Australian Journal of Basic and Applied Sciences, 5(8): 781-788, 2011
ISSN 1991-8178

Design Optimal in Pitch-controlled Variable-speed under Rated Wind Speed WECS using Fuzzy Logic Control

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Abstract: On a small scale wind energy conversion system (WECS) which are installed in area with low wind speed, pitch angle on a blade is an important method in the power regulation. With a constant position of the blade, wind turbine which is installed on the low speed wind field 5-7 m/s causes the produced power of the wind turbine not optimum. In that case multi input multi output plant requires control system design to be more complex. In order to overcome that condition, it is important to develop intelligent control based on fuzzy logic. In this paper, the design of fuzzy logic control (FLC) is performed, which is implemented on a small scale wind turbine system operated on a low wind speed. The analysis is carried out by visualize and define the correlation between wind power, power of wind turbine, and electricity power which are produced by system and optimisation criteria of the control system and system performance as well as linked compromises between controlled power and the limited actuation of nod angle.

Key words: Pitch angle, Wind turbine, Fuzzy logic control, performance.

INTRODUCTION

It is reported in 2009 that the world's wind turbine capacity has reached 159.21 GW (Musyafa *et al.,* 2010). Most of wind tubine power generators have been successfully developed, especially in sub-tropical countries which have an average wind speed more than 12 m/s. USA has the largest wind turbine (38.478 MW), followed by China and Germany with nearly the same capacity (26.000 MW), and then followed by Spain, Italy, France UK, Portugal and Denmark (DJLPE, 2004). Indonesia as a tropical country has a relatively low rated average wind speed; however, the use of wind turbine for remote regions electricity supply are needed. In 2008, Indonesia has wind turbine power generation system with a capacity of 1.2 MW, and it is targeted to reach 255 MW in 2025 (Ata and Kocyigit, 2010). Therefore, it is a challenge to extract energy from low rated wind speed area.

Wind energy conversion system (WECS) is important to extract varying wind into electricity, especially in the low rated wind speed areas. In WECS, control community concerns on pitch regulated and variable speed wind turbines (Galdi, *et al.,* 2008). A pitch angle control is a common method which is not only used to reduce the excess load of the WECS at high wind speeds, but also used to increase the angular velocity when the average wind speed decreases (http://w.w.w.energi-angin.com). One approach to control the pitch angel is utilizing a proportional integral (PI) control, but it requires the knowledge of system dynamics (Bianchi *et al.,* 2004). Advanced control strategies such as a fuzzy logic controller can be used when the system is not well known or contains non-linearities (Evgenije Adzic,Zoran Ivanovic, 2009; OnderOzgener, 2006). A pitch angle control using fuzzy logic for power system stabilization has been proposed (Ajao, 2009). In (Pintea *et al.,* 2010), the simulation and comparisons of the PI controller and fuzzy logic controller has been carried out.

In this paper, a pitch angle controlled WECS using fuzzy logic for low rated wind speed is proposed and demonstrated. A wind turbine prototype, gear box, induction generator, and fuzzy logic controller (FLC) are built. The FLC is optimized to achieve high performance of energy conversion for the low rated wind speed.

MATERIALS AND METHODS

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Fig. 1 shows a block diagram of WECS. It consists of an aerodynamic sub-system, a gear box, induction generator, batery/load, and pith angle-blade controller. An aerodynamic sub-system has a function to convert wind energy kinetic into mechanical energy. In the aerodynamic sub-system, a rotational speed of wind turbine is controlled via pitch angle position. There are three parameters in the aerodynamic sub-system: an input wind velocity V, pitch angle β and rotational speed turbine ΩT. The output of the aerodynamic sub-system is torsion which can be expressed as:

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

The blade turbine rotation yields mechanical power which be transmitted through turbine rotation. The turbine rotation is used to rotate the rotor generator which be connected via the gear box. The power generator output is design to be in a region which correlated with the span of wind speed available. Therefore, to maintain the power generator within the desired level, a pitch angle control can be carried out.

In the wind turbine, a detailed of mechanism to convert the wind into wind turbine power can be found in (Helen Markou, Torben Larsen, 2009). The output wind turbine power can be formulated using eq. (2)

$$Pw = ½\ Cp\ (\lambda,\theta).\rho.A.v^3 \quad (2)$$

where Cp is a performance coefficient which can be determined using aerodynamics law [x], ρ is air density, A is wind turbine blade swept area, and v is input wind velocity (m/s). The system performance of wind turbine depends on a pitch angle (θ) and a tip-speed ratio (TSR) (λ). TSR can be calculated using eq. (3):

$$\lambda = \omega_t\ R/v \quad (3)$$

where R is a blade radius, ωt is rotational speed. The performance coefficient can be determined according to the pitch angle and the tip speed ratio (Calderaroa *et al.,* 2007).

$$Cp = (0,44 - 0,167\ \theta).\ \text{Sin}\ \{\pi(\lambda\text{-}3)/(15\text{-}0.3\lambda)\} - 0.00184(\lambda\text{-}3)\theta \quad (4)$$

An equation for electromagnecit torsion per unit can be written into eq. (5)

$$T_e = \varphi_{qs} i_{qs} - \varphi_{qs} i_{ds} \quad (5)$$

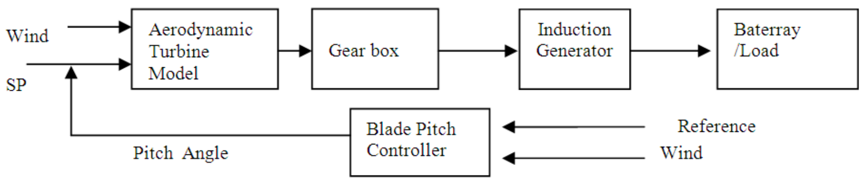


Fig. 1: A WECS block diagram with the capability to change the pitch angle

Fig. 2 ilustrates a full wind turbine generator including a power electronic. A unit generator block changes mechanical energy supply from wind turbine power into electricity. This sub-system includes electric generator and an electronic converter. In general, dynamics of generator unit can be modeled using a flux model for an induction generator as in (Wikipedia, 2011).

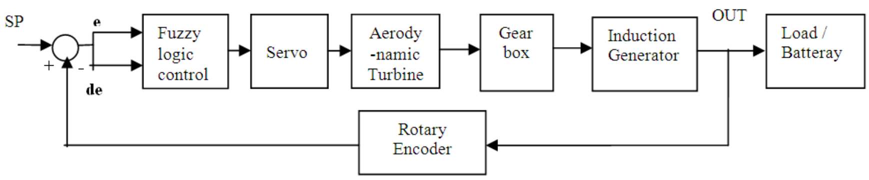


Fig. 2: Block diagram wind turbine with generator system

Ideally, fuzzy logic control system directs the process variable in relationship power coefficient Cp, λ and β, to the optimum values as ditujukkan by Fig. 3.

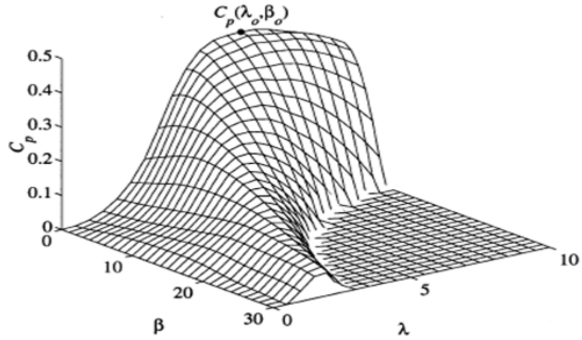


Fig. 3: Typical power coefficient C_p (λ,β).

RESULTS AND DISCUSSION

Power regulation in pitch-controlled WECS below rated wind speed can be explained that the mechanical power resulted by to the aerodynamic system are congruent with the blade angle that is expressed in equation 5. Part associated with wind power $(\frac{\pi\rho R^2(\lambda,\beta)}{2}V^3)$ is converted into mechanical power and value is determined by Cp (.). These coefficients can be interpreted as a variable gain controlled by the λ and β. Coefficient power at average wind speed should be maintained to obtain optimum value of maximum energy capture, as well as for wind speed above the average speed should be maintained, wind turbines should not be exceed the maximum speed, the settings for this target is required to become a power coefficient, Cp.

$$P_r = \frac{\pi\rho R^2 C_p(\lambda,\beta)}{2}V^3 \quad (6)$$

The model velocity change with the FLCFuzzy logic controllers developed in this design is focused to control the angular velocity of the wind turbine shaft. Fuzzy methods used are included in the Mamdani method, as mentioned defuzzyfication, The *Midle of Maximum Method (MOM). In the fuzzy control system is used equations of* lines, rather than area (area) as in Matlab or other software. This is done to simplify and facilitate the writing in a programming language. So the values of memberships are grouped in the equation. Input in this system is the angular velocity and the output is data representing the signal to change the blade angle. By changing the angle of attack of wind caught, then the angular velocity will also change. Flowcharts and system block diagram in Figure 4.

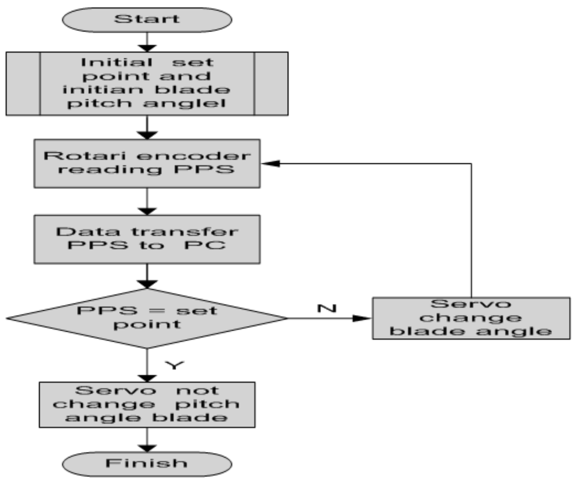


Fig. 4: Flow Chart Control System

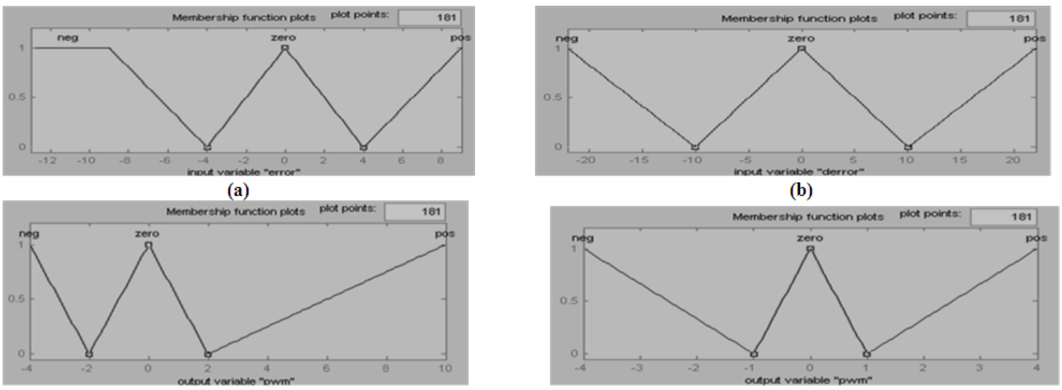
Model Of Fuzzy Rules For FLC-1 and FLC-2:

Fuzzy systems are applied to wind turbine through microcontroller implemented with the programming language C, the membership function of fuzzy system is written in the form of line equation. From these programs are integrated with the controller hardware system further receives input system can work and execute to make decisions and to activate position blade angle for producing optimum power. In the first experiment, data was collected on a wind turbine system that works without the controller (FLC-0), performed by using a blower that wind speed can be adjusted in the range of 0-7 m / s. In this test, the position of blade angle changed in step 5.6 ^{0} in the range $(0\text{-}90)^0$ to the left or right. The data are collected and processed and used to perform design and construction of fuzzy logic control strategy version 1 (FLC-1) which involve the whole of blade angle range (00-90) 0, then these are performed the testing phase two, where the data is processed and recorded and analysed after it. The third stage is to design a three-stage fuzzy logic control, by limiting the working area blade angle positions that generate power only. The design of FLC-2 is to improve the FLC-1. Blade angle position of the working area is limited to areas that generate power only (0-67) 0, then it will be found the midpoint of where that point is assumed as the optimal working range generator (set point). Membership functions of inputs and outputs have been designed in such a way, so that database tables will be arranged in a simple rule that can describe the relationships between membership functions and input; error input and error delta with the following output membership functions as shown in Fig. 5. Fig. 5. Input membership function of (a) error (d) delta error, output membership function (c) FLC-1, (d) FLC-2

Table 2: Control Fuzzy Rules A Lookup Table for FLC-1 and FLC-2

RULES		Error		
		neg	zero	Pos
dError	neg	neg	neg	Zero
	zero	neg	zero	Pos
	pos	zero	pos	Pos

The Prototype wind turbine testing and its fuzzy rules shown in Table-2 are conducted in ITS laboratory as shown in Fig. 4. To view the performance of the system, both with or without control systems FLC-1 and FLC-2, was done by giving varieties of wind speeds on wind turbine systems. Varieties of wind speed changes are given in three circumstances, ie, speed up, speed down and varied speed in the region (4-7) m / s. as shown in Fig. [7.a]. Examiners of systems with varying wind speed on wind turbine with blade angle position varied Fig. 7.c, can produce mechanical power as indicated by the Fig. 7.b. The test is run without the control system FLC-0 or with system control FLC-1 and FLC-2. As seen as in the system with FLC-2, it produces consistent mechanical power production.



(c) (d)

Fig. 5: Input membership function of (a) error (d) delta error, output membership function (c) FLC-1, (d) FLC-2

The electric power generator is directly proportional to the average value of the angular velocity generator. With the existing formulation and involving the speed of the generator Fig. 7.d. and calculating of electrical torque as shown by drawing the electric power 7.e so electric power are caused by torque (Fig. 7.e.) and these are divided by ω. Wind turbines experiment that is controlled and uncontrolled produces mechanical torque which increases as shown in Fig. 8. It appears that by using the control system, torque of wind turbines will increase 1.6-fold compared with uncontrolled. The relations between electrical angular velocity and torque are shown by Fig. 9. Maximum torque values in the range (40-100) N m. And it is in the range of multiplying factor (2.25 to 3.25) rad/s.

Fig .6: The wind turbine prototype testing

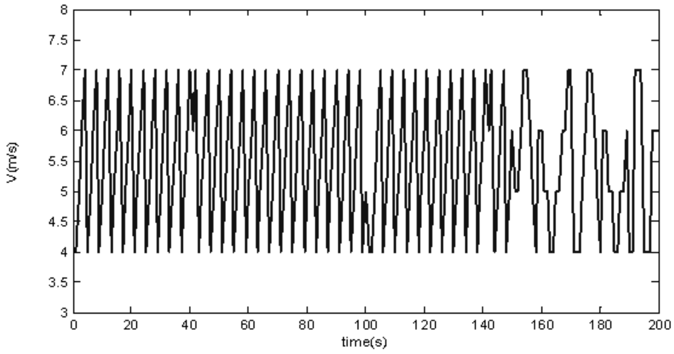


Fig. 7.a: Input wind speed (m/s)

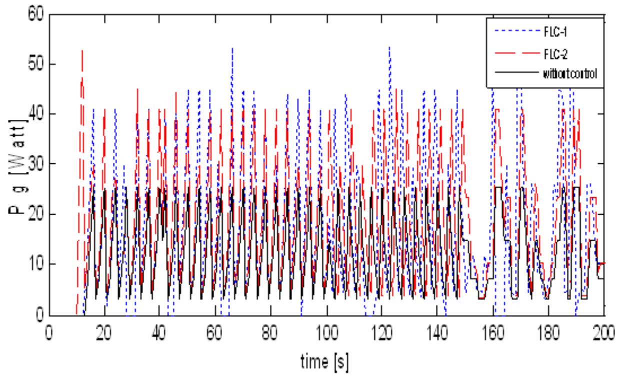


Fig. 7.b: Wind power generation at pitch angle fixed and control in wind speed variatif

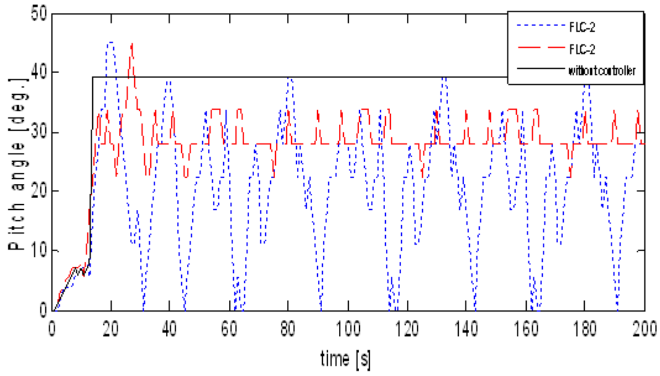


Fig. 7.c: Corresponding to change in wind speed from 4 to 7 m/s for three different variabel speed controllers.

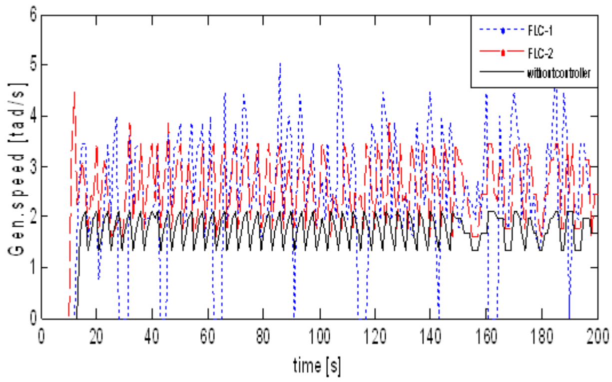


Fig. 7.d: Generator speed of wind turbine for pitch angle fixed and control in variatif wind speed

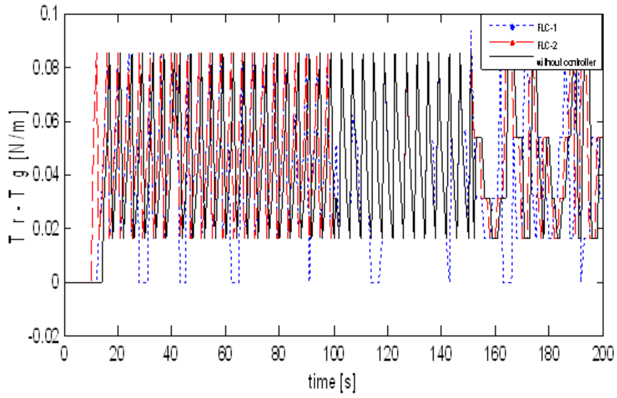


Fig. 7.e: Torque of Wind turbine in pitch angle fixed and control for variatif wind speed

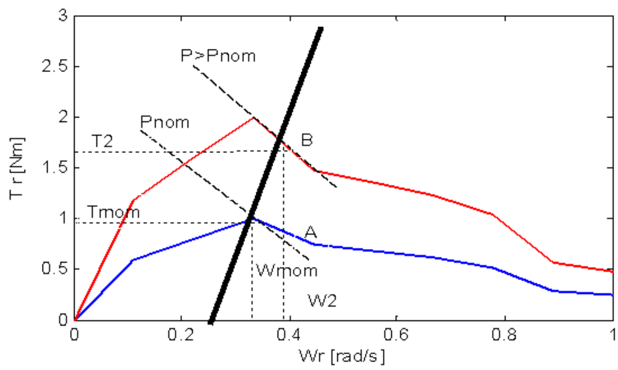


Fig. 8: Fixed-speed power regulator on the torque –speed plane

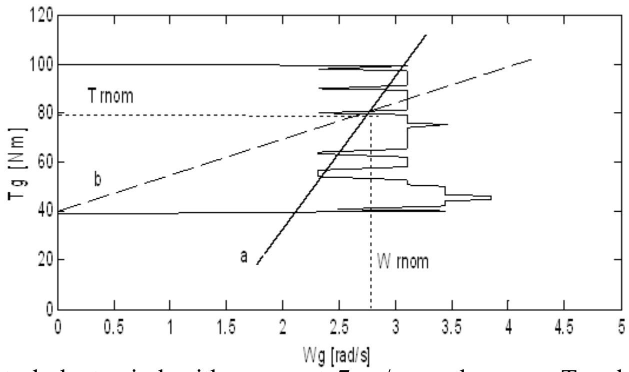


Fig. 9: Corrresponding to a turbulent wind with mean at 7 m/s on the ωg - Tg plane (a) fixed-pitch, (b) variable speed

Table 3: Responses of FLC

Fuzzy Logic Control Type	Rise Time (sec)	Max Over shoot (PPS)	Settling Time (sec)	ESS (%)	ITAE
FLC-0	08	2	14	5.00	350
FLC-1	18	5	87	6.61	25016
FLC-2	07	1	20	3.64	328

Table 4: Conversion of wind energy to mechanical energy and electrical energy with varied wind speeds: increase, decrease and random; with the uncontrolled system (FLC-0), with fuzzy logic control (FLC-1) and (FLC-2)

FLC-0					
Vwin	P_{wind} (Watt)	$P_{mec.}$ (Watt)	$P_{elec.}$ (Watt)	Voltage, (Volt)	Curren, (Amp.)
Vw.inc. 4-7	8991	1574	1102	9,2	1,2
Vw .dec.7-4	8991	1510	1057	7,8	1,2
Vw.var. 7.4,4.7	8991	1362	953	9,5	1,1
Average	8991	1542	1080	8,5	1,2
FLC-1					
Vwin	P_{wind} (Watt)	$P_{mec.}$(Watt)	$P_{elec.}$ (Watt)	Voltage, (Volt)	Curren, (Amp.)
Vw.inc. 4-7	8991	2281	1597	9,4	1,1
Vw .dec.7-4	8991	2161	1513	9,6	1,0
Vw.full 7.4,4.7	8991	1834	1284	10,4	1,2
Average	8991	2221	1555	9,5	1,1
FLC-2					
Vwin	P_{wind} (Watt)	$P_{mec.}$ (Watt)	$P_{elec.}$ (Watt)	Voltage, (Volt)	Curren, (Amp.)
Vw.inc. 4-7	8991	2434	1704	10,4	1,3
Vw .dec.7-4	8991	2493	1745	10,7	1,3
Vw.full 7.4,4.7	8991	1992	1395	13,1	1,3
Average	8991	2464	1725	10,6	1,3

Conclusions:

From the test results for the 200 seconds in average wind speed of 4-7 m/s for the system uncontrolled (FLC-0), it can be seen that it obtains mechanical power production of 1542 watts or 1080 watts of electrical power, although for design systems with fuzzy logic control 1, (FLC-1) obtain mechanical power of 2221 watts or 1555 watts of electrical power and then for systems with fuzzy logic control 2, (FLC-2) obtain 2464 Watts of mechanical power or 1725 watts of electrical power. See more details in table-3. By applying the FLC-1 control system, it can improve electric power production which is increase in average, 44%, and for FLC-2 increase in average = 60%. Power deviation from the uncontrolled system, $\mu = 0.03$, FLC-1, $\mu = 0.04$ and $\mu = 0.03$ for FLC-2, with the result that power production uncertainty requirement is <4%, then they all meet the requirement if the maximum deviation of the uncertainty set 5%. In the FLC system produces an voltage average of 8.5 volts and the current average 1.2 A, for FLC-1, the voltage average of 9.5 volts and electric current 1.1 amperes, and for FLC-2 produces 10.6 voltage average and current average of 1.3 amperes. All three systems generate uncertainty value voltage for FLC-0 $\mu = 0.21$, $\mu = 0.46$-1 FLC and FLC-2, $\mu = 0.31$. The three current measurement uncertainty $\mu = 0.07$. The best criteria of the three systems, as seen from characteristics of control systems, power production performance, voltage and current, it can be concluded that the system using FLC2 can produce the best performance.

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