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PID CONTROL SYSTEM FOR A VARIABLE SPEED HORIZONTAL AXIS WIND MILL

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ABSTRACT

In this work, a control system is designed for a horizontal axis wind turbine (HAWT). The suggested control system includes a conventional PID controller of a closed loop feedback. The nonlinear and linear models have been established for the turbine blades. Open loop Simulation was conducted using MATLAB/Simulink software, and results showed a considerable match to the actual system. A closed loop system was conducted and PID controller gains were tuned considering desired system performance characteristics until final gains were simulated in closed loop form which showed a considerable systems performance improving. Experimental results were analyzed and showed system stability and performance can be established.

Keywords: Wind turbine, Dynamic Modeling, PI, PID Controller
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1. INTRODUCTION AND MOTIVATION

In the last decades, wind turbines have been widely used as an alternative power source [1], rather than fossil fuel and nuclear power plants, which has a shortage potential amount or cause undesirable pollutions. However, due to wind fluctuating behavior, it is highly costly to design a reliable wind turbine [2]. Moreover, one drawback of windmill electricity generators is the unstable wind velocity. The instability decreases the generated power, as well as blades torque load change causes blades fatigue failure [3]. There are two ways to reduce dynamic loads on blades; either stall control or pitch control can be persuaded in order to maximize system performance. In the stall control, the blades are fixed but they are optimally designed such that their profiles reduce the effect of torque load [4]. However, pitch control is a way to overcome this issue is variable angle blades that can rotate around their axes while propeller rotates. Even more, variable blade angles can also attributes in maximizing the wind power captured by the turbine blades by optimizing blades angle corresponding to a certain wind speed. Many researchers have been trying to optimize variable speed wind turbine performance. Designing a control system is an efficient way to enhance the turbine efficiency by applying variable pitch angle blades [5], [6]. By controlling the blades pitch angle, the windmill RPMs will be updated according to wind speed change in a shorter amount of time, and therefore maximize the amount of energy captured. For the interaction between the variables as they related to the power coefficient, the reader is referred to [7]. These control systems vary depending on algorithms used in the design. Conventional and modern control systems have been conducted considering pitch angles. The unpredictable behavior of the wind, as well as the uncertain system model parameters values causes controlling wind mill blades even more challenger. Therefore, more advanced control algorithms have been persuaded. Both PID and PI controllers were compared individually opposing to fuzzy controller. In [8], [9], and [10]. It was noticed that fuzzy controller had showed reasonable stability performance but less error and settling time characteristics. A modified PID controller was combined with neural network for control variable tuning was tried in [11]. Tests revealed improvement in stability and performance Charestestics; however, pretests were needed to estimate system variables parameters. Updated PI gains can be used to ensure stability under system model deviation as shown in [12]. Considerable improvement in system stability. Nevertheless, poor maximum overshoot was noticed.

From all the previous work, there was a common problem, that is the uncertain system model; and due to this uncertainty, the control system cannot be relied on for varying work conditions. The uncertainty source is either wind unpredictable behavior, or system parameters deviation. Thus, complicated control algorithms are needed. This results in more complexity added to the system; and the more complicated controller, the costlier the device is. To deal with such issue, this study is dedicated to design a conventional PID controller used to regulate windmill blade pitch angle. With PID controller, in addition to the superiority in enhancing the stability and error depression performance, both PID controller design and implantation enables to simply control the system. However, to overcome system uncertainty, an algorithm will be followed to precisely model the experimental system. The experimental nonlinear system model will be based on experimental MATLAB/Simulink model, which contribute in precise system parameters and disturbances modulation. The system parameters and their uncertain values will be calculated from system open loop model. The same nonlinear model will be linearized and PID Controller gains will be tuned for on the linearized model [13]. Both open and closed loop linear model are verified. Then the controller is implemented and experimental results are analyzed.

2. WIND MILL SYSTEM EXPERIMENTAL MODELING &CONTROLLER DESIGN

To perform the experimental modeling and test, the edibon EEEC system was used [14]. The system is located in department of mechanical engineering at Al-Mustansiriyah University. It basically converts the wind kinetic energy to electrical energy using wind turbine positioned in a tunnel exposed to axial fan energy source. It consists basically of an axial fan, tunnel, rotor of two blades, sensors, wattmeter and loads module. The axial fan is used supply air in the tunnel of (2 to 5.6) m/s, to simulate the same wind speed range in many regions in Iraq that have the range of wind speed of (3.5 to 5 m/s) which is considered useful for the application of wind energy [15]. The tunnel is manufactured from a stainless steel of (2 x 0.55 x 0.55 m) approximately. The turbine is a simple injection model that joins the tips of the blades. There is no twist in blades due to small blade size. The blade is placed along a perpendicular direction to that of the wind and can be changing the angular position of blades (0° to 90°) by using electric actuator controlled using the lab view software program. The turbine is supplied with wind speed, torque load and blades position sensors. The system is interfaced and controlled by lab view software using control interface unit (CIB). Figure (1) shows the experimental system set up and schematic diagram is shown in figure (2).

Figure 1 Shows System Components

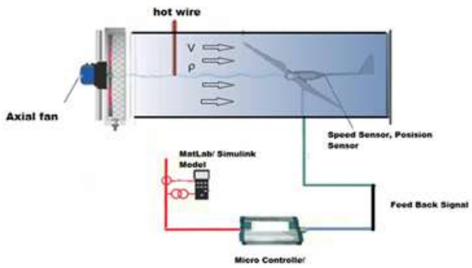


Figure 2 Shows System Scematic Diagram

The model was modeled and exact system parameters were measured to match the actual system variables. Figure (3) shows the whole wind MATLAB/ Simulink system model built to design a control system to a whole system. However, in this work, only blades pitch angle is considered. The system was simplified, then, a classical closed loop control design technique was followed [16]. Knowing that a controller is needed, a simplified version of the system model was created in Simulink. This model can be seen in Figure (4).

The model depends mainly on wind speed, single blade inertia, and the motor used to rotate the blade around its axis. Table (1) illustrates the system uncertain variables calculated and validated experimentally to be used in the system modeling.

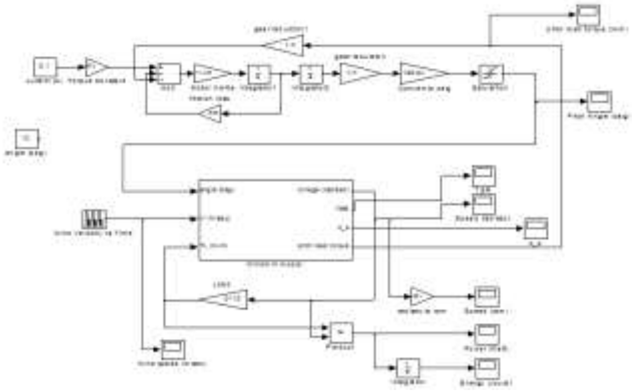


Figure 3 Nonlinear System Model

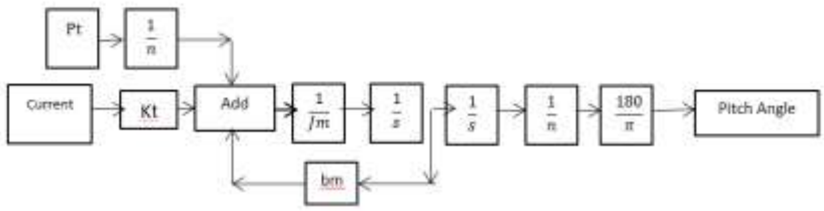
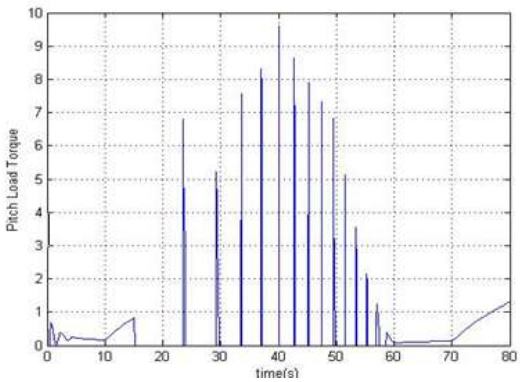


Table 1 Blade Model Parameters

J_m	Blade Inertia	(J_m =0.0006 kg .m^2
Kpt	Pitch angle torque Load disturbance coefficient	=1/R*.05
n	pitch motor gear reduction	n=5
K_t	Motor Torque coefficient	Kt=0.5 (N-m)/A
$\theta_{f.r}$	$Final\ and\ refrence\ angles$	
D	System Disturbance	Ramp Modulation
E	Error	
R	Rotor Radius	0.2 m

Practically based system model and its parameters calculations enable the model uncertainty to be taken into the account. The main uncertain source of the windmill model uncertainty is the pitch load torque results from wind speed variation. Random change in the wind speed results in unpredictable pitch torque load. In this model the pitch load torque acting on the blades is used as a disturbance input. This disturbance input can be modeled using a ramp function. It was seen from the experimental open loop data that the pitch load torque followed this form shown in figure (5). A simple signal was chosen to simplify the original response in order to find the slope and is shown in figure (6). Using the following coordinate points (23.44.3) and (23.46, 6.8) the calculated slope is 190 (Nm/s).



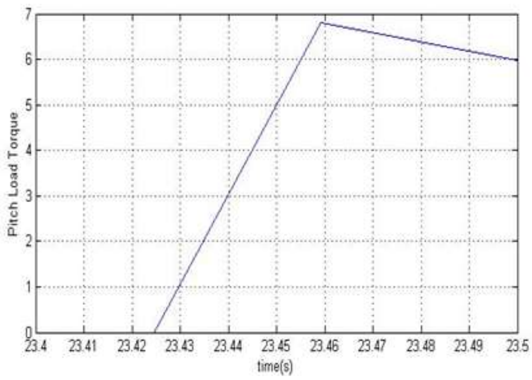


Figure 5 Pitch Load Torque Response **Figure 6** Zoomed in Area of Simplified Model Response

After the system was modeled and simplified, the next step is to determine the system type; this model was simplified using block diagram reduction and is shown in reduction figure (7).

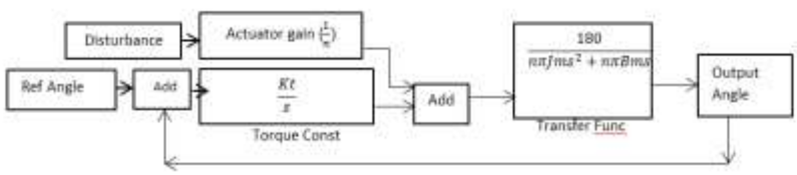


Figure 7 Reduced Block Diagram

After preforming a block diagram reduction, an open loop transfer function, Eq. 1, and linear closed loop transfer functions for inputs of reference input and disturbance input, and outputs of pitch angle and error were calculated. These four transfer functions are listed in Eqs. 2 –5

$$\text{OLTF}=\frac{180\,K_t}{(J_m s+B_m)(\pi n s)} \quad (1)$$

$$\frac{\theta_f}{\theta_r}=\frac{180\,K_t}{(J_m s+B_m)(\pi n s)+(180K_t)} \quad (2)$$

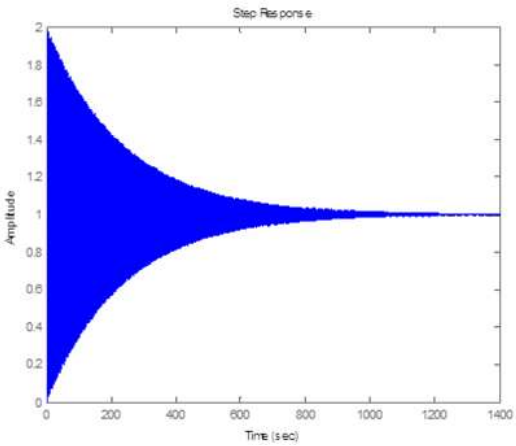
$$\frac{\theta_f}{D}=\frac{-180/n}{(J_m s+B_m)(\pi n s)+(180K_t)} \quad (3)$$

$$\frac{E}{\theta_r}=\frac{(J_m s+B_m)(\pi n s)}{(J_m s+B_m)(\pi n s)+(180K_t)} \quad (4)$$

$$\frac{E}{D}=\frac{180/n}{(J_m s+B_m)(\pi n s)+(180K_t)} \quad (5)$$

It can be seen from Eq. 1 that this system is type 1 for tracking reference inputs. Using the final value theorem, [17], on Eq. 4 and Eq. 5 shows the system is a type 0 for disturbance rejection. This system is 2nd order and is stable. The system was noted to be stable as it only has poles in the left hand side of the complex plan.

A controller is needed for this system when the disturbance input is modeled as a ramp function. This type of disturbance requires a Type 1 system to attain constant steady state error. To transform the system from a “Type 0” to a “Type 1”, an integrator is required for the system. The proportional controller is needed to improve the response by improving the rise time and the maximum percent overshoot. However, from Figures 8,9, show pole locations and response of a system, it can be concluded that no enhancement exists in performance requirements.



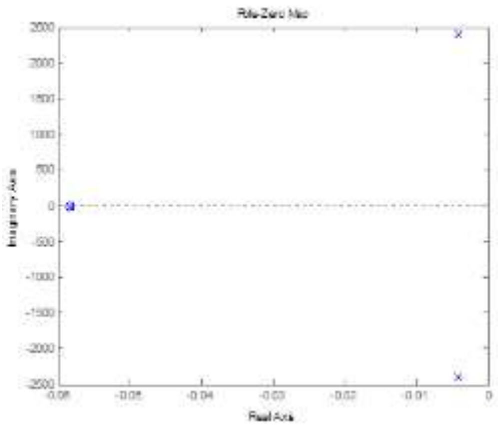


Figure 8 Simulation Response due to Kp=6000, Ki=350 **Figure 9** Pole Locations due to Kp=6000, Ki=350

Thus, a derivative is added to enhance poles locations. A PID controller will be used to satisfy a steady state error of ≤ 2%, rise time ≤ 2 Sec. and an overshoot ≤ 10%. figure (10), shows the system with a PID controller introduced in the system. In order to satisfy the steady state error and Routh stability criterion, Ki needs to be greater than 304 and Kp (0.002π+90Kd) must be greater than 0.03Ki. Using Ki of 400, Kd of 1, and change the value of Kp until the performance requirements are satisfied. It was noticed that as Kp increase, the characteristic roots move to the desirable region. With the Kp value of 40, the system response and pole locations are reported in figures (11,12).

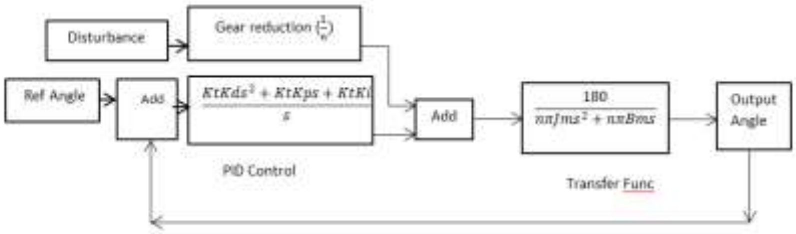


Figure 10 System with PID Controller

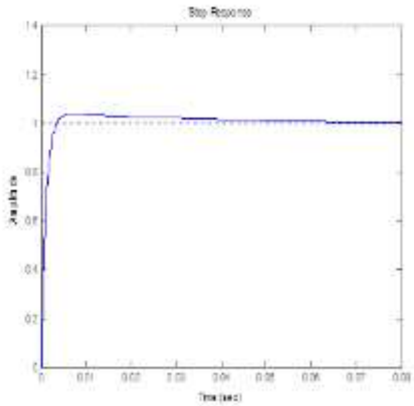


Figure 11 Simulated System Model Pitch Angle Response due to PID Controller with Ki=400, Kp=40, Kd=1

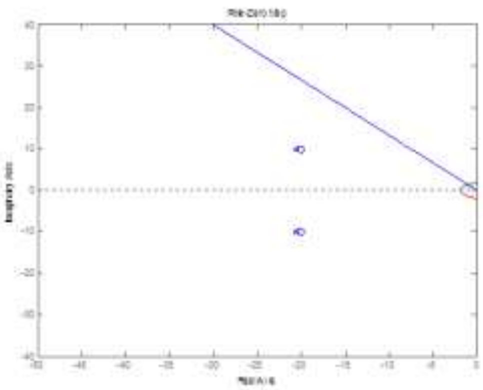


Figure 12 Zoomed Poles Locations due to PID Controller with Ki=400, Kp=40, Kd=1

3. EXPERIMENTAL RESULTS

After numerical controller parameters were selected, the next step is to validate the design experimentally. This is conducted by implementing the controller to the closed loop system. The input to the system is the desired blade pitch angle, and the output is the actual angle in the presence of blade torque load as a disturbance. The wind turbine described before was used after applying the controller variables to Lab VIEW software to process the signal to the actuator controlling the blades through (CIB). A position sensor was calibrated and used to measure the position of each blade in order to check steady state error. The system was given a desired angle as the wind speed was changed. Then by the CIB the current signal according to the desired angle is sent to the blades actuator which rotates the blades around their axis. Then to RPM velocities and output pitch angle was measured. The error signal results after comparing both desired and output signals, measure by blades position sensor is sent through PID controller to the actuator to accommodate for the design preselected performance characteristics. The test was repeated for different desired blade angles, and stability and error were inspected observing the stable operation of the propeller RPM, measured by the turbine speed sensor. Figure (13) shows the experimental closed loop test results, it can be noticed that the effective wind speed is between 1.8M/s and 5.6m/s. Also, the uniform increasing of blades rotating velocity reveals the reasonable system stability. Moreover, error and other performance characteristics collected from sensors indicated a reasonable improvement. It is worth to mention that changing the wind speed was noticed to cause disturbance torque change which was considered as a source of system uncertainty disturbance. The superiority of the designed controller is revealed by depressing the disturbance uncertainty effect to a minimum value. This is obvious from the figure which shows no fluctuation or sharp changes in the turbine speed. The experimentally based model is proved to be the best system emulation in designing PID controller system. Table [2] illustrates both desired and achieved system performance characteristics. It is obvious that the activity of the controller is advantageous. Moreover, the main challenge of PID controller, torque load, was overcome and perfect percentage overshoot was noticed, using robust system model.

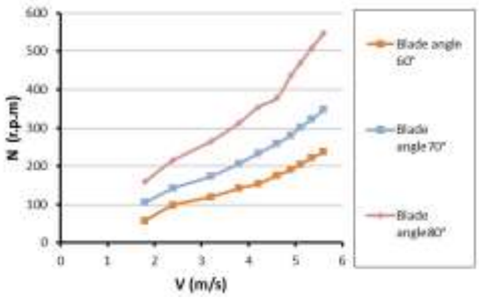


Figure 13 Experimental Closed Loop RPM Vs Wind velocity at Desired Test Blade Angles

Table 2 Both desired and achieved Performance Characteristics

	ωn(Natural Frequency)	**ζ(Damping Ratio)**	**%OS(Over Shoot)**	**t_r(RiseTime)**	**e_{ss}(Error)**
Required	≥1.8rad/sec	≥0.59115	≤10%	≤2 sec	≤2%
Achieved	3.5rad/sec	0.802	6 %	2sec	2%

4. CONCLUSIONS

1. This study shows that even simple mechanical systems require complex calculations for reliable control. This particular system required the implementation of a PID controller into a feedback control loop.
2. This controller was designed to meet certain performance requirements that would help attain maximum energy production.
3. The PID controller was chosen due to its superiority to the PI controller. The final design used a Kp value of 40, resulted in a rise time of 0. 78 sec, and a maximum overshoot of 2.5E-2 %.
4. The practical work was performed to validate the designed controller. Different desired blade angles were selected as input and feedback error was used to calculate error. Stable increasing of the RPM of the blades as the wind velocity increases proposes a stable behavior of blades.
5. Thus it can be concluded that based on precise system modeling, closed loop classical controller can closely perform characteristics as more advance controller technique without adding complicity to the design.

6. More advanced controller technique can be tried to establish better performance and stability characteristics.

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