Reinforcement Learning Based PID Control of Wind Energy Conversion Systems

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ABSTRACT

In this paper an adaptive PID controller for Wind Energy Conversion Systems (WECS) has been developed. The adaptation technique applied to this controller is based on Reinforcement Learning (RL) theory. Nonlinear characteristics of wind variations as plant input, wind turbine structure and generator operational behavior demand for high quality adaptive controller to ensure both robust stability and safe performance. Thus, a reinforcement learning algorithm is used for online tuning of PID coefficients in order to enhance closed loop system performance. In this study, at start the proposed controller is applied to two pure mathematical plants, and then the closed loop WECS behavior is discussed in the presence of a major disturbance.

KEYWORDS: Adaptive control, WECS, Reinforcement learning

1. INTRODUCTION

According to increasing consumption of fossil fuels in recent years and their limited resources, it is very vital to use unlimited natural energy resources such as water, wind and sun. A very common application of such resources is electrical energy generation. Water and wind energy are mostly used to rotate shafts of prime movers to generate energy [1, 2].

WECS are very challenging from the control system. In fact, wind turbine control enables a better use of the turbine capacity as well as the alleviation of aerodynamic and mechanical loads, which reduce the useful life of the installation [3].

Various approaches were introduced in literature in order to control WECS. In [4] a combined adaptive supervisory control approach is introduced which has a radial basis Z-function adaptive controller and a simple supervisor. In [5] a PID controller is proposed in which PID parameters are tuned via a wavelet neural network that is a single layer network with wavelets of type RASP1 as hidden nodes. This network proposes a pre specified model structure to identify the unknown plant. In [6-7] a self tuning control method for wind energy conversion system is introduced using wavelet networks.

Many predictive control algorithms were proposed during the last decades, such as Dynamic Matrix Control (DMC), Model Algorithmic Control (MAC) and Generalized Predictive Control (GPC). Although they can obtain high performance of the controlled system, few of them have been realized in electrical machine or drive application due to the heavy calculation power required by them [8].

In this paper a self-tuning PID controller is proposed for a WECS in PID coefficients which are tuned through a reinforcement learning algorithm. So far none of the mentioned approaches in the literature analyzed the WECS in the presence of external disturbances. But, in this study, a major disturbance is applied to the close loop WECS and then system performance is analyzed. Furthermore, it will be shown that the system response in the proposed controller is considerably faster while no fluctuations are mounted on the control or output signals.

This paper is organized as follows: in section II the reinforcement learning algorithm is explained. In section III the proposed controller is applied to two pure mathematical plants with two different characteristics. Section IV introduces the WECS as a major plant in power system. Section V shows the advantages of the proposed controller over classic PID controller. Finally, section VI contain conclusion of proposed algorithm.

2. PROPOSED CONTROL STRATEGY

Reinforcement learning method is based on trial-and- error algorithm and also is trained to apply suitable control action on different plants indirectly. In this method, for each states of system, one different control action is applied. For example if $x_t$andu_t denote the system state and control input at time t, let the system dynamics are given as follow [9]:

$$\begin{aligned} x_{t+1} &= f(x_t, u_t) \\ u_t &\in U, \forall t > 0 \end{aligned} \tag{1}$$

For each control action in any intervals, a reward or a punishment is assumed. In other word, if this action improves the system error, a reward will be assumed for this action and Otherwise a punishment will be applied. According to figure1, the selection of reward or punishment specified by comparison between error in t and t+1.So reward selection in t instance for each action given below equation:

$$R(x_0, u\{t\}) = \sum_{t=0}^{\infty} \gamma^t r(x_t, u_t) \tag{2}$$

Where γ is discount factor between 0, 1 and r(x,u)≤ B is reward function.

Then, a value function is defined via these obtained values. By this function, suitable control signal for the next time will be chosen.

$$V(x) = \max_{u(t)} R(x, u(t)) \tag{3}$$

By use of Bellman equation [10] the value function is given by:

$$V(x) = \max_{u\in U}[r(x,u) + \gamma V(f(x,u))] \tag{4}$$

Optimal control policy can be shown below:

$$\left\lfloor u^*(x) = \arg\max_{u\in U}[r(x,u) + \gamma V(f(x,u))]\right\rfloor \tag{5}$$

According to mentioned relationships for each interval, a reward or punishment function called Q function can be defined as follow:

$$Q(x,u) = r(x,u) + \gamma V(f(x,u)) \tag{6}$$

Re-express V(x) in terms of this function by:

$$V(x) = \max_{u \in U} Q(x,u) \tag{7}$$

And , optimal control policy is shown below

$$u^{*}(x) = \operatorname{argmax}_{u \in U} Q(x,u) \tag{8}$$

In the proposed PID controller, for each coefficient, five different actions are considered. In each step, adaptation unit must select one action among 125 possible actions. Some of the actions are eliminated through the evaluation of their punishment functions and then a random selection process is applied to the other actions. The need for a random selection process decreases by time. In this method the degrees of freedom is number of the adaptation parameters and the number of the corresponding actions. The proposed control structure is shown in figure 1

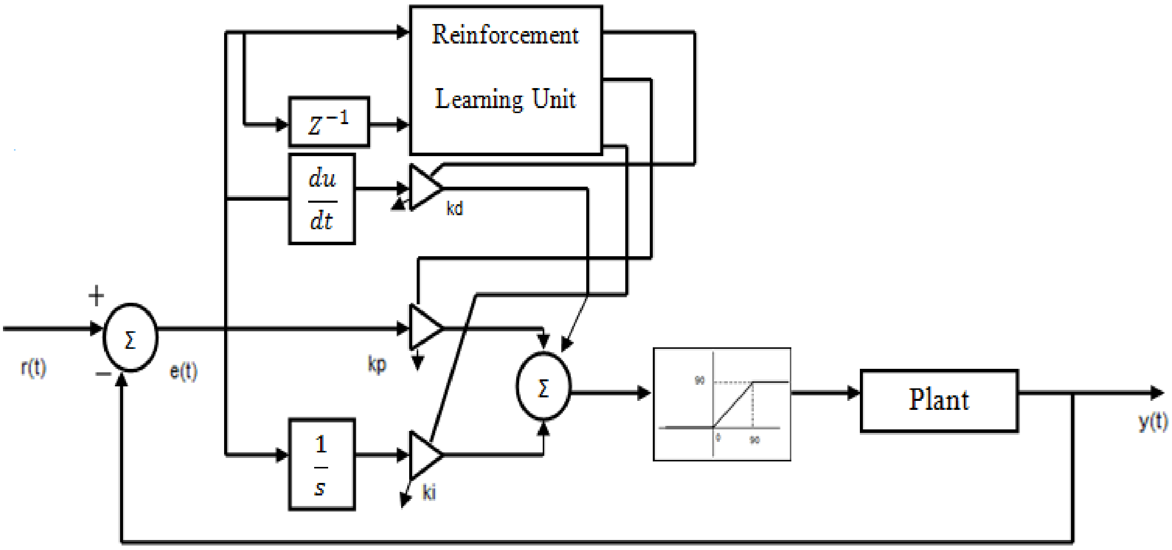

Fig.1. Proposed method block diagram

3. STEADY STATE ANALYSIS OF TWO PURE MATHEMATICAL PLANTS USING PROPOSED CONTROLLER

According to specifications of the proposed controller, the plant dynamics do not have any significant effects on the performance of the closed loop system. In order to analyze the tracking capability of the proposed controller, two mathematical plants are discussed.

A. Time-variant exponential plant e^{-t}

Figure 2 depicts the close loop system output to a random input signal. It could be seen that the proposed controller gives a satisfactory response to the random changes in the input.

The variations of controller parameter are shown in figures 3 - 5.

B. Linear plant with this transfer function

$$: H(s) = \frac{s+4}{s^2+3s+2}$$

Figure 6 depicts the close loop system output to a random input signal. It could be seen that the proposed controller gives a satisfactory response to the random changes in the input Regardless of the Dynamic Systems.

The variations of controller parameter are shown in figures 7 - 9.

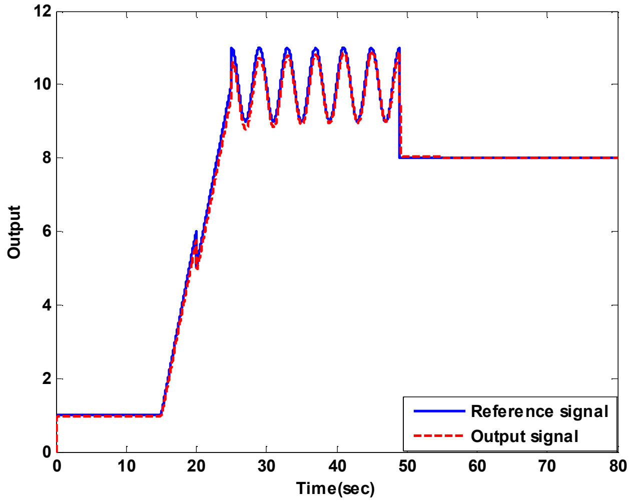

Fig.2. System convergence using proposed algorithm.

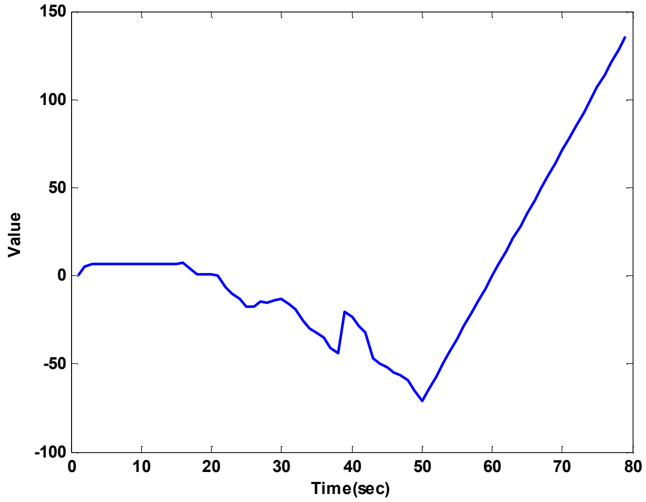

Fig.3. Proportional coefficient (k_P) variations

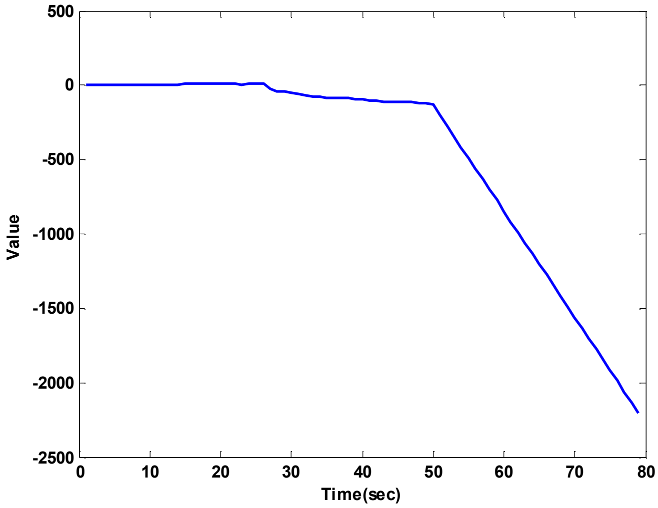

Fig.4. Integral coefficient (k_I) variations

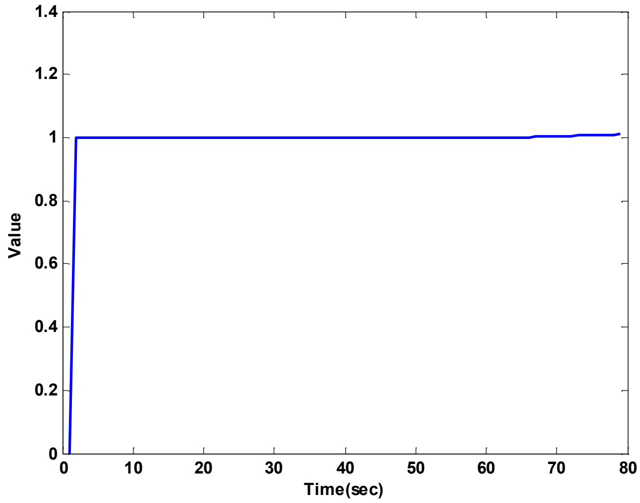

Fig.5. Derivative coefficient (k_D) variations

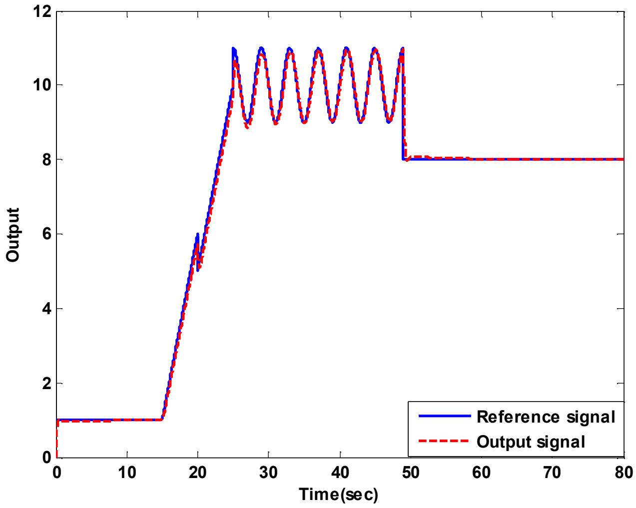

Fig.6. System convergence using proposed controller.

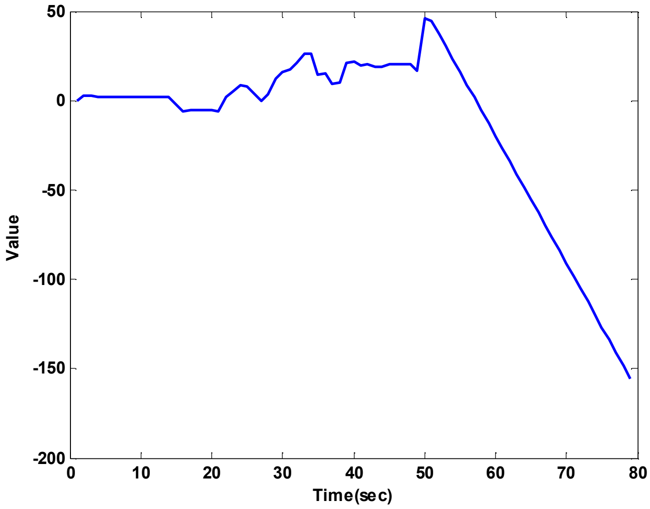

Fig.7. Proportional coefficient (k_P) variations

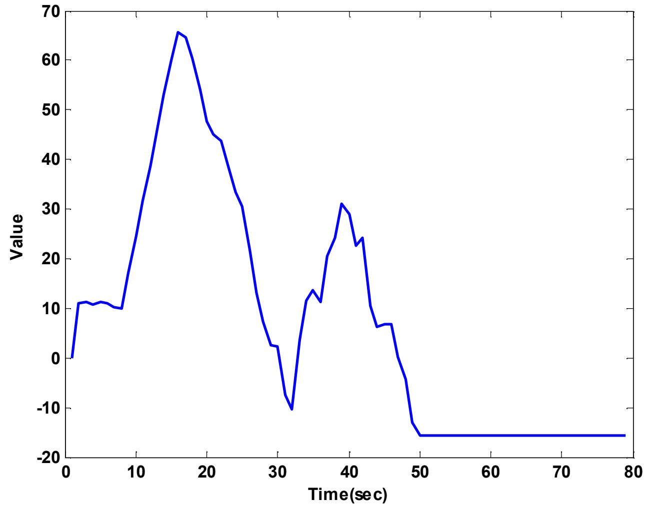

Fig.8. Integral coefficient (k_I) variations

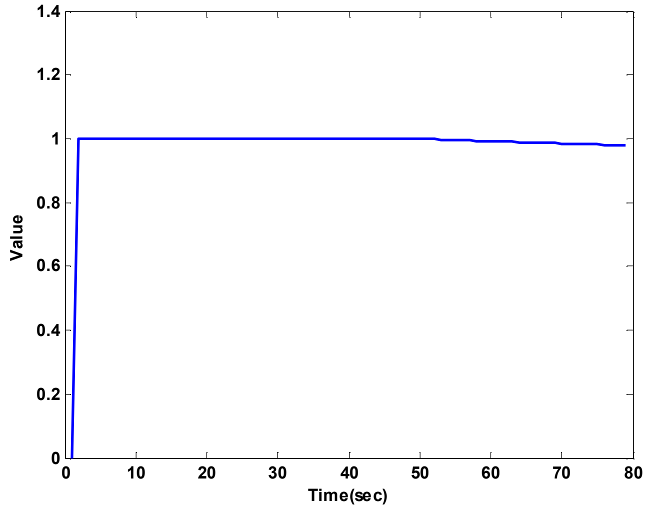

Fig.9. Derivative coefficient (k_D) variation

4. WIND ENERGY CONVERSION SYSTEM AS A MAJOR PLANT IN POWER SYSTEMS

Wind energy conversion systems have very interesting specifications such as simplicity, high reliability and low maintenance expenses. These systems are more cost-effective than all the other renewable energy resources. A WECS could be used in three different topologies: standalone, hybrid and grid-connected. The first topology is used in battery chargers for applications such as illumination, remote radio repeaters and sailboats. The second topology is used in combining wind turbines with solar and diesel generators [2].

In this study, we discuss a horizontal-axis wind turbine which has been discussed for the output power, which is defined as below [11]:

$$P_w = 0.5\rho_a C_p V_\omega^3 A_r \tag{9}$$

Where ρ is the air density, A is the area swept by blades, V_ω is the wind speed and C_P is the power factor which is a nonlinear function of $\lambda = \frac{\omega.R}{V_\omega}$ where R is the radius of the blades and ω is the angular speed of the turbine blades. C_P is usually approximated as $C_P = \alpha.\lambda + \beta.\lambda^2 + \gamma.\lambda^3$ where α,β,γ are constructive parameters for a given wind turbine.

According to physical and mathematical equations of the system, the generation torque of the wind turbine could be obtained as below [11]:

$$T_t = 0.5\rho_a \left(\frac{C_p}{\lambda}\right) V_\omega^2 \pi R^2 \tag{10}$$

The dynamics of the whole system (turbine plus generator) are related to the total moment of inertia. By ignoring of torsion in the shaft, electric dynamics of the generator and other higher order effects, the approximate system's dynamic model is:

$$J\omega' = T_t(\omega, V_\omega) - T_g(\omega, \alpha) \tag{11}$$

The input of studied wind energy conversion system is a time-varying wind speed. In this paper Characteristics of wind is shown in figure (10).Reduce steady state error of the output signal Reject disturbance.

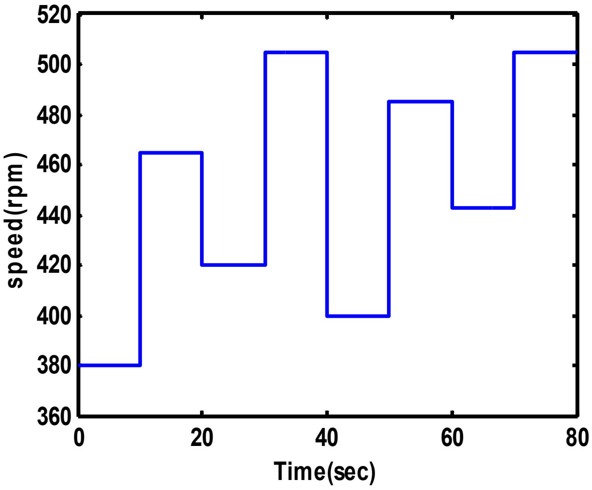

Fig.10. Wind speed as a time-varying input

The open loop system response depicted in figure (11) shows the vital need of advanced controller for reducing error and convergence increment.

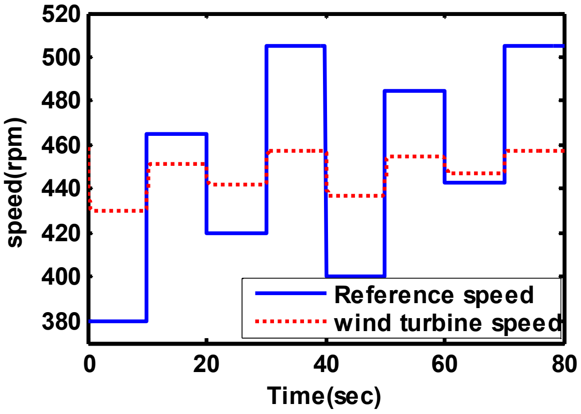

Fig.11. Open loop system response

It seems that, one of the simplest controllers to be capable of satisfying all the above conditions is a PID controller.

5. PROPOSED CONTROLLER IN ORDER TO CONVERGENCE INCREMENT IN PRESENCE OF A MAJOR DISTURBANCE IN WECS

The new proposed PID controller has proportional, integral and derivative coefficients as below:

$$\begin{aligned} k_P &= 0.1 \\ k_I &= 0.5 \\ k_D &= 0.005 \end{aligned} \tag{12}$$

Closed loop system response to the references input is shown in figure (10). Also figure (12) is shown same response with no disturbance .

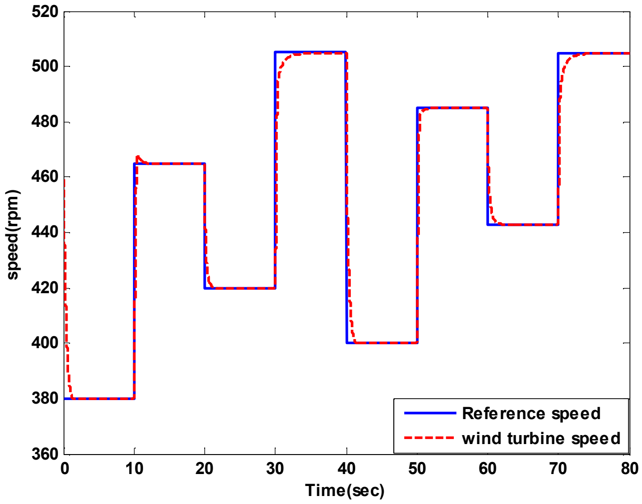

Fig.12. System response with PID controller

According to result of figure (12), PID controller gives a satisfactory closed loop response when there is no disturbance. In order to check the capability of the designed PID controller in the presence of disturbance, a major disturbance on the firing angle of the SCR at 55 seconds is applied.

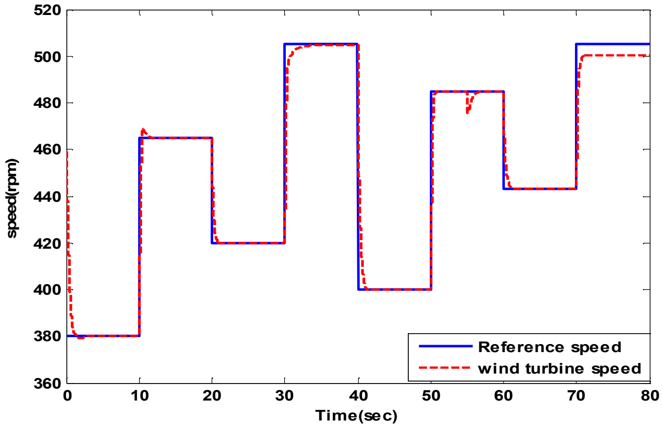

Fig.13. System response with PID controller-disturbance applied to firing angle

Figure (13) is shown applying the disturbance to major element of WECS plant, shows the inability of PID controller to overcome the error increment in many intervals of plant performance. Because of this reason, using another advanced controller which can overcome this problem is necessary. The proposed controller shows its power in overcoming this problem incredibly. Figure (14) shows the response of proposed controller as an adaptive controller on the basis of mentioned disturbance. Variations of proportional, integral and derivative coefficients are depicted in figures 15-17.

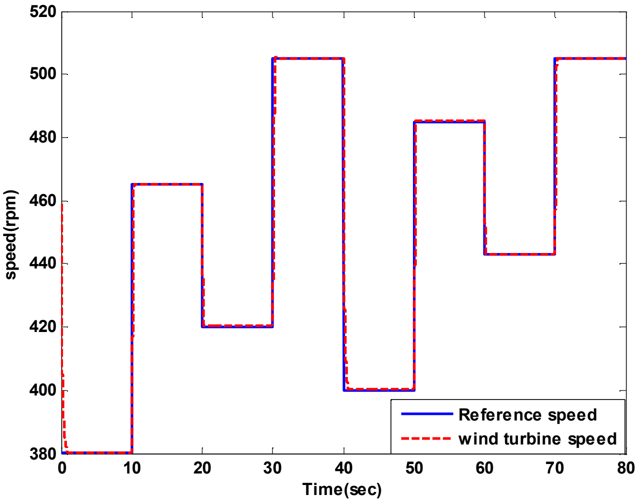

Fig.14. Response of proposed controller with disturbance.

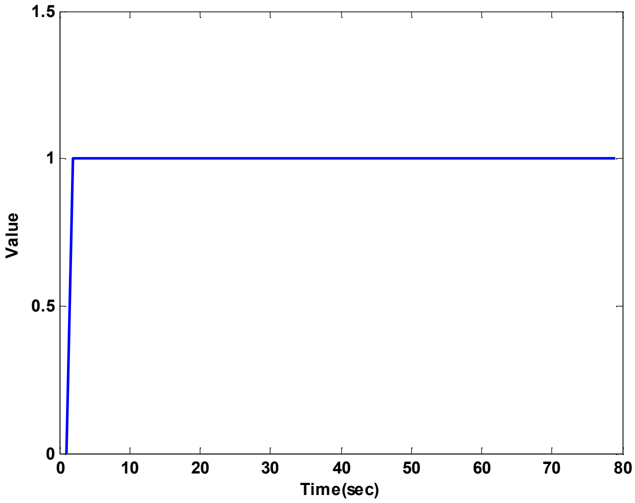

Fig.15. Proportional coefficient (k_P) variations

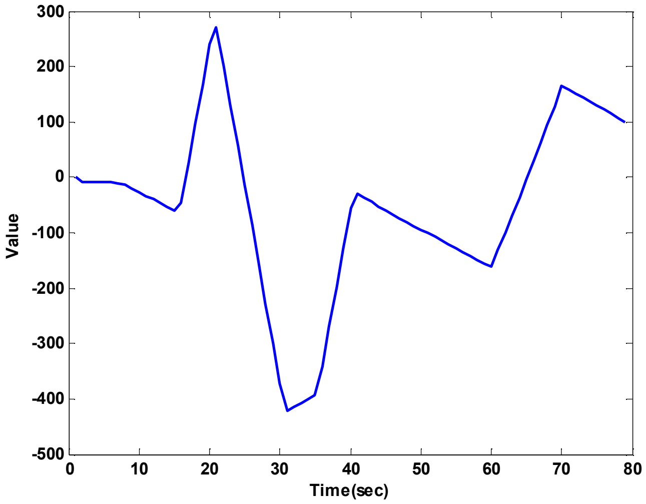

Fig.16. Integral coefficient (k_I) variations

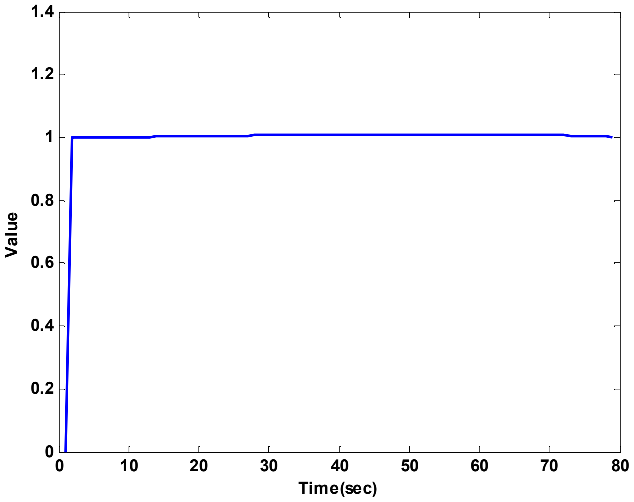

Fig.17.Derivative coefficient (k_D) variations

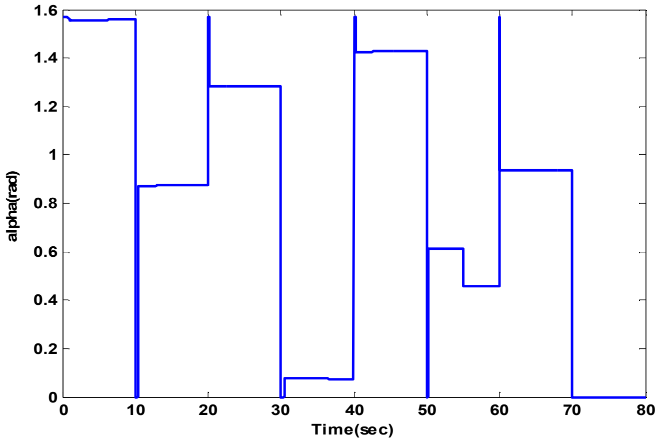

Fig.18.Control signal when disturbance is applied

Figure (14) is shown disturbance rejection has been perfectly carried out via the proposed controller. Figure 18 epicts the control signal (firing angle) when the disturbance is applied it could be easily seen that there is no chattering in the control signal, while it is a very common problem in most of the adaptive controllers..

6. CONCLUSION

In this paper, an adaptive PID controller was proposed to WECS systems. The proposed strategy used a RL algorithm in order to adapt the PID coefficients. It was seen that the proposed controller offered a desired closed loop response when the system was subjected to major external disturbance. High adaptation speed and chattering-free response were shown to be the most significant characteristics of the proposed controller.

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