC) for output power smoothing [17, 18].The FLC algorism is an efficient solution due to the simplicity of control structure, inexpensive coast, and ease of its design, but it may result in steady state errors if the system does not have an inherent integrating property and it usually generates few oscillations around the desired value. As large scale WECS is a time-varying and a nonlinear system, FLC and proportional- integral -derivative (PID) control is difficult to accomplish the required influence. Therefore, adaptive Fuzzy-PID control is designed to overcome the big problems in the PID control and FLC strategies. The AF-PID combined FLC adaptive PID, incorporating the PID control and FLC, which cannot solely play the FLC features of sensible dynamic response, robustness, rapid rise time and overshoot small, but also have advantages of both quality and regular accuracy dynamic tracking specifications. It creates good static and dynamic characteristics for the system [19, 20].

In this paper, AF-PID is suggested to improve the optimum control performance of WT based on developing the classical control techniques. A comparison between AF-PID control strategy and traditional control strategies (PID and FLC) has been carried out to prove that the pitch-angle based on AF-PID algorithm has the ability to reduce aerodynamic stresses and maintain the mechanical power in its limited design. furthermore, the mechanical power has been selected as the input variable of AF-PID, instead of wind-speed, which reduced the need for an expensive anemometer.

2. Dynamic Model of WECS

Variable speed wind turbines (VSWT) firstly transforms the kinetic energy to mechanical energy thereafter to electrical energy through the DFIG, The mechanical power generated by WT is given as follows [21, 22]:

$$P_m = \frac{1}{2}\pi\rho R^2 C_p(\lambda,\beta) {v_w}^3 \quad (1)$$

With;

$$\lambda = \frac{\Omega_t R}{v_w} \quad (2)$$

Where $P_m, \rho, R, C_p, \lambda, \beta, \Omega_t$ and v_w are mechanical power, air density, blade radius, performance coefficient, TSR, pitch-angle, rotor shaft speed, and wind-speed, respectively.

Generally, the performance coefficient (C_p) is a nonlinear function of the pitch-angle (β) and TSR (λ)which expressed by:

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) e^{\frac{-C_5}{\lambda_i}} + C_6\lambda_i \quad (3)$$

With:

$$\lambda_i = \left[\frac{1}{(\lambda + C_7.\beta)} - \frac{C_8}{(\beta^3+1)}\right]^{-1} \quad (4)$$

The ruling equation for WT below wind loadings is calculated as [23, 24]:

$$F_{Damping} + F_{Inertia} + F_{Elastic} = F_{Hydro.} + F_{Aero.} \quad (5)$$

Where, $F_{Damping}, F_{Inertia}, F_{Elastic}, F_{Hydro.}, F_{Aero.}$ Is the damping, inertia, elastic, hydrodynamic, and aerodynamic forces.

3. DFIG Modelling

Fig. 1 shows the WECS configuration based on large-scale grid-tied of 1.5 MW DFIG. The rotor and stator flux linkages, in addition to voltage equations of DFIG as follows [25, 26]:

$$\begin{cases} \psi_r = L_r i_r + L_m i_S \\ \psi_s = L_m i_r + L_s i_S \end{cases} \quad (6)$$

And,

$$\begin{cases} v_r = R_r i_S + \frac{d}{dt}\psi_r - j\Omega_t\psi_r \\ v_s = R_s i_S + \frac{d}{dt}\psi_s \end{cases} \quad (7)$$

where R_r and R_s are rotor and stator resistances; L_r, L_s and L_m are stator, rotor and magnetizing inductances; and j is imaginary unit.

The stator output active and reactive powercan be expressed as follows:

$$P_s = \frac{3}{2}(V_{ds}i_{ds} + V_{qs}i_{qs}) \quad (8)$$

$$Q_s = \frac{3}{2}(V_{qs}i_{ds} - V_{ds}i_{qs}) \quad (9)$$

where $(P_{s,}Q_s)$ are the active power and reactive power of the stator. Under wind loadings the dynamic behavior of the WT can be expressed as follows

4. Control Strategy

The WT work will be limited in three specific zones, relying upon wind-speed [27]: MPPT control zone, pitch-angle control zone, and parking zone, "Fig.2" illustrates the ideal power-speed curve for a variable-pitch angle WT.

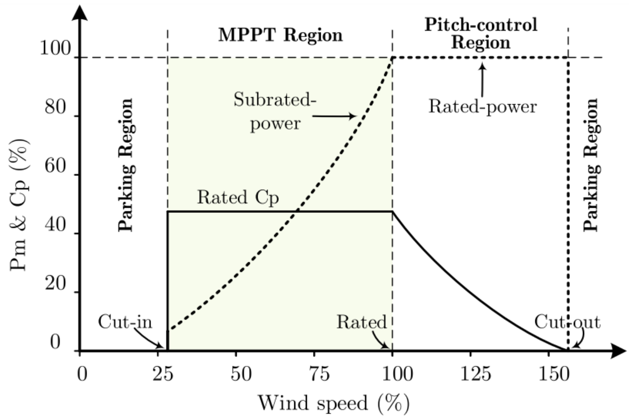


Fig. 2. The ideal power curve for variable-pitch angle WT.

- In Maximum Power Point Tracking (MPPT) control zone ($V_{ci} \le V_w \le V_{rat}$) or ($5 \le V_w \le 12$), the pitch-angle is specified to its minimum value (mostly set as zero) and the torque is controlled with the generator that way which the MPP of a WT is traced at various wind-speeds.
- In pitch control zone ($V_{rat} < V_w \le V_{co}$), the pitch-angle is controlled by its mechanism somehow which the generated power kept constant at the power rated.
- In parking zone ($V_w < V_{rat}$ OR $V_w > V_{co}$), the pitch-angle is adjusted to its extreme value and the WT brake is active to turn WT off.

Where $V_{ci} = 5\ m/sec, V_{rat} = 12\ m/sec, V_{co} = 25m/sec$

At the point when the wind-speed is larger than the (V_{rat}), the WT power produced will be above its rated value (P_{rat}), which increases the electrical stresses on the power processing device and the DFIG. Therefore, the pitch-angle control has become necessary to keep the delivered power constant, to achieve a higher wind energy production, and to minimize the aerodynamic stresses of WT. This control purposed for decrease stresses and enhances the WT performance without external energy expenditure by means of passive technique or with external energy active technique, or auxiliary power.

5. The Control Algorithm

Three algorithms, in this paper, had been applied; these algorithms are PID, FLC and the AF-PID.

5.1. PID CONTROL Strategy

The desired pitch-angle is achieved depending on the power error ($e_P(t)$) to regulate the output power to the rated value. A PID controller is utilized to carry out the pitch-angle, as shown in "Fig.3". The efficacy of the conventional control depends totally on its gains, as the output pitch-angle of PID controller is defined by [28]:

$$\beta = K_P\left[e_P(t) + \frac{1}{T_i}\int_0^t e_P(t).dt + T_d.\frac{d(e_p)}{dt}\right] \quad (10)$$

Where: $$\begin{cases} K_i = \frac{K_P}{T_i} \\ K_d = \frac{K_P}{T_d} \end{cases} \quad (11)$$

And: $$e_P = P_{ref} - P_{ACT} \quad (12)$$

where, K_P, K_I and K_d are the gains of proportional, integral and the derivative controllers, and T_i, T_d are the integral and derivative time constant, respectively. The PID controller parameters are represented in Table.1 [29].

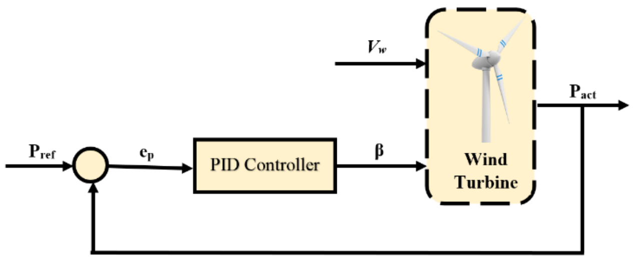


Fig. 3. PID controller block diagram.

Table. I PID-CONTROLLER Gains

K_p	40
K_i	12
K_d	1

5.2. Fuzzy Logic Control Strategy

Commonly, it is hard to control the non-linear systems. The traditional controller will not work well in terms of damping and regulation. Subsequently, to fix this problem, an enhanced FLC was applied. FLC MATLAB Toolbox was employed to developing the FLC [30]. The fuzzy logic controller is composed of three steps fuzzification, decision logic and defuzzification as shown in "Fig.4" [31].

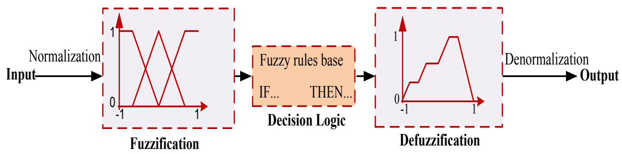


Fig. 4. FLC diagram.

the FLC is executed by employing three input signals and one as output. First signal is the wind-speed (V_w) is helpful to compensate the non-linear sensibility of pitch-angle to the wind-speed, the second inputs measured from the deviation of the WT power from its rated value and called the power error signal (e_p), and the power error variation through the sampling time δ(ΔP), which used as the third input variable, as follows:

$$\begin{cases} e_p = P_{ref} - P_{act} \\ \delta(e_p) = (e_p)_n - (e_p)_{n-1} \end{cases} \quad (13)$$

The fuzzy sets are included in , which are very positive The rule bases are defined from the knowledge gained from the open-loop operation.

5.3. Auto-tuning Fuzzy PID Controller (AF-PID) Strategy

With the fast development of FLC techniques, completely difference FLC strategies are developed supported various traditional control techniques, like PID-fuzzy control, neural FLC, sliding-mode FLC. The AF-PID controller reliable for the traditional PID controller as a foundation, that employed the notion of the variable discourse of universe and FLC reason to automatically regulate the PID parameters [32]. The power error and the power error changing rate are only two inputs to the AF-PID controller, displayed in "Fig.5" suggested AF-FLC which executed by employing two input signals and one as output. In the otherwise, the parameters of the PID controller are the output variables and they can be calculated from the expressions:

$$k_p = k_p(pid) + \{k_{pf}(\text{FZ}) * k_p(pid)\} \quad (14)$$

$$k_i = k_i(pid) + \{k_{if}(\text{FZ}) * k_i(pid)\} \quad (15)$$

$$k_d = k_d(\text{pid}) + \{k_{df}(\text{FZ}) * k_d(pid)\} \quad (16)$$

For maintaining the pitch-angle at optimal value, to protect the WT from any damage at high wind speed, the three parameters $[k_{pf}(\text{FZ}), k_{if}(\text{FZ}), k_{df}(\text{FZ})]$ of the output FLC interference are auto-tuning at different wind speeds. The fuzzy sets are included in [33], which are very positive The rule bases are defined from the knowledge gained from the open-loop operation.

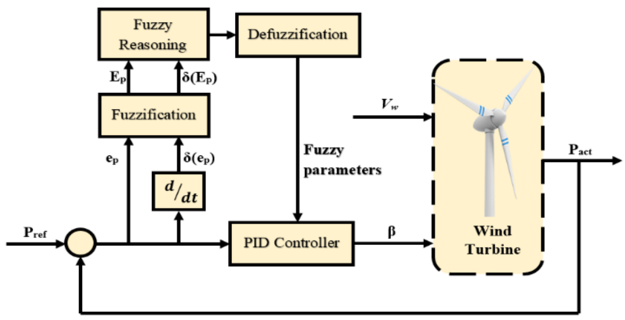
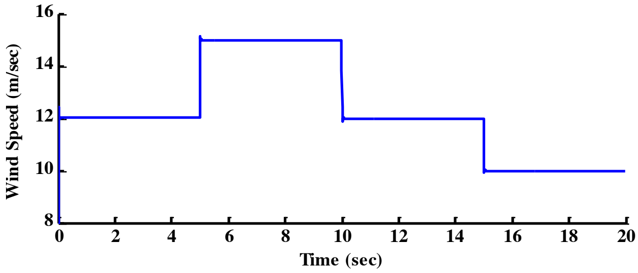


Fig. 5. Auto-Tuning PID Controller block based on pitch-angle.

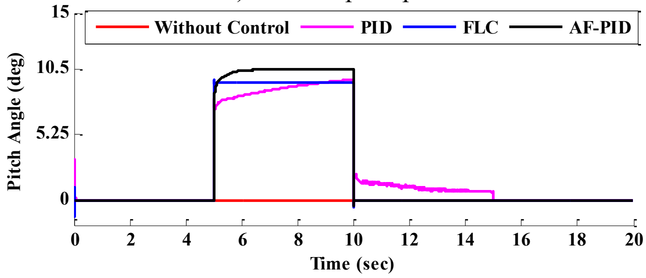
6. Simulation Results

Pitch-angle control systems use Simulink module based on MATLAB software for numerical simulation. The parameters of the WT are as follow; number of blades=3, rated output power =1.5 Mw, rated wind speed=12 m/sec, optimal TSR=8.1, optimal performance coefficient=0.48 and grid frequency=60 HZ. During 20 s, we have applied to the

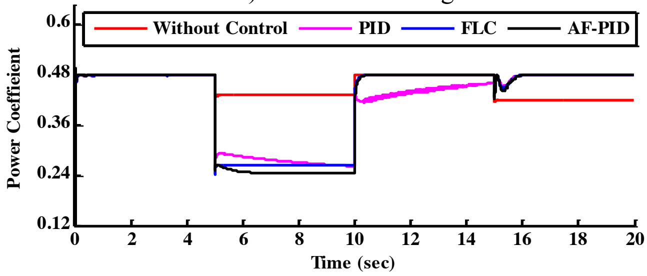
WT model a step and ramp wind profile between 10 and 15 m/s represented in Fig.6(a) and Fig.7(a).



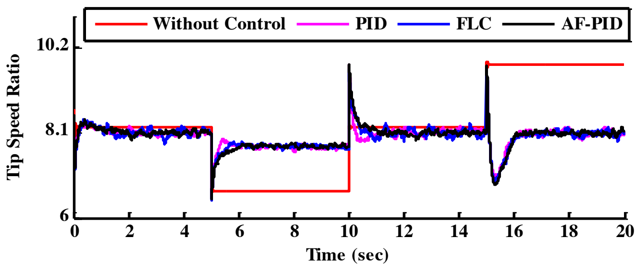
a) wind-speed profile



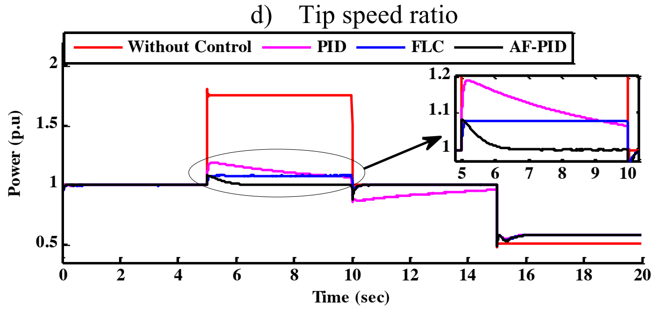
b) Blade-Pitch angle



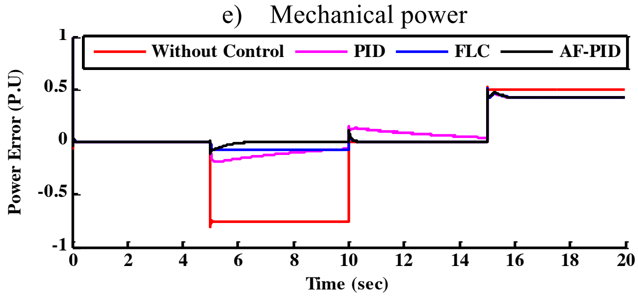
c) Power coefficient



d) Tip speed ratio



e) Mechanical power



f) Power deviation

Fig. 6. WT performance during Step variation wind-speed.

6.1. Step Change Wind Speed

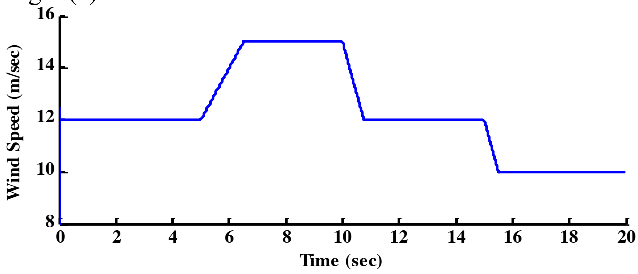
Fig.6 shows a step variation in the wind speed, the change of pitch-angle due to the variation of wind, performance coefficient, TSR, mechanical power and the mechanical power error of the DFIG. According to wind turbine characteristic, the pitch-angle control techniques do well. When the wind speed existing between (V_{ci}) and (V_{rat}) values the pitch-angle is nearby zero degree ($\beta = 0°$) that makes the power coefficient and the TSR in its optimum values (0.48 and 8.1, respectively). Therefore, the mechanical output power is maximum with the variation of wind speed. When the wind speed exceeds the rated value (V_{rat}), the controllers adjusts the pitch-angle intentionally to reduce the power coefficient for maintain the output mechanical power at its limited value (1 P.U = 1.5 Mw) protecting the WT from fatigue damage. Generally, in Fig. 6(e), in zoomed area, the system response with fuzzy logic method (FLC) is faster than both, the AF-PID and the PID Controller, with a settling time of 300 msec., however, the drawback of steady state error of 9 %. On the other hand, the AF-PID technique out the steady state error problem with small settling time of 800 msec. with respect to the PID settling time (7000 msec.). Moreover, the average value of Cp of the AF-PID technique is highest compared with both PID and fuzzy, which adversely influences the output power. Moreover, the TSR is often stationary following their optimal values (8.1) for the entire simulation period. In Fig. 6(e) The proposed technique AF-PID exhibits further effectiveness than conventional PID and FLC techniques. It is clear that the average power error is nearly zero for AF-PID control algorithm and its moderated in the FLC algorithm, however, its big in the classical PID control. The results of the conventional and suggested techniques are listed in Table II.

Table. II Comparison between the conventional and proposed pitch technique for WECS

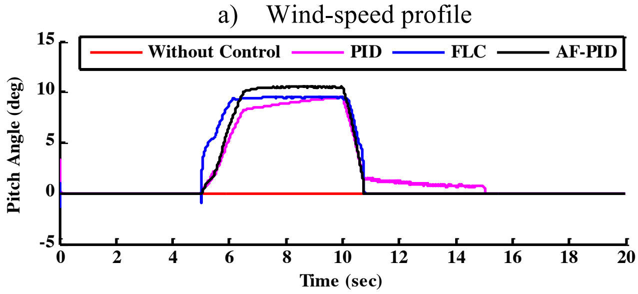
Pitch Algorithm	Settling time (msec.)	Steady state error (%)
PID	**7000**	**zero**
FLC	**300**	**9**
AF-PID	**800**	**zero**

6.2. Ramp Change Wind-speed

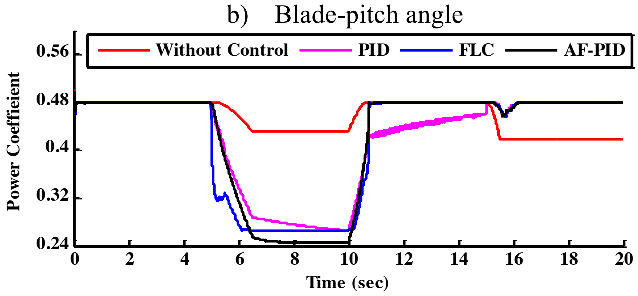
The effectiveness of the implemented control strategies has been investigated with Ramp wind-speed variation profile. Fig.7 shows the effectiveness of the turbine over the step variation wind-speed. the output turbine mechanical power is controlled to track its optimal value. The aims of the pitch-angle control techniques have been achieved, from the output mechanical power, that is almost constant value at (1 P.U) at higher rated wind-speed (12 m/sec) as shown in Fig. 7(c) and



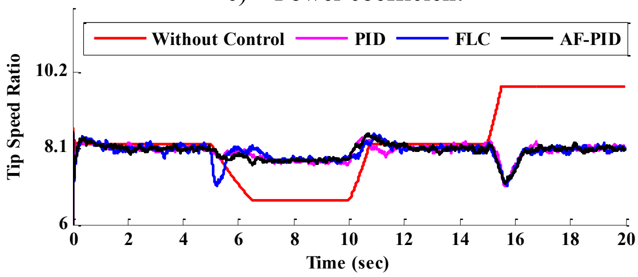
a) Wind-speed profile



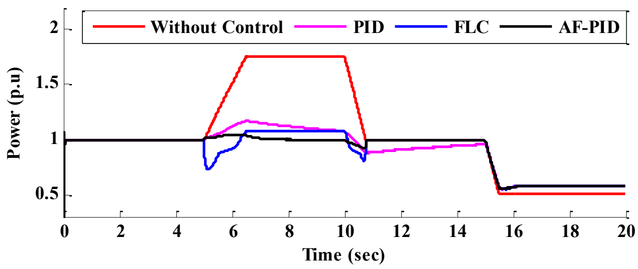
b) Blade-pitch angle



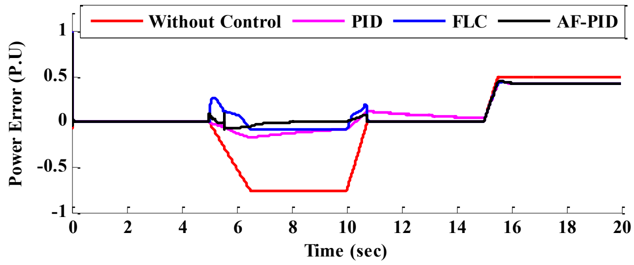
c) Power coefficient



d) Tip speed ratio



e) Mechanical power



f) Power deviation

Fig. 7. WT performance during ramp variation wind-speed.

the variation of the tip speed ratio which changes in a relatively tiny range around the optimal value of (8.1) as shown in Fig. 7(d).The output mechanical power is always controlled - at a higher wind-speed than 12m/sec - to be constructed at its limited design value based on reducing the power factor, whereas, the TSR is almost constant at the optimal value. The AF-PID accomplishes faster transient response compared with the PID, In addition to the lack of a steady state error compared with FLC. so, reduces the stresses over the turbine and optimal power is injected into the utility grid which augmented the overall efficiency, as shown in the power deviation Fig. 7(f).

7. Conclusion

This paper investigated the dynamic performance of the WT with PID, FLC and AF-PID of pitch-angle. Simulation results prove that the pitch-angle algorithms has the ability to reduce the aerodynamic stresses and maintain the mechanical power in its limited design, and the AF-PID is the most suitable strategy has been achieved these aims. The results presented that the use of AF-PID controller for WT variable pitch control of the implementing agencies can achieve good control effect, it has low fatigue loads and low power peak. Also, the results illustrated that the AF-PID controller eliminates the mechanical stress on the WT during ramp and step variations of the wind-speed. The simulation was implemented using simulating program MATLAB /Simulink on the model 1.5 MW wind turbine. From the analysis, it is concluded that the AF-PID controller illustrates that the TSR maintains constant at its optimal value.

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