Pitch Angle Control for a Permanent Magnet Synchronous Generator-based Wind Energy System based on Proportional Resonant (PR)

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ABSTRACT

The study presents the development of a Proportional-resonant (PR) based pitch angle control strategy for a 2MW Permanent magnet synchronous generator (PMSG) based wind energy system. The model in this work comprises of wind turbine, Permanent Magnet Synchronous Generator (PMSG), AC-DC converter, DC-DC boost converter and Pitch angle of a standard 2MW wind turbine. The PR pitch angle controller was designed, gains optimized using Teaching Learning Based Optimization (TLBO) Algorithm and the performance of PR TLBO was compared with that of TLBO tuned fractional order non-linear PID (FONPID). It was then evaluated in terms of rise time, settling time, overshoot and undershoot of the frequency deviation; While FONPID takes 1.99 seconds to recover, PR took 1.860 seconds indicating its faster recovery from step wind speed. This in turn results to elimination of steady-state error which can not be achieved by FONPID when used with sinusoidal references.

1. INTRODUCTION

The world's population is increasing rapidly, which results to decrease in conventional resources and up-surging ecological consequences; this therefore emphasizes the need to discover feasible resources of renewable energy (Ghodsi *et al.*, 2019). Wind energy has emerged as the most fortunate alternative source of energy among the renewable energy sources. The first nation to employ wind power to produce electricity was Denmark. (Gary *et al.*, 2006). Wind turbine converts the kinetic energy into mechanical power. The wind blows turbine blades/propellers which are attached to a rotor. The rotor then spins a generator to generate electricity (Sahu *et al.*, 2018). Wind is clean, free and inexhaustible energy source. Wind power system has low maintenance cost and it can be built on existing farms and ranches. Wind power is 30-40% efficient (World-bank 2015). However, wind cannot be stored (requires batteries); it is inconsistent, the system has high upfront capital cost though this trend has changed tremendously from two million dollars per MW to one million in the last decade (Mone *et al.*, 2017). It causes noise pollution to the nearby community (Zhu *et al.*, 2018).

The foremost problem of wind power system is power fluctuation above or below rated value due to the dynamic nature of wind speed (Wright *et al.*, 2019). To minimize such large fluctuations due to variable wind speed, a pitch angle control method needs to be implemented and hence plays a very important part in the effective operation of the wind energy system. The conventional method of pitch angle could involve the PI/PID controller. This method of pitch angle control is extensively used due to their feasibility, cost effectiveness and ease of implementation. The PID controller-based pitch angle control can be achieved based on the error generated between the control signals. The system can be treated as a black box even if wind turbine parameters are not known. However, the PID pitch angle controller has to achieve balanced gains in order to deal with the transient response of wind turbine, which are settling time, rise time, overshoot etc. if the pitch angle controller gains cannot be accurately achieved, the designed pitch angle control method may not deal with the problem due to uncertainties in wind speed. Also, due to lack of wide range of flexibility, the PID pitch angle controller shows low rate of robustness as compared to the robust controllers for the system under highly nonlinear characteristics of wind speed. It is also noted that, for a ramp signal as an input variation, the controller displays offset and gives a poor performance for slow disturbance rejection. More importantly, the PID controller offers large oscillations in output for step varied input signals.

Wind energy conversion system (WECS) is a complex plant from the control engineering viewpoint, as it involves generators, rectifiers, converters etc. with nonlinear characteristics, in addition, the performance of WECS depends on the highly variable wind profile. Therefore, the implementation of an easy-structure and adaptive control method for pitch angle control is required, which can deal with the transient behavior of the wind energy system during highly uncertain wind speed, minimizes large fluctuations in output power, eradicates steady-state error and also preserves the demands of robust and adaptive control.

Artificial Intelligence (AI) supervised pitched angle controllers using Fuzzy logic (FL), Artificial Neural Network (ANN) and hybridized controllers have been testified effective (Silpa *et al*., 2017). However, these pitch angle controllers have the disadvantages of computational complexity which limit their implementation in real-time, large amount of data of wind turbine parameter required for proper training of ANN-supervised pitch angle controller. To deal with these disadvantages, several combinations of FL and optimization techniques have been analyzed, for example, GA has been applied to tune the membership functions of FL, which is implemented for performance enhancement of electrical generator. AI supervised pitched angle control methods have been merged with Intelligent Search Algorithm (ISA) due to their ability to deal with large oscillations in output power but AI-based controllers are limited to implement in real-time. As such, researchers came up with PI/PID pitch angle controllers. An improved structure of PI pitch angle controller is proposed where the integral term of the PI controller has been converted to Fractional-order integral gain. The number of controller gain is increased. However, these approaches of pitch angle control results in a steady-state error which cannot be eliminated when used with sinusoidal references (Ahmed *et al*. 2017). Given the shortcomings of the PI, an alternative solution for a current controller has been presented which is the Proportional resonant (PR). The PR controller is a combination of a proportional term and a resonant term. The PR controller has been used in the stationary reference frame method (Tarasantisuk *et al*., 2019). Within the control system; grid current is conveyed to the stationary reference frame using Clerk's transformation from three-phase $i_{a,b,c}$ to $i_{\alpha,\beta}$ coordinates. Hence, PR controller variables are sinusoidal. In addition, a PR controller has the ability to eradicate steady-state error by offering extra gain at the particular resonant frequency of the controlled signal. The PR controller has the capability to implement harmonic compensator (HC) without introducing any deviation in dynamic control; thus this accomplishes a high-quality current.

2. PITCH ANGLE REPRESENTATION

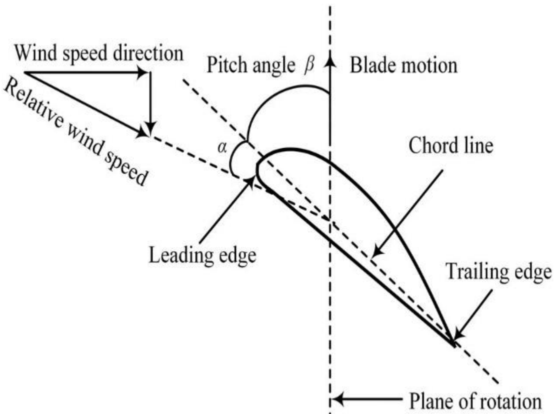

Fig. 1 Representation of pitch angle

$\Delta\beta=\frac{1}{T_t}(\beta\text{req}-\beta\text{act})$ and $\beta\text{act}=(\frac{m}{TiS+n})\,\beta\text{req}$...... (1)

βreq and βact are required and actual values of the Pitch angle, respectively. The value of m and n are assumed unknown. The performance of the

Pitch angle controller is also governed by time constant, T_t (0.25 second), of the pitch servo. A rate limiter and saturation block are also provided to achieve reasonable execution of the Pitch servo system.

This paper presents comparison of the performance of the developed pitch angle controller, proportional resonant (PR) to that of FONPID (fractional order non-linear proportional integral derivative). FONPID is an advanced configuration of a conventional PID controller. The controllers were optimized using Teaching Learning based Optimization Algorithm (TLBOA) using four performance metrics: Rise time, Settling time, Overshoot and average power oscillation range.

3.0 OPERATING PRINCIPLES OF PROPORTIONAL RESONANT

Proportional resonant controller (PR) is a particular type of transfer function that is often implemented for the closed-loop control systems with a sinusoidal behavior. As their name indicates, they possess both a proportional and a resonant term, which can be tuned independently.

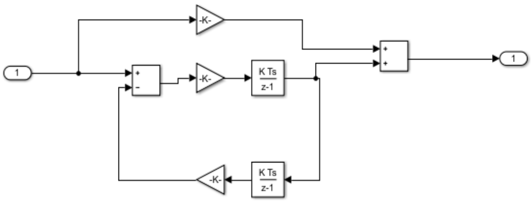

Fig. 2 PR controller implementation

The controller transfer function is given as:

$$G_{PR}(s) = K_p + K_i(\frac{S}{S^2+\omega_o{}^2}) \text{ .... (2)}$$

The denominator, $S^2+\omega_o{}^2$ in the above equation (2) creates infinite control gain at ω_o $(target\ resonant\ frequency)$. The equation is considered ideal and since the ideal PR may suffer from stability issues due to the infinite gain at the resonant-frequency, in the above equation the PR controller can be made practical by adding the damped term. Therefore, a non-ideal PR controller is given in equation (3)

$$G_{PR}(s) = K_p + K_i(\frac{2\omega_c{}^2 S}{S^2+2\omega_o s+\omega_o{}^2}) \text{ .... (3)}$$

Where K_p is the proportional constant, K_i is the integral constant, and ω_o is the resonant frequency

ω_c designates the resonant cut-off frequency i.e. width of the resonant filter. The gain at ω_o is now finite, but still high enough for enforcing a sufficiently small steady-state error.

Using the bilinear (Tustin) transform, the resulting discrete transfer function for the resonant term, discretized with a period T_s yields;

$$G_{pr}(z) = \frac{Y(z)}{E(z)} = \frac{a_1\,(1-z^{-2})}{b_0+b_1 z^{-1}+b_2 z^{-2}} \text{ ....(4)}$$

Where: a = $4K_1T_sW_c$

$$b_0 = T_s^2W_0^2 + 4T_sW_C + 4$$
$$b_1 = 2T_s^2W_0^2 - 8$$
$$b_2 = T_s^2W_0^2 - 4T_sW_C + 4$$

Then the resonant part yields;

$$y_{(x)} = \frac{1}{b_0}\,[a_1 . e(k) - a_1 . e(k-2) - b_1 . y(k-1) - b_2 . y\,(k-2)]$$

The above equation is useful for generating run time code for possible implementation on Simulink below;

Table 1. Wind Turbine Parameters

S/N	Wind Turbine Parameters	
	Parameters	Values
1	Rated wind speed (Vw)	12m/s
2	Rated power	2MW
3	Radius of blade (R)	38.3m
4	Air density (p)	1.225kg/m3
5	Maximum power coefficient	0.41
6	Blade Inertia	$6.3 * 10^6$ kgm^2

Table 2: PMSG Parameters

S/N	**PMSG Parameters**	
	Parameters	***Values***
1	Grid Voltage	690V
2	Stator Resistance	0.00855 Ω
3	Stator Inductance	38.3m
4	Air density (p)	1.225kg/m3
5	Maximum power coefficient	0.41
6	Blade Inertia	$6.3 * 10^6$ kgm^2

4.0 RESULTS AND DISCUSSION

The solution diagrams of figures 2 and 3 were implemented in MATLAB/Simulink and the results are presented and discussed in this section. Figures 5a-e shows rotor speed response, power coefficient, tip speed ratio and electromagnetic torque under different profiles of wind speed.

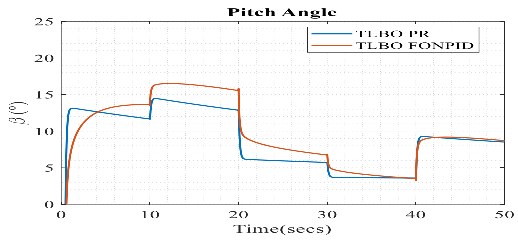

Fig. 4. Different profiles of wind speed to calculate recovery time

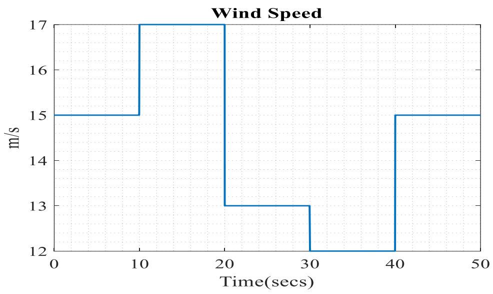

Fig. 5a. Electromagnetic Torque

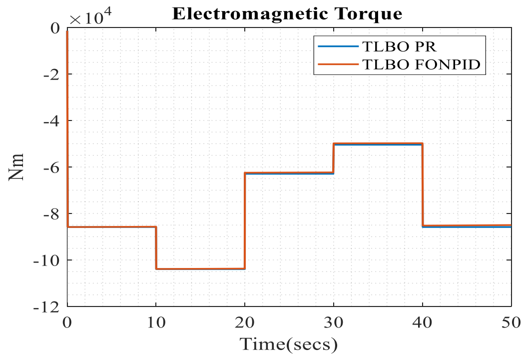

Fig. 5b: Tip Speed Ratio

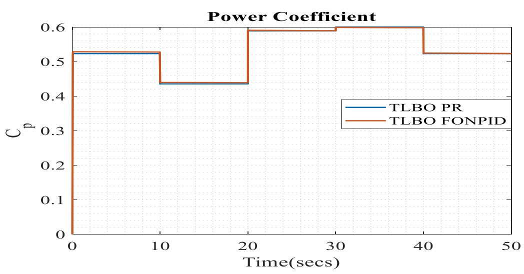

Fig.5c. Power coefficient

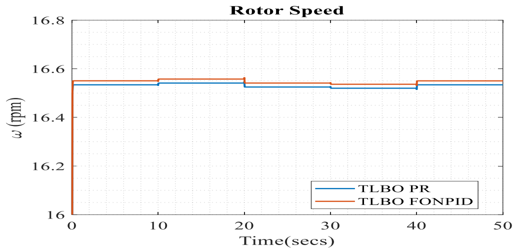

Fig. 5d: Rotor speed response

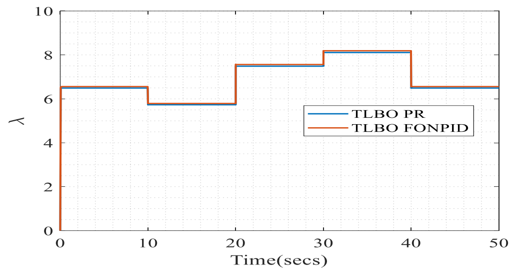

Fig. 5e: Pitch angle responses

Figures 5 (a-e): Convergence plots of TLBO tuned pitch angle controllers (PR and FONPID)

Table 3. Performance Evaluation

Performance Evaluation				
Considered controllers	***Settling time (s)***	***Rise time (s)***	***Average power oscillation range (MW)***	***% Overshoot***
FONPID	1.990	0.199	0.22	0.11
PR	1.860	0.190	0.17	0.09

5.0 CONCLUSION

PR has been proposed and investigated for output power regulation of the 2MW wind turbine. The simulation span is considered 50 seconds, under the step changed and perturbed profiles of the wind speed. In figure 4 above, initially, wind speed is 15m/s, where the expected output power is 2MW, corresponding to 16.6rpm rotor speed. At t = 10seconds, wind speed is increased to 17m/s. At this instance, output power increased initially, however, it recovers its final value within a few seconds for both pitch angle controllers. While FONPID takes 1.99 seconds to recover its final value, PR took 1.860 seconds as shown in table 3 above.

From the simulation results, the performance of the developed PR optimized control scheme as against FONPID was evidenced with an average percentage improvement of 0.09 as against 0.11

representing 18.2% in overshoot. Also, the settling time for PR was observed to be 1.860seconds as against 1.990seconds representing 6.5% improvement. Furthermore, the rise time was observed to be 0.190seconds as against 0.199seconds, which represent 4.5% percentage improvement. The average power oscillation was recorded to be 0.17MW as against FONPID with 0.22MW which represent 22.7percentage reduction. The recovering time from step wind change in comparison with PR and FONPID was observed to be 1.84seconds and 2.001seconds which represent 8.0% improvement.

However, Implementation of the developed scheme on real 2MW wind turbine should be considered for future researches.

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