

The MPPT algorithm combined with pitch angle control for the small-scale wind turbine in a wide speed range

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ABSTRACT

This research proposes the control system structure for a small-scale wind turbine. Significantly, the maximum power point tracking algorithm (MPPT) and the pitch angle controller are deeply analyzed; this is the base for proposing the strategy of the MPPT algorithm combined with pitch-angle control in a wide speed range of wind. This article also researches the converters, then analyses the advantages of each converter to choose the suitable converter for the small-scale wind turbine. In the MPPT algorithm design, the expert experience takes advantage through the fuzzy controller. The pitch angle controller is built based on the PID controller with its parameters adjusted by Fuzzy logic. The results showed that the effectiveness of the proposed control strategy is much better than that of the traditional control strategy. Moreover, in high and low wind speeds, the proposed control system operates reliably and stably.

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1. INTRODUCTION

Wind energy is one of the largest renewable energy sources on earth, and this is clean energy with great potential for future growth. The wind energy of turbines used in economic development has significantly reduced the demand for fossil fuels [1]. The small-scale wind turbine (SSWT) popularly applies in wind generators because of its low cost and ease of maintenance [2]. Therefore, the SSWT has the advantage when it installs in mountains and islands. However, in these places, the wind source is very complicated and often changed. Three main problems need addressing: maximum power point tracking (MPPT), controlling the pitch-angle, and building the converters to reach the efficiency maximize of converting wind energy to electricity. There are still few studies on MPPT, pitch angle control, and converters for small wind turbines. Thus, this paper focuses on proposing the MPPT algorithm combined with pitch angle control and the design of the converter for the SSWT system to exploit wind energy effectively.

The common method of controlling the pitch angle of SSWT systems is passive angle flipping. However, the disadvantage of this method is that the rotor is susceptible to damage during high winds. To overcome the above limitation, the authors propose combining the MPPT algorithm with Pitch angle control to ensure the continuity of electrical energy fed into the grid and avoid damage to the turbine rotor. In medium and large wind turbine systems, the MPPT-Pitch angle method has been studied extensively. In these systems, the relationships between the emitted power and the wind speed based on controlling the pitch angle shown in Figure 1. In the wind speed range of V_{cut-in} - V_0 , the emitted power is changed, the MPPT

controller operates. In the wind speed range of V_0 - V_N , the system operates in norm wind speed, the power value is below the norm. In the last range, the wind speed is V_N - $V_{cut-out}$, the turbine operates with maximum power, but the rotor speed is limit by controlling the pitch angle. There has been a lot of research on the MPPT algorithm, divided into four main types, summarized in Figure 2.

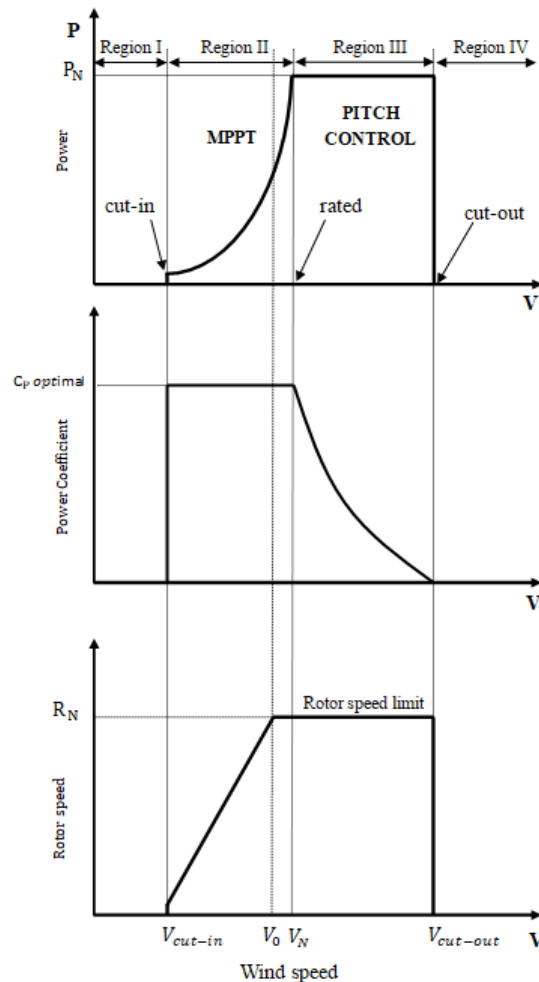


Figure 1. Effects of selected regions of small-scale wind turbine

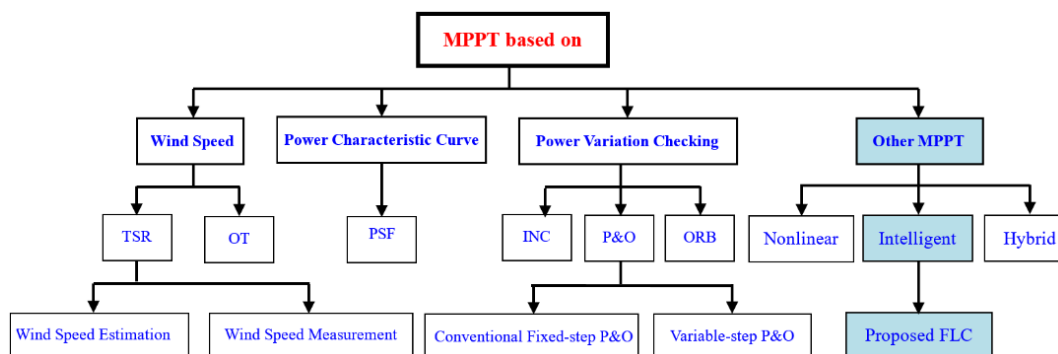


Figure 2. The classification of MPPT algorithms

The first type is a method based on wind speed. It includes two methods: optimal torque (OT) and tip speed ratio (TSR). The method TSR determines the wind speed through a sensor. This method is simple

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and easy to apply to the practice, but the sensor value is disturbed because of the wind speed changing [1], [3]. In the method OT, the rotor speed is the input of the system. This method is simple and effective, the response is fast, but the wind speed is not measured directly, so the response value is not reflected immediately [4]. The second type is based on power variation checking, and it includes three methods. The first is the perturbing and observing (P&O) method, with the other name is hill climb searching (HSC). In this method, the perturbing is added to the input variable, and then we observe the response variable. The result is achieved when the slope of the target function equal to zero [3]. This method is very effective for adjusting the rotor speed of a wind turbine system. While operating, the system creates step-sizes with two types: fixed and variable step-size [5]. In the system with the fixed step size, while wind speed changes, the response is slow compared to the wind speed [6]. Therefore, some research proposes a control system with variable step-size [5], [7]. These methods have high quality, but the algorithm is complex, and the response is slow, while the wind turbine system is highly nonlinear, and the parameters are rapidly changed.

The incremental conductance (INC) algorithm is commonly used in solar systems [8]. This system uses two independent parameters: one direct current and the voltage of the converter [4]. Based on these parameters, we define the power and then build the relationship characteristic between power and voltage (P-V). This characteristic is equal to zero at maximum power point (MPP). The optimal-relation-based (ORB) algorithm is built based on the optimal relationship among the wind speed, power, voltage, and direct current [4]. There are two kinds of ORB algorithms: the sensor-based approach and the sensor-less approach algorithm [9]. The advantage of these algorithms is the fast observer of wind speed, but the disadvantage is the requirement of known parameters of the system. The third type is the power characteristic curve which requests the exact power parameter and speed [10]. The most common is the power signal feedback (PSF) algorithm which demands the apparent maximum power curve of the wind turbine. This algorithm used the sensor for measuring the speed and the error between the measured turbine power and the desired power for the input signal [11].

Other MPPT includes three algorithms: intelligent, nonlinear, and hybridization algorithm. The hybridization algorithm and overcomes the disadvantages of each method. The most common hybridization algorithm is built based on the combination of P&O and ORB presented in research [4], [9], [12]. In addition, some other hybridization algorithms are presented in studies [13]-[15], such as linear extrapolation-P&O, firefly algorithm-fuzzy, improvised binary sequence-P&O, artificial bee colony adaptive neuro-fuzzy inference system, fractional short circuit current-P&O. Some intelligent algorithms such as neural network (NN) and fuzzy logic control (FLC). The FLC algorithm is built based on expert experience, and it is not required to know the parameter of the wind turbine system [4]. The advantage of this method is the fast response to the change of wind source [16], [17]. The NN algorithm has the advantage of learning and not needing an object model [4]. However, this algorithm's disadvantage is that the controller's requirement with high speed and large memory, the long time to collect samples and train the algorithm. The nonlinear algorithm includes the sliding mode control (SMC) [18]-[20] and the backstepping method [21], [22]. These methods have the advantage of fast and exact control processes, but the control algorithms are complex.

Based on the above analysis, each control method has its advantages and disadvantages. However, the above algorithms only apply to large-scale wind turbine systems and solar cell systems. There are not many works that research on the SSWT system. Therefore, in this study, the authors will study to build an MPPT algorithm for the SSWT system with the fuzzy logic controller based on HCS with a variable step size. The control methods for SSWT Pitch angle are summarized as Figure 3, divided into four categories. The first is a linear method, proportional-integral-derivative (PID), and linear quadratic regulator (LQR). The PID algorithm has the advantage of the sustainable and simple control technique, so it is widely used in practice [23]-[25]. But with the nonlinear system, the PID controller is not suitable, and the control quality is not high.

The LQR method is a stable algorithm with a small error. The control system is stable around the working point through solving the Riccati equation [25], [26]. The control system's quality depends on the choice of matrix Q and matrix R, so the LQR method is usually combined with the intelligent algorithm for the setting of matrix K. The nonlinear method includes two types, such as the sliding mode control and backstepping control. The SMC method has the advantage of fast and stable response, so it widely applies to the nonlinear control system [27], [28]. However, this method request knows the mathematical model and parameters of the object. Otherwise, this method makes chattering in the control signal, which negatively affects the control system's quality. The backstepping control (BSC) method requests to know the dynamic equation of the control object. This method works well in the stable wind source or the minor changing wind source [29]. However, the wind source is constantly changed, so the BSC method is not suitable. Therefore, this method usually combines with another technique, such as adaptive backstepping control [30] or SMC [31].

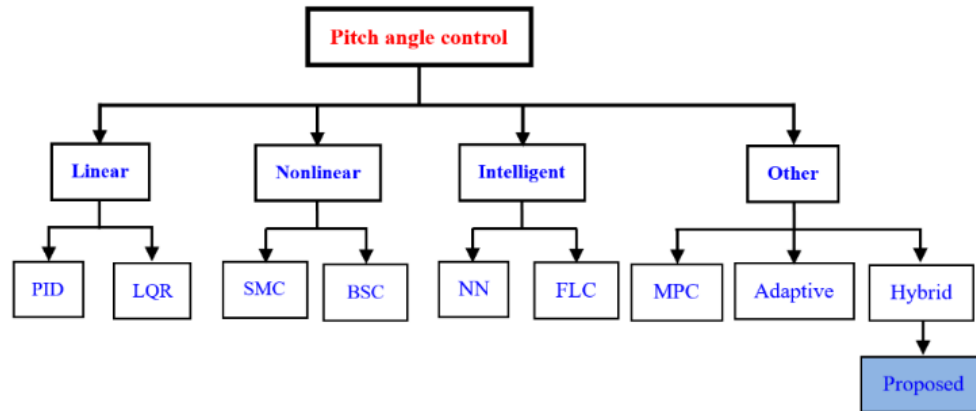


Figure 3. The classification of pitch angle control methods

The neural network method does not need a mathematical model of the system. It can control accurately and adaptively. The studies [32], [33] have proposed a neural network controller to estimate the set values of pitch angle. The downside of this method is that it takes many trials to find the optimal algorithm. In a system with a large nonlinearity, such as a wind turbine system, expert experience in the control process is advantageous for the control strategy. The fuzzy logic control (FLC) is a good solution for controlling the strategy wind turbine system [34]. Furthermore, this method includes the rule table based on expert experience, so the control strategy has consolidation and high efficiency. Some other techniques are model-predictive control (MPC), adaptive control, and hybrid control. The MPC uses the past input for building the control strategy in the operating mode of real-time [34]. The disadvantage of this method is that when exiting errors between signals, the system will not stabilize. In addition, the adaptive control has a long sampling time, so it reduces the system computation speed [35], [36]. Especially for a large nonlinear wind turbine system, the calculation time must be real-time, so the adaptive control is not suitable for applying in the SSWT system.

Hybrid control is a method of combining two or more algorithms. It takes advantage of each algorithm to improve the quality of the system. According to research [37], the PI controller is used when the system model is linear, the output power is constant, and the wind speed is over the norm. The fuzzy controller is used when the system model is nonlinear, and the wind speed changes. In summary, the MPPT and Pitch angle methods have been applied to large-scale wind turbines, but there are no studies on the MPPT algorithm combined with pitch angle control strategy for SSWT. This research will study the converters and then compare each type to show each converter's advantages, disadvantages, efficiency, and output energy. In addition, the authors will compare different controllers to find out the suitable structure for the SSWT system.

2. DESIGNING THE CONTROL SYSTEM FOR SSWT

2.1. The model of the SSWT system

The power of wind turbine is presented as following (1)-(4) [1], [34]:

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

The coefficient C_p is given as follows:

$$C_p(\lambda, \beta) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \quad (2)$$

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

The ratio of the blade tip speed is calculated as follows:

$$\lambda = \frac{\omega_t R}{V} \quad (3)$$

The moment of the turbine is calculated as follows:

$$M_t = \frac{P_t}{\omega_t} \quad (4)$$

The relationship curve between C_p and λ is shown in Figure 4. The parameters of the SSWT turbine model are presented in Table 1.

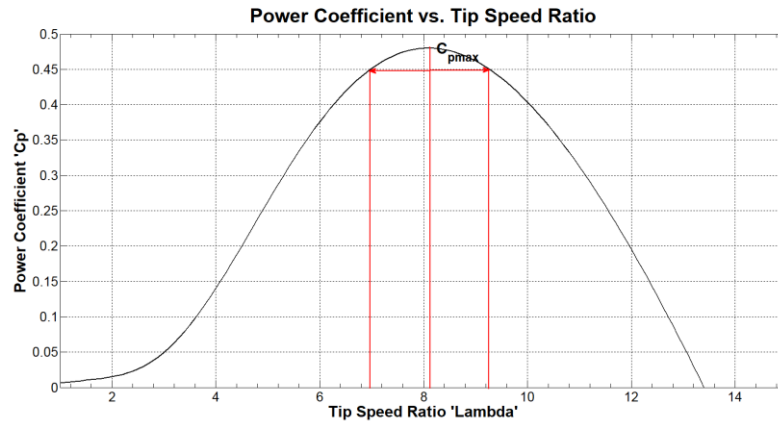


Figure 4. The relationship curve between C_p and λ

Table 1. The parameters of the SSWT turbine model [1]

Rated power (kW)	The radius of rotor (m)	Air density (kg/m^3)	Power coefficient of optimal	Tip speed ratio of optimal	Rated wind speed (m/s)
2.5	1.8	1.225	0.48	8.1	9.5

2.2. Designing the converter

There are four common converters. The first is a diode rectifier converter, widely used in the SSWT because of its simple structure and cheap price [38]. In the MPPT mode, this converter is not an optimal solution because there are the subsystems such as the dummy load, the passive angle flipping, and the tail folding system [34]. In the generator using PMSG, when the wind speed is low, the DC voltage is not enough to generate the output voltage fed into the grid. However, the uncontrolled diode rectifier converter can be applied to the wind turbine systems using a changeable polar number generator. The system can operate when the wind speed is low. When the wind speed exceeds the limit, the devices such as the dummy load, the passive blade flipping, and the tail folding system operate to consume a portion of the wind energy. These subsystems make the control system cumbersome and inefficient.

The second type is the boost DC-DC [39], [40], which includes a diode rectifier connected to the generator PMSG, so this rectifier is called a machine-side converter (MSC). The role of the MSC is converting the AC source into the DC source, then through the boost circuit for adjusting the voltage, finally through the grid side converter (GSC) for converting the DC source into the AC source with its frequency, amplitude, and phase coincide to the grid. The boost converter used in MSC has two main advantages: it is easy to define the maximum power point [38], and it is flexible to control the GSC. This system has a low price and a simple fabrication but low efficiency. The device's lifespan is low due to the high reverse voltage of the diode and the high-frequency switching of the boost converter when working in high wind speed conditions. The third is the Z-source converter [41] that can increase the output voltage without the boost-voltage device, so it is convenient when the structure on the MSC side is the diode bridges [42], [43]. This solution saves costs because the MSC uses diodes. However, this conversion system has the disadvantage of low efficiency due to two capacitors and two inductors. This structure makes the system inefficient.

The last is the back-bo-back converter PWM. The rectifier is built based on the insulated gate bipolar transistor (IGBT) with pulse-width-modulated (PWM). The capacitor has the role of linking the mediate source with the inverter for connecting the PMSG with the grid [1], [7]. The MSC controls the current to reduce the high-order harmonics of input current and electromagnetic torque. This structure allows the MSC to adjust the generator speed in a wide range while the GSC adjusts the current fed into the grid to

keep the DC voltage constant and improve the output power quality by reducing the harmonic distortion. This system's advantages include the simple structure of the back-to-back converter, the high efficiency of maximum power point tracking, and the consolidation. In conclusion, the authors point out the comparison summary of the converters applied to the SSWT, as shown in Table 2 and Figure 5. Then, basing on the advantages and disadvantages of each type and the experience, the authors chose the back-to-back converter PWM for the system.

Table 2. The properties of each converter

Property \ Converter	Diode bridge	Boost DC-DC	Back-to-Back PWM	Z-Source
Diode	6	8	6	6
Switch	0	1	6	0
Capacitor	1	1	1	2
Inductor	0	1	0	2
Control	None	Simple	Complex	None
The efficiency of MPPT	Low	Medium	High	Medium
Out Power	III	II	I	II
Cost	Low	Medium	High	High

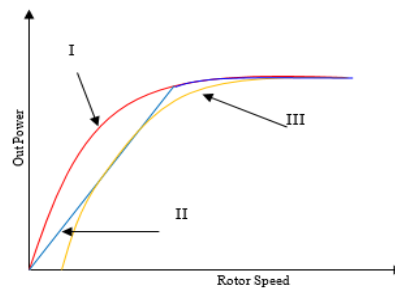


Figure 5. The relationship between the output power and the rotor speed

2.3. Designing the MPPT controller

The proposed system is shown in Figure 6. The Fuzzy controller has the inputs such as the power of the wind turbine and the rotor speed. The experience is applied to fuzzy law. G_1 and G_2 are pre-processing stages, G_3 is the post-processing stage for the controller. The rotor speed reaches the optimal value from the fuzzy controller in the step k , and it is calculated as follows:

$$\omega_{t,opt}^{fuzzy}[k] = \omega_t[k-1] + \Delta\omega_{t,0}^{fuzzy} \quad (5)$$

The optimal set-speed of the fuzzy controller:

$$\omega_t^{fuzzy_ref} = \omega_{t,opt}^{fuzzy} - \omega_t \quad (6)$$

The input and output values are fuzzy as follows: decrease big (DB), decrease medium (MD), decrease small (DS), zero (ZE), increase small (IS), increase medium (IM), increase big (IB). The laws are set based on seven inputs and seven outputs, so there are 49 fuzzy laws, such as Table 3.

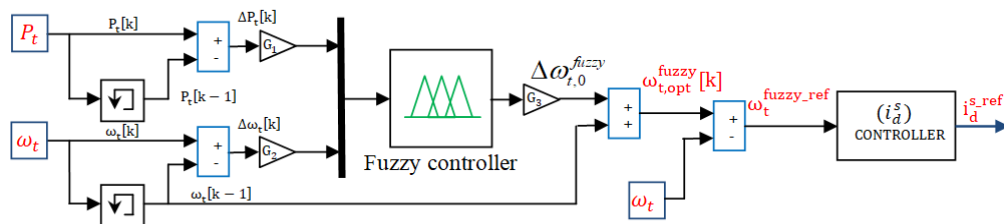


Figure 6. The structure of MPPT based on the fuzzy algorithm

Table 3. The fuzzy laws of MPPT

$\Delta\omega_{t,0}^{fuzzy}$					ΔP_t			
	DB	DM	DS		ZE	IS	IM	IB
$\Delta\omega_t$	DB	IB	IM	IS	ZE	DM	DB	DB
	DM	IB	IM	IS	ZE	DS	DM	DB
	DS	IS	IS	IS	ZE	DS	DM	DM
	ZE	DB	DM	DS	ZE	IS	IM	IB
	IS	DB	DM	DS	ZE	IS	IS	IS
	IM	DB	DM	DS	ZE	IS	IM	IB
	IB	DB	DB	DM	ZE	IS	IM	IB

2.4. Designing the pitch angle controller

We used the servo motor to control the pitch angle, which may be the AC or DC electric machine [44], [45]. This motor servo must be controlled through the driver circuit [46]. The entire control system of the servo motor considering the input and output has the differential as:

$$\frac{d\beta}{dt} = -\frac{1}{T_{servo}}\beta + \frac{1}{T_{servo}}\beta_{ref} \quad (7)$$

The transfer function of servo motor:

$$\frac{\beta(s)}{\beta_{ref}(s)} = \frac{1}{T_{servo}s + 1} \quad (8)$$

Where:

$$\begin{aligned} \beta_{\min} &\leq \beta \leq \beta_{\max} \\ \dot{\beta}(t) &\leq \dot{\beta}(t) \leq \dot{\beta}(t) \end{aligned}$$

with β_{\min} and β_{\max} are the minimum and maximum values of Pitch angle.

In this research, the authors propose the fuzzy-PID controller for the SSWT, shown in Figure 7. The fuzzy logic algorithm applies the expert experience not to request the exact mathematical model of the control object. Each input value includes five language variables such as Negative Large (NL), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Large (PL). Each output values include five language variables such as Positive Small (PS), Positive Medium (PM), Positive Medium Large (PML), Positive Large (PL), and Positive Very Large (PVL). There are two input parameters and three out parameters, so there are 75 fuzzy laws present in Table 4.

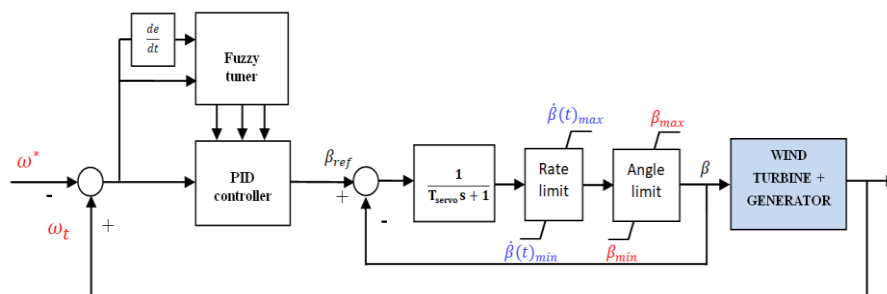


Figure 7. The Fuzzy-PID controller for the pitch angle

Table 4. The fuzzy laws of pitch angle

K_P, K_I, K_D		e				
		NL	NS	ZE	PS	PL
\dot{e}	NL	PS/PVL/PS	PS/PVL/PS	PS/PVL/PS	PM/PM/PM	PML/PS/PML
	NS	PS/PVL/PS	PS/PVL/PS	PS/PVL/PS	PM/PM/PM	PML/PS/PML
	ZE	PS/PL/PM	PM/PL/PM	PML/PML/PML	PL/PS/PL	PL/PS/PL
	PS	PML/PL/PM	PL/PML/PML	PL/PL/PL	PL/PL/PL	PVL/PVL/PVL
	PL	PML/PML/PML	PML/PM/PML	PL/PS/PVL	PL/PS/PVL	PVL/PS/PVL

The error of control system:

$$e(t) = -\omega^*(t) + \omega_t(t) \quad (9)$$

3. THE RESULTS AND ANALYSIS

To control and emit continuous power, the authors propose the MPPT algorithm combined with pitch angle control. The structure diagram of the control system is shown in Figure 8. If the wind speed is under the norm value, the pitch angle has the minimum value, such as $\beta = 0$. In this case, the control system works in the mode of maximum power point tracking. Besides, the authors also set up the traditional controller HSC for comparison with the proposed controller. In the structure diagram of the control system, there are two pitch angle controllers, such as the PID controller and Fuzzy-PID controller, to compare the quality of the proposed controller with the traditional controller PID. For the simulation results to be objective, the system model also has the back-to-back converter, the filter, and the transformer (220/380).

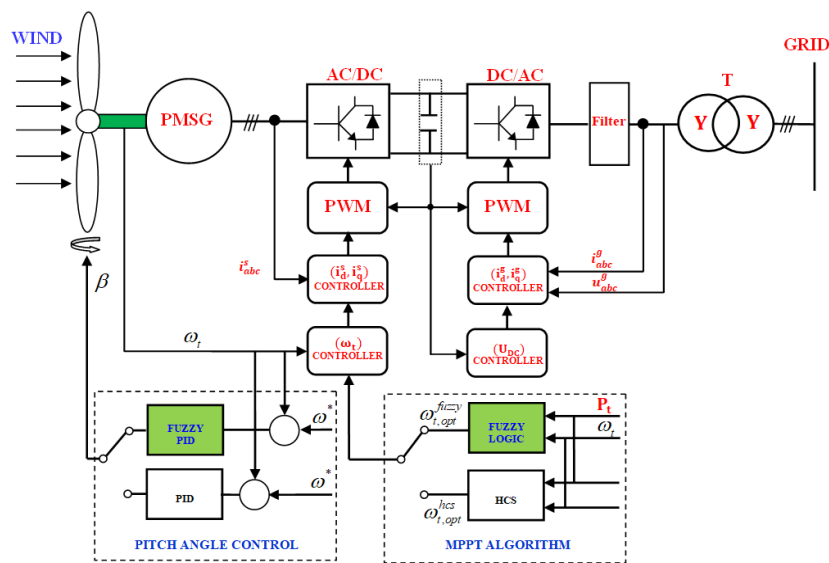


Figure 8. The proposed structure of the control system for SSWT

The simulation result is shown in Figures 9-12. Figure 9 shows the wind source profile with the range of wind speed valid from 3m/s -13m/s. We can determine the efficiency of all working modes of MPPT-Pitch angle control in this wind speed range. In the case of the wind speed under 9.5m/s, the MPPT controller operates. In the case of the wind speed over 9.5m/s, the Pitch angle controller is active.

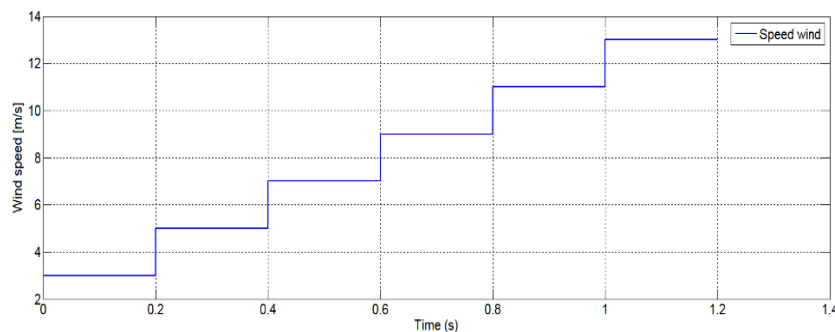


Figure 9. The wind source profile with wind speed is valid from 3m/s -13m/s

Figure 10 shows the pitch angle reactive when the wind speed changes. For example, at the time of 0.8s, the input wind speed is 11m/s, the pitch angle is about 6 degrees. At the time of 1s, the input wind speed is 13m/s, and the pitch angle is about 15 degrees. With the different controllers, we have different values of pitch angle. There are two control systems as the HSC-PID and the Fuzzy-PID. The traditional control system is the HSC-PID with MPPT used HSC algorithm and the pitch angle controller used PID controller. The proposed control system is the Fuzzy-PID with the MPPT used the Fuzzy algorithm, and the pitch angle controller used the fuzzy-PID controller. The result shows that the proposed method has a faster response than the traditional system. Figure 11 shows the output power of PMSG in the range of wind speed 3-13m/s. The result shows that the proposed method has a better quality. The output power response of the Fuzzy-PID system is faster than the HSC-PID system's one.

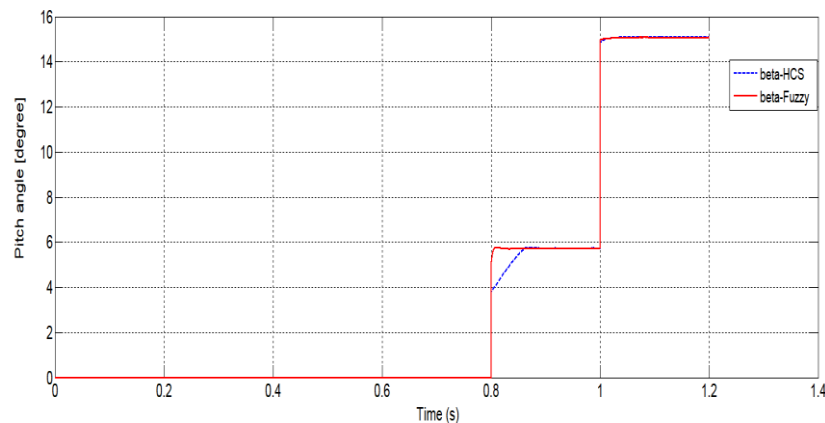


Figure 10. The pitch angle of wind turbine

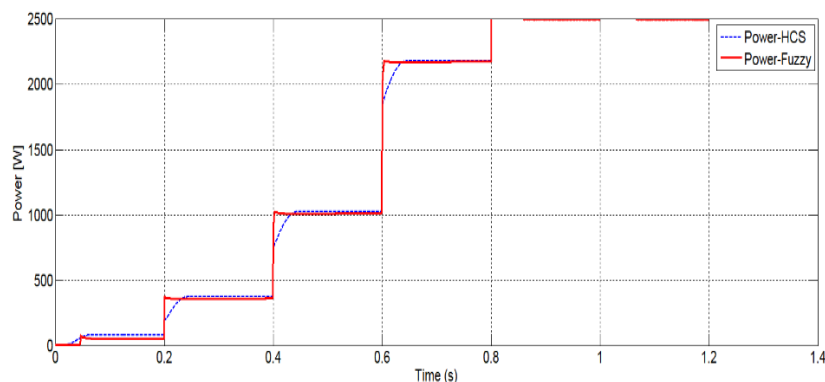


Figure 11. The output power of PMSG

Figure 12 shows the power coefficient C_p of control system with two cases of controllers. At the first stage, with low wind speed, the power coefficient of the proposed method is not high. It equals approximately the optimal value in a short time. But after the time of 0.2s, the Fuzzy-PID system has better properties than HSC-PID, the power coefficient reaches approximately the optimal value. Moreover, when changing the wind speed, the power coefficient of the Fuzzy-PID system has a faster response than the HSC-PID system's one.

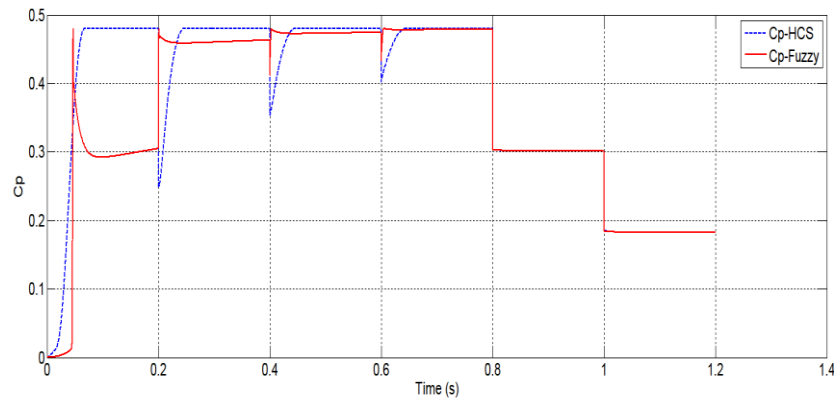


Figure 12. The power coefficient

4. CONCLUSION

The authors have proposed the MPPT algorithm combined with pitch angle control and offered a suitable converter to exploit maximum power in a wide range of variable wind speeds for the SSWT system. The MPPT controller is built based on the Fuzzy algorithm to apply the expert experience. The pitch angle controller is built based on the PID with its parameters adjusted by the Fuzzy controller. The converter is built according to back to back PWM model. The advantages of the proposed solution are shown through the results in Figures 10-12. In the case the wind speed is under 9.5m/s, the MPPT controller works. In the case of wind speeds over 9.5m/s, the pitch control system operates. The results show that the efficiency of the proposed control system is much better than that of the traditional control system. In high and low wind speed cases, the proposed control system operates with high efficiency and fast response.

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