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RESEARCH ARTICLE

Pitch Control of Variable Speed Wind Turbine with Permanent Magnet Synchronous Generator (PMSG) Using Single-Neuron PI Controller

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Abstract

Variable-speed wind turbines with Permanent Magnet Synchronous Generator (PMSG) offer high efficiency in converting wind energy into electrical power. However, under wind conditions exceeding the rated speed, a pitch angle control mechanism is required to maintain output power stability and protect the system from overloading. Pitch angle control is commonly implemented using conventional PI controllers. This study aims to implement a single-neuron PI controller as an adaptive solution for regulating the pitch angle in a PMSG-based wind turbine system. The proposed control method combines the basic structure of a PI controller with adaptive learning based on a single neuron, enabling real-time adjustment of the controller weights based on output power error. The simulation and modeling of the wind energy conversion system are carried out using MATLAB/Simulink, including the modeling of wind turbine, PMSG, conventional PI-based pitch control, and single-neuron PI-based pitch control. Simulation results demonstrate that the single-neuron PI controller effectively maintains the output power close to the reference value, with minimal deviation and high stability across various wind speeds exceeding the rated condition. Compared to the conventional PI controller, this method offers superior adaptability to system parameter variations and dynamic wind speed changes.

Keywords: wind energy conversion system, variable speed wind turbine, pitch control, PMSG, Single-neuron PI Controller

1. Introduction

In today's modern world, electricity has become a fundamental necessity for all levels of society. Disruptions to electricity supply can directly impact industrial, social, and economic activities, potentially slowing down economic growth. Generally, electricity is generated by thermal power plants through the combustion of fossil fuels. However, the utilization of fossil fuels in power generation significantly contributes to global environmental issues such as global warming and presents challenges related to energy security. Over the past few decades, concerns over energy crises and environmental degradation have driven many countries to transition from fossil-based power generation to more environmentally friendly and sustainable alternatives—renewable energy sources. Among these, wind energy has shown great potential for development due to its abundance in nature, zero fuel cost, and zero greenhouse gas emissions during the conversion process. Consequently, extensive research has been conducted to explore efficient methods for converting wind energy into electrical energy.

The operation of wind turbine generator systems can be classified into two main categories: grid-connected systems and stand-alone systems. Modern wind energy systems typically consist of several key components, including wind turbines, drive trains, generators, power electronic converters, and control systems. The performance of wind energy systems highly depends on both energy conversion efficiency and the effectiveness of their control strategies. Several types of generators commonly used in wind energy conversion systems include Induction Generators (IG), Doubly-Fed Induction Generators (DFIG), and Permanent Magnet Synchronous Generators (PMSG). Among these, PMSGs are widely employed due to their high power density, high efficiency, and simpler structural design [1], [2], [3].

Based on their operational characteristics, wind turbines are categorized into two main types: fixed-speed wind turbines and variable-speed wind turbines. Fixed-speed turbines operate at a constant rotational speed regardless of wind speed variations, while variable-speed turbines are capable of adjusting rotor speed according to wind speed in order to optimize energy capture and reduce mechanical stress. When the wind speed exceeds the rated value, the generated power may surpass the design capacity of the system, potentially causing damage to the turbine components. To prevent this, a control mechanism is required to maintain the output power at its rated value even under high wind speeds. Variable-speed wind turbines generally employ two different control objectives depending on the wind speed range. At low to medium wind speeds, the control system aims to maintain an optimal tip speed ratio to maximize aerodynamic efficiency. At high wind speeds, the main control objective is to regulate the output power to its rated value to avoid overloading the system [4]. There are two main methods for maintaining stable power output in wind turbines: stall control and pitch control. Stall control is typically used in fixed-speed turbines, while pitch control is applied to variable-speed systems [5]. Pitch control works by adjusting the angle of the turbine blades relative to the wind direction to regulate the amount of aerodynamic force captured by the turbine. This adjustment increases or decreases the energy absorbed from the wind, ensuring that the turbine's output remains at its nominal power even when wind speeds exceed the rated value. The most commonly used pitch control strategy is the conventional PI controller. In addition, several advanced pitch control methods have been proposed, such as linear active disturbance rejection control [6], adaptive integral sliding mode control [7] [8], control techniques for both below and above rated wind speeds [9], fuzzy logic-based pitch angle control [10], and nonlinear PID-based strategies for variable-pitch wind turbines [11].

This research focuses on simulating a pitch control system using a Single-Neuron PI (SNPI) controller to regulate the output power of a wind turbine system connected to a Permanent Magnet Synchronous Generator (PMSG), ensuring that the output remains at its nominal value when wind speed exceeds the rated level (the speed at which the turbine reaches its maximum power output). A single-neuron is the basic model of an artificial neural network consisting of a single-layer structure. The SNPI controller is capable of learning based on output error changes, thus offering a faster and more precise response compared to the conventional PI controller. The SNPI-based pitch control system adjusts the wind turbine's blade pitch angle by comparing the actual generator output power with the nominal reference value. The entire wind turbine system, including the pitch control mechanism using the SNPI controller, is modeled and simulated in the MATLAB/Simulink environment.

2. Wind Energy Conversion System

2.1 Wind Turbine Model

The wind energy conversion system (WECS) consists of several components that convert wind kinetic energy into electrical energy in a controlled, reliable and efficient manner. The main components of WECS can be generally divided into mechanical, electrical and control systems [6]. Wind kinetic energy is transmitted from the wind turbine blade to the generator shaft in the form of mechanical power. Eventually, the generator converts the mechanical power generated into electrical energy. The generated (mechanical) power extracted by the wind turbine from the wind is represented by the following equation.

$$P_m = C_p(\lambda, \beta)\frac{\rho A}{2}v_{wind}^3 \tag{1}$$

where P_m is Mechanical output power of the turbine (W), C_p is the wind energy utilization coefficient or the performance coefficient of the turbine representing the wind turbine efficiency that converts the kinetic energy from the wind into mechanical energy, ρ is the air density (kg/m^3), A is the swept area of the turbine blades (m^2), v_{wind} is the wind speed (m/s),$\lambda = \omega R / v_{wind}$ is the tip speed ratio of the rotor blade tip speed to wind speed, ω is the wind turbine rotor speed (rad/s), and β is the pitch angle of the blade (deg) [5]. The equation (1) can be normalized into the per unit (pu) system as following

$$P_{m\_pu} = k_p C_{p\_pu} v_{wind\ pu}^3 \tag{2}$$

where P_{m_pu} is power in pu of nominal power for particular values of ρ and A, C_{p_pu} is the performance coefficient in pu of the maximum value of C_p, $v_{wind\ pu}$ is the wind speed in pu of the base wind speed, the base wind speed is the mean value of the expected wind speed in m/s, and k_p is the power gain for C_{p_pu} =1 pu and $v_{wind\ pu}$ =1 pu, k_p is less than or equal to 1. The relation between the wind speed and aerodynamic torque is expressed by the following equation [4], [12]

$$T_w = \frac{1}{2}\frac{C_p(\lambda, \beta)}{\lambda}\rho\pi R^3 v_{wind}^2 \tag{3}$$

where T_w is the aerodynamic torque extracted from the wind (Nm), C_p is the wind turbine performance coefficient, λ is the tip speed ratio of the rotor blade tip speed to wind speed, β is the pitch angle of the blade (deg), ρ is the air density (kg/m^3), R is the wind turbine rotor radius (m), and v_{wind} is the wind speed (m/s). The power coefficient of the turbine $C_\rho(\lambda, \beta)$ is the function of tip-speed (λ) and pitch angle (β), it is a nonlinear function which depends on aerodynamic design of the blade and wind turbine operating conditions. According to Betz's law, the extreme value for the power coefficient C_p is 0.593 which means the maximum power that can be extracted is is 59.3% [13]. In Simulink model, a generic equation is used to model $C_p(\lambda, \beta)$. This equation, based on the modeling turbine characteristics of [14]

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

the coefficients C1 to C6 are: C1 = 0.5176, C2 = 116, C3 = 0.4, C4 = 5, C5 = 21 and c6 = 0.0068. The maximum value of power coefficient $C_p(C_pmax = 0.48)$ can be obtained at a blade pitch angle β = 0 degrees and tip speed ratio λ = 8.1 [15]. Fig. 1 shows the relationship between the power coefficient C_p, blade pitch angle β, and the tip speed ratio λ. The power coefficient will decrease with the increase of the pitch angle as shown in Fig. 1.

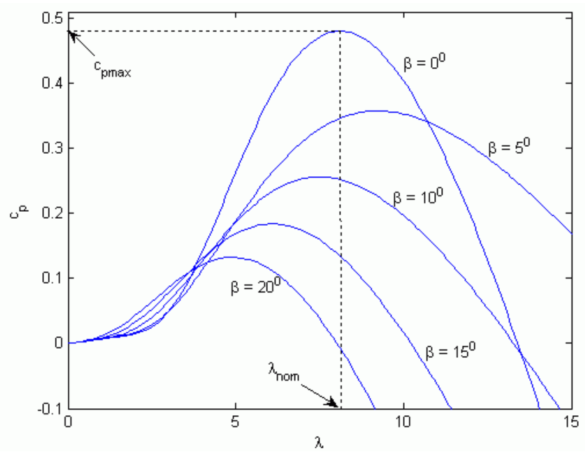

Figure 1. relationship between the power coefficient C_p, blade pitch angle β, and the tip speed ratio λ

2.2 Generator Model

This simulation used permanent magnet synchronous generator (PMSG) that connected to the wind turbine to convert the mechanic energy into the three-phase electricity power. PMSG is popular because of its compact size and high power density [5]. The model of the PMSG is based on dq equivalent model shown in Fig. 2.

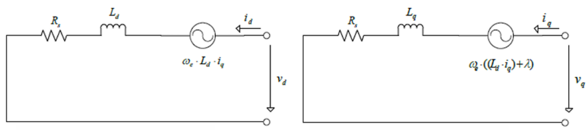

Figure 2. D -q equivalent circuit of PMSG at synchronously rotating reference frame

The three-phase sinusoidal model electrical system of PMSG can be expressed by following equation

$$\frac{di_d}{dt} = \frac{1}{L_d}v_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_r i_q \tag{6}$$

$$\frac{d}{dt}i_q = \frac{1}{L_q}v_q - \frac{R}{L_q}i_q + \frac{L_d}{L_q}p\omega_r i_d - \frac{\lambda p\omega_r}{L_q} \tag{7}$$

The electromagnetic torque can be written as following

$$T_e = 1.5p\left[\lambda i_q + (L_d - L_q)i_d i_q\right] \tag{8}$$

Where,
L_d, L_q : d and q axis inductances
R : Resistance of the stator windings
I_d, i_q : d and q axis currents
vd, vq : d and q voltages
ω_r : Angular velocity of the rotor
λ : Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases
p : Number of pole pairs
T_e : Electromagnetic torque
The dynamic equation of the model are given by

$$\frac{d}{dt}\omega_r = \frac{1}{J}\left(T_e - T_f - F\omega_m - T_m\right) \tag{9}$$

$$\frac{d\theta}{dt} = \omega_r \tag{10}$$

Where,
J : Inertia of rotor
F : Friction of rotor

θ : Rotor angular position
T_m : Shaft mechanical torque
T_f : Shaft static friction torque
ω_r : Angular velocity of the rotor (mechanical speed)

2.3 Pitch Control System

Pitch angle β is the angle by which a wind turbine blade is rotated around its longitudinal axis to control the interaction between the wind and the blade surface. Adjusting the pitch angle of the blades, provides an effective means of regulating or limiting turbine performance in strong wind speeds. In the pitch-adjusting variable-speed wind turbines, the angle of attack α decreases when the pitch angle β increases, as shown in Fig. 3. The lift force F_L decreases as well and this causes reduction of the mechanical power of the wind turbine. According to equation 1, the power of the wind turbines will increase as the wind speed increases. The wind turbine must be protected against mechanical overloads and possible risk of damages at strong wind. This can be achieved by pitching the blades into the position where a part of incoming wind will pass by the wind turbine [16]. The power will be kept at its rated value at this region. To put the blades into the necessary position, pitch servos are employed which may be hydraulic or electrical systems. The conventional blade pitch angle control strategies are shown in Fig. 4.

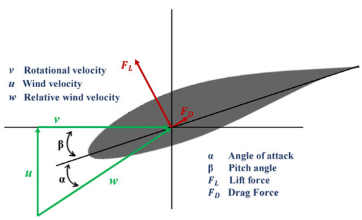

Figure 3. Blade Element of Wind Turbine

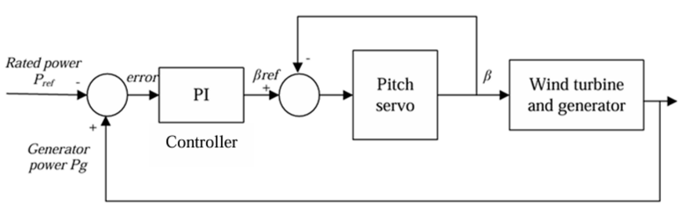

Figure 4. Conventional Pitch Angle Control Strategy Using PI Controller

The error signal between the actual generated power P_g by generator and the rated power P_ref of the generator is sent to a PI controller. The PI controller produces the reference pitch angle β_ref. The actuator of the variable pitch system is realized by the hydraulic system or the servo motor. Generally, the moment of inertia in the rotor blades is very large, so the pitch system can be expressed by Laplace transform of the first-order equation as shown in equation 11 [6].

$$\beta = \frac{1}{\tau s + 1}\beta_{ref} \tag{11}$$

where β is the pitch angle, β_ref is the pitch angle reference given by the control system, and τ is a turbine dependent time constant of the pitch actuation system, in this case τ = 0.1 [17].

2.4 PI Controller

The proportional-integral (PI) controller combines two primary control actions, proportional and integral, to generate a control signal u(t) that directs the system output to follow the reference value. The general equation of the PI controller is:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)\, dt \tag{12}$$

where K_p is the proportional gain, K_i is the integral gain, $e(t)$ is the error signal, and $u(t)$ is the control signal. To be implemented in a digital system, the continuous form of the PI equation must be converted into the discrete form as follows:

$$u(k) = K_p\, e(k) + K_i\, T \sum_{j=1}^{k} e(j) \tag{13}$$

where T is sampling time (s) and k is the discrete index [18].

2.5 Single-neuron Model

The single-neuron is a basic model of an artificial neural network consisting of a single layer as shown in Fig. 5.

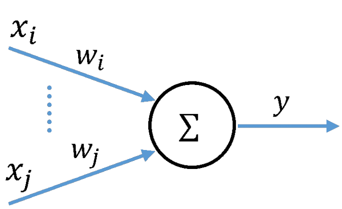

Figure 5. Structure of Single-neuron

each input x_i is multiplied by the weight w_i and summed to:

$$u = \sum_{i=0}^{n} w_i x_i \tag{14}$$

the result of this summation is then processed through an activation function to produce the neuron output:

$$y = f(u) \tag{15}$$

to enable the self-learning process, the weight w_i is updated using the supervised Hebbian learning rule, which is defined as:

$$\Delta w_i(k) = \eta_i \left(r(k) - y(k) \right) y(k)\, x_i(k) \tag{16}$$

where η_i is the learning rate, $r(k)$ is is the target output, $y(k)$ is the neuron output, and $x_i(k)$ is the input at time step k [19].

Single-neuron controllers are widely categorized as lightweight neural adaptive controllers because they employ a simplified neural structure with online weight adaptation capability. Compared with deep or multilayer neural networks, the single-neuron approach requires significantly lower computational complexity and does not require extensive offline training data. Therefore, single-neuron controllers are particularly attractive for real-time renewable energy applications such as wind turbine pitch control, where fast adaptation and computational efficiency are essential.

3. Research Methods

The parameter values of the wind turbine and generator, as well as the configuration of the permanent magnet synchronous generator used in this simulation, are presented in Table 1 and Table 2 below.

Table 1. Wind Turbine Parameter

Parameter	Value
Nominal mechanical output power (MW)	1
Base power of the electrical generator (MVA)	1
Base wind speed (m/s)	8
Maximum power at base wind speed (pu of nominal mechanical power)	1
Base rotational speed (p.u. of base generator speed)	1

Table 2. PMSG Configuration and Parameter

Parameter	Value
Number of phases	3
Back EMF waveform	Sinusoidal
Rotor type	*Round/cylindrical*
Stator phase resistance Rs (Ohm)	0,0485
Armature inductance (H)	0,000395
Flux linkage	0,1194
Inertia (Kg.m^2)	0,0027
Viscous damping (N.m.s)	0,0004924
Pole pairs	9
static friction (N.m)	0

3.1 Wind Energy Conversion System without Pitch Control

In this study, prior to developing the pitch angle control system for the wind turbine, a wind energy conversion system model was first designed. The model consists of a variable-speed wind turbine equipped with a direct-drive permanent magnet synchronous generator, implemented using MATLAB/Simulink. A simplified illustration of the wind energy conversion system is shown in Fig. 6.

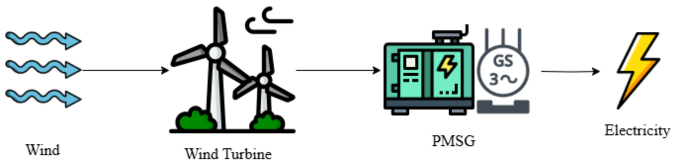

Figure 6. Wind Energy Conversion System without Pitch Control

Wind is a moving air caused by differences in temperature and atmospheric pressure. It flows from high-pressure areas to low-pressure areas. Wind carries kinetic energy, the magnitude of which depends on wind speed and air density. When wind strikes the blades of a wind turbine, it causes the rotor to spin, producing mechanical motion. The kinetic energy of the wind is thus converted into mechanical rotational energy at the turbine shaft. This shaft is connected to the rotor of a generator. As the turbine shaft rotates, the generator rotor also spins, converting the mechanical energy into three-phase AC electrical power. The permanent magnet synchronous generator (PMSG) is commonly used in wind turbines due to its high efficiency, the absence of a need for external excitation, and relatively low maintenance compared to other types of generators.

3.2 Wind Energy Conversion System with Pitch Control Using PI Controller

Pitch control in wind turbines is used to maintain the generator's output power at its rated value, even when the wind speed exceeds the turbine's rated wind speed. Based on a review of existing literature, pitch angle control in wind turbines is generally implemented using a conventional PI controller. An illustration of the wind energy conversion system with a conventional PI-based pitch control is shown in Fig. 7.

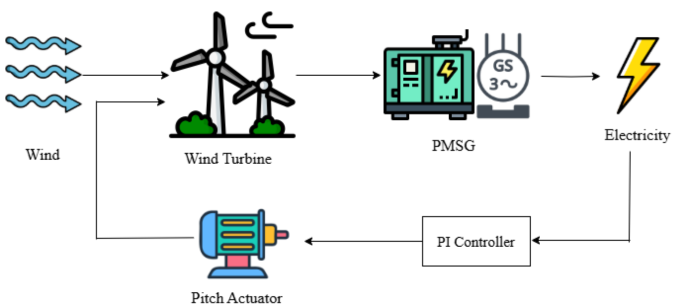

Figure 7. Wind Energy Conversion System with Pitch Control Using PI Controller

The process of converting wind energy into electrical energy is the same as that described for the system without pitch control. However, the wind energy conversion system with pitch control operates in a closed-loop configuration. In this system, the generator's output power at rated wind speed serves as the reference value and is compared with the actual generator output power. The conventional PI controller receives the error signal, which is the difference between the actual power and the reference power. It then calculates the control correction based on the proportional (P) and integral (I) components of the error, and generates a control signal that is sent to the pitch actuator to adjust the pitch angle of the turbine blades accordingly.

The Simulink model and the basic structure of the conventional PI controller used in the pitch control simulation are shown in Fig. 8. The values of the proportional and integral gains, K_p = 2 and K_i = 8, were determined through a trial-and-error approach.

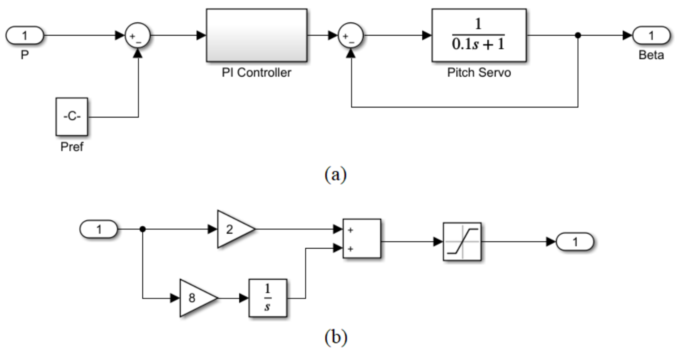

Figure 8. (a) Pitch Control Using PI Controller, (b) Structure of the conventional PI Controller

3.3 *Wind Energy Conversion System with Pitch Control Using Single-neuron PI Controller*

In this study, an adaptive single-neuron PI (SN-PI) controller is proposed as an alternative to the conventional PI controller for pitch angle control of a wind turbine. The schematic diagram of the wind energy conversion system with pitch control using the SN-PI controller is shown in Fig. 9.

The adaptive single-neuron PI controller is a PI-based controller developed using a simple single-layer neural network that mimics the functionality of a conventional PI controller with an adaptive approach, allowing it to automatically adjust its control parameters in response to system changes and external disturbances. The single-neuron PI controller uses a single neuron as the processing unit, which functions similarly to a PI controller but dynamically adjusts the weights (gains) through self-adaptation. The implementation of the single-neuron PI controller as follows:

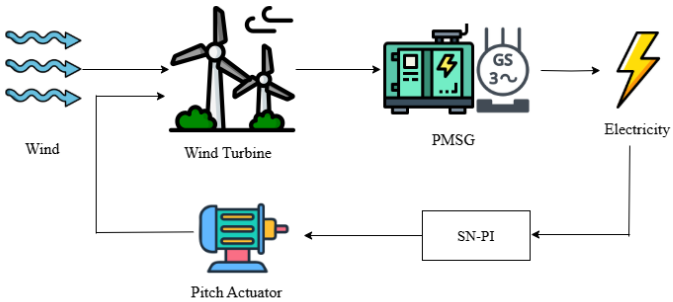

Figure 9. Wind Energy Conversion System with Pitch Control Using SN-PI Controller

Step 1: discrete form of conventional PI controller

$$u(k) = K_p\, e(k) + K_i\, T \sum_{j=1}^{k} e(j) \tag{17}$$

based on Equation (17), the previous control signal $u(k-1)$ is expressed as:

$$u(k-1) = K_p\, e(k-1) + K_i\, T \sum_{j=1}^{k-1} e(j) \tag{18}$$

the incremental form of the PI controller is given by:

$$\begin{aligned} u(k) - u(k-1) &= K_p\left[e(k) - e(k-1)\right] + K_i Te(k) \\ \Delta u(k) &= K_p\left[e(k) - e(k-1)\right] + K_i Te(k) \end{aligned} \tag{19}$$

The error is calculated as the difference between the actual output power of the generator and the reference output power:

$$e(k) = P(k) - P_{\text{ref}}(k) \tag{20}$$

Step 2: integration with neuron model the incremental form of the PI controller in Equation 20 is redefined as:

$$w_1(k) = K_p \tag{21}$$

$$w_2(k) = K_i T \tag{22}$$

$$x_1(k) = \Delta e(k) = e(k) - e(k-1) \tag{23}$$

$$x_2(k) = e(k) \tag{24}$$

The neuron weights w_1 and w_2 are normalized to maintain control stability by limiting the contribution of each weight:

$$w'_i(k) = \frac{w_i(k)}{\sqrt{w_1^2(k) + w_2^2(k)}} \tag{25}$$

the output of the SN-PI controller is given by:

$$\Delta u(k) = w'_1(k)\, x_1(k) + w'_2(k)\, x_2(k) \tag{26}$$

Where $w'_1(k)$ and $w'_2(k)$ are the normalized weights. The incremental control signal $\Delta u(k)$ is defined as the difference between the current and previous control signals.

Step 3: pitch angle control signal generation

$$\Delta u(k) = u(k) - u(k-1) \tag{27}$$

The actual control signal is obtained by adding the previous control signal to its incremental value:

$$u(k) = u(k-1) + K\,\Delta u(k) \tag{28}$$

$$u(k) = u(k-1) + K\left[w'_1(k)\, x_1(k) + w'_2(k)\, x_2(k)\right] \tag{29}$$

this value becomes the reference pitch angle β_ref:

$$\beta_{\text{ref}} = u(k) \tag{30}$$

Step 4: adaptive weight updating

subsequently, the weights w_1 and w_2 are updated based on the Hebbian Learning Rule:

$$w_1(k) = w_1(k-1) + \eta_1\, e(k)\, u(k)\, x_1(k) \tag{31}$$

$$w_2(k) = w_2(k-1) + \eta_2\, e(k)\, u(k)\, x_2(k) \tag{32}$$

where η is the learning rate.

The adaptive SN-PI controller requires initial values for the neuron weights and learning rate to ensure stable controller operation during the early stage of the adaptive process. In this study, the initial neuron weights were selected as w1(0) = 0.5 and w2(0) = 0.5. These initial values were chosen to provide balanced contributions between the proportional action represented by the error difference term and the integral action represented by the accumulated error term. The learning rate parameter η determines the adaptation speed of the neuron weights. In this study, the learning rate was selected as $\eta = 0.01$ based on several simulation trials. This value provides a good compromise between adaptation speed and system stability. Smaller learning rates resulted in slower adaptation to wind speed variations, whereas larger learning rates tended to introduce oscillatory behavior in the pitch angle and output power response.

The adaptive learning process of the proposed single-neuron PI controller is illustrated in Fig. 10. The controller continuously updates the neuron weights based on the power error and system response. The actual generator output power is compared with the reference power to produce the error signal. This error is then processed by the SN-PI controller to generate the appropriate pitch angle reference. Subsequently, the adaptive Hebbian learning algorithm updates the neuron weights to improve the control performance under varying wind speed conditions.

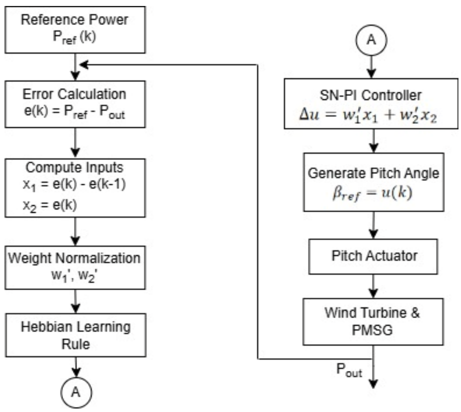

Figure 10. The adaptive learning process of the proposed single-neuron PI controller

This process allows the SN-PI controller to adaptively adjust its gains in response to system dynamics or external disturbances. In this study, the SN-PI controller is implemented as a program code within a MATLAB Function block in Simulink.

4. Results and Discussion

The simulation results of the wind energy conversion system without pitch angle control under increasing wind speeds are presented in Table 3. The cut-in wind speed is at 3 m/s. At this speed, the wind turbine and generator system begins to produce an output power of 0.000318 MW or 318 Watts, with a rotor speed of 5.811 rpm. As the wind speed increases, both the output power and rotor speed also increase. At the rated wind speed of 8 m/s, the system generates an output power of 0.99 MW $\approx$ 1 MW with a nominal rotor speed of 325 rpm. At wind speeds above 8 m/s, the output power and rotor speed continue to increase significantly beyond their nominal values.

Table 4 shows the simulation results of the wind energy conversion system with pitch control using a conventional PI controller under sequentially increasing wind speeds. At wind speeds above 8 m/s, the output power and rotor speed are slightly above the rated power (0.99 MW $\approx$ 1 MW) and nominal rotor speed (325 rpm), but the deviations from the nominal values are relatively small.

Table 5 presents the simulation results of the wind energy conversion system with pitch control using the proposed single-neuron PI controller under sequentially increasing wind speeds. At wind speeds above 8 m/s, the output power and rotor speed remain close to the rated output power (0.99 MW $\approx$ 1 MW) and nominal rotor

Table 3. Output Power, Rotor Speed, and Pitch Angle Values in the Wind Energy Conversion System Simulation without Pitch Control

Wind Speed (m/s)	Output Power (MW)	Rotor Speed (r/min)	Pitch Angle (deg)
1	0	0	0
2	0	0	0
3	0,000318	5,811	0
4	0,001008	10,33	0
5	0,2224	153,5	0
6	0,425623	212,3	0
7	0,680945	268,6	0
8	0,995922	325	0
9	1,373369	381,4	0
10	1,815073	438,5	0
11	2,322334	496	0
12	2,896158	553,9	0
13	3,537343	612,1	0

Table 4. Output Power, Rotor Speed, and Pitch Angle Values in the Wind Energy Conversion System Simulation with Pitch Control Using Conventional PI Controller

Wind Speed (m/s)	Output Power (MW)	Rotor Speed (r/min)	Pitch Angle (deg)
1	0	0	0
2	0	0	0
3	0,000318	5,811	0
4	0,001008	10,33	0
5	0,2224	153,5	0
6	0,425623	212,3	0
7	0,680945	268,6	0
8	0,995922	325	0
9	1,054848	334,3	4,737
10	1,100193	341,4	9,408
11	1,122895	344,9	13,4
12	1,132505	346,4	16,81
13	1,136788	347	19,74

speed (325 rpm), with only very small deviations from the nominal values.

A comparison of rotor speed values from the simulation results of the wind energy conversion system without pitch angle control, with pitch angle control using a conventional PI controller, and with pitch angle control using the proposed single-neuron PI controller is shown in Fig. 10.

Fig. 11(a) presents the comparison of rotor speed simulation results under varying wind speeds for three cases: without pitch control, with conventional PI pitch control, and with the proposed single-neuron PI pitch control. As shown in the Fig., the rotor

Table 5. Output Power, Rotor Speed, and Pitch Angle Values in the Wind Energy Conversion System Simulation with Pitch Control Using Single-Neuron PI Controller

Wind Speed (m/s)	Output Power (MW)	Rotor Speed (r/min)	Pitch Angle (deg)
1	0	0	0
2	0	0	0
3	0,000318	5,811	0
4	0,001008	10,33	0
5	0,2224	153,5	0
6	0,425623	212,3	0
7	0,680945	268,6	0
8	0,995922	325	0
9	0,998429	325,2	5,608
10	0,999502	325,4	10,88
11	0,999605	325,4	15,1
12	0,999328	325,4	18,57
13	0,999016	325,3	21,47

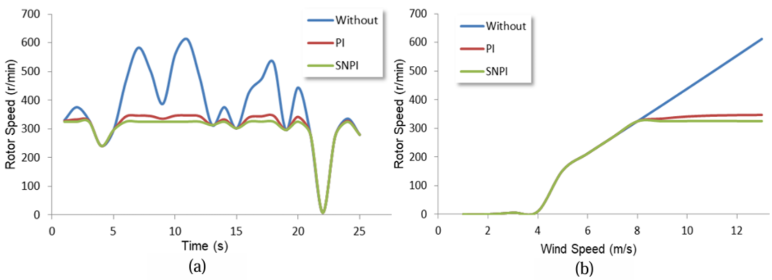

Figure 11. Comparison of Rotor Speed Simulation Results without Using Pitch Control, with Pitch Control Using PI, and with Pitch Control Using SN-PI (a) at varying wind speeds, (b) at increasing wind speeds

speed in the system using the SN-PI controller exhibits the smallest deviation and maintains precision around the rated value.

Fig. 11(b) shows the comparison of rotor speed simulation results under progressively increasing wind speeds for the same three control strategies. The rotor speed without pitch control continuously increases as wind speed increases. When the wind speed exceeds 8 m/s, the rotor speed in systems equipped with pitch control remains regulated around the rated value. Notably, the system employing the SN-PI controller demonstrates a significantly smaller deviation of rotor speed from the rated value, indicating that the SN-PI controller performs better in maintaining the output power at its rated value, thereby ensuring the rotor speed remains at its nominal level.

A comparison of output power values from the simulation results of the wind energy conversion system without pitch angle control, with pitch angle control using a conventional PI controller, and with pitch angle control using the proposed single-neuron PI controller is presented in Fig. 11.

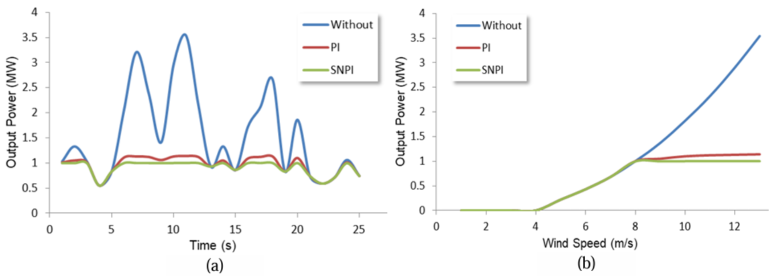

Figure 12. Comparison of Output Power Simulation Results without Using Pitch Control, with Pitch Control Using PI, and with Pitch Control Using SN-PI (a) at varying wind speeds, (b) at increasing wind speeds

Fig. 12(a) shows the comparison of output power simulation results under varying wind speeds for three cases: without pitch control, with conventional PI pitch control, and with the proposed single-neuron PI pitch control. The Fig. illustrates that the system using the SN-PI controller exhibits the smallest deviation and maintains precision around the rated output power value.

Fig. 12(b) presents the comparison of output power simulation results under progressively increasing wind speeds. In the system without pitch control, the output power continues to rise along with increasing wind speed. When the wind speed exceeds 8 m/s, the output power in the systems with pitch control remains regulated around the rated value. Specifically, the system with the SN-PI controller shows very small deviations from the rated output power, demonstrating that the SN-PI controller provides superior performance in maintaining the output power at its rated level.

A comparison of the pitch angle magnitude from the simulation results of the wind energy conversion system without pitch angle control, with pitch angle control using a conventional PI controller, and with pitch angle control using the proposed single-neuron PI controller is shown in Fig. 12.

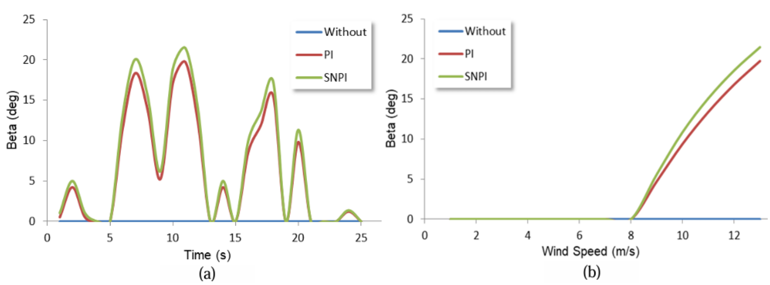

Figure 13. Comparison of Pitch Angle β Simulation Results without Using Pitch Control, with Pitch Control Using PI, and with Pitch Control Using SN-PI (a) at varying wind speeds, (b) at increasing wind speeds

Fig. 13(a) presents a comparison of the pitch angle values in response to varying wind speeds for three cases: without pitch control, with conventional PI pitch control, and with single-neuron PI (SN-PI) pitch control. The Fig. shows that the pitch angle in the system using the SN-PI controller is larger than that in the system using the conventional PI controller. This indicates that the SN-PI performs better in generating the reference pitch angle (beta) to maintain the output power at its rated value.

Fig. 13(b) shows a comparison of the pitch angle under a stepwise increasing wind speed profile for the three systems. In the system without pitch control, the pitch angle is fixed at zero, which is the optimal value for extracting maximum wind energy. In systems with pitch angle control, both using conventional PI and SN-PI controllers, when the wind speed exceeds 8 m/s, the pitch angle increases to maintain the actual output power at the rated value. The pitch angle provided by the SN-PI controller is greater than that generated by the conventional PI controller, indicating that the SN-PI responds more effectively to deviations between actual and rated power, producing a more precise pitch angle to ensure the output power remains at the nominal value.

The performance of the proposed SN-PI controller is influenced by the selection of neuron weights and learning rate parameters. In general, the learning rate η determines the adaptation speed of the controller. When the learning rate is too small, the controller adapts slowly to changes in wind speed, resulting in slower pitch angle adjustment and larger steady-state error in the output power. Conversely, when the learning rate is excessively large, the controller response becomes more aggressive and may introduce oscillations in the rotor speed and output power response. Based on simulation observations, moderate weight initialization and learning rate values provide the best overall performance in terms of response stability, output power regulation, and rotor speed tracking. The adaptive learning capability of the SN-PI controller allows the controller parameters to self-adjust according to changing wind conditions, thereby reducing the need for frequent manual retuning compared to the conventional PI controller.

In practical applications, the proposed SN-PI controller can potentially be implemented in real-time digital control platforms such as DSPs, FPGAs, or industrial microcontrollers because the computational structure of the single-neuron algorithm is relatively simple compared to multi-layer neural network approaches. Therefore, the proposed method offers a good balance between computational simplicity and adaptive control capability. Furthermore, the proposed controller may also be generalized for other renewable energy conversion systems requiring adaptive control under nonlinear and time-varying operating conditions, such as photovoltaic maximum power point tracking systems, hydro turbine governors, and hybrid renewable energy systems. However, this study is limited to simulation-based validation under predefined wind speed profiles. Real-world implementation may involve additional challenges such as measurement noise, actuator saturation, communication delays, and mechanical uncertainties that were not fully considered in this work.

Therefore, future work should include experimental validation and hardware-in-the-loop implementation to further evaluate the robustness and practical applicability of the proposed controller.

5. Conclusion

This paper presents a simulation model of pitch control on variable speed wind turbines with a PMSG using single-neuron PI controller developed in the simulation tool of MATLAB/Simulink. On the basis of the developed wind turbine, PMSG model, and corresponding control scheme, pitch angle control scheme is realized by the output power of the variable speed wind turbine with PMSG. The output power from the generator is compared to the reference value of the output power to regulate the pitch angle. The base wind speed considered in this simulation is 8 m/s. When the wind speed exceeds the base value then the output power will be higher than the reference or rated power, thus the difference between the actual output power and the reference value will be processed to get the suitable pitch angle β to be sent to the actuator or wind turbine pitch control system to change the pitch angle of the blades. Simulation results show the performance of the single-neuron PI controller in controlling the pitch angle is better than the performance of the conventional PI controller. At wind speeds higher than the rated wind speed of the turbine, the single-neuron PI controller keeps the output power around the rated output power value with very small deviations.

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