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Study of Supervisory Control Implementation in A Small Scale Variable Speed Wind Turbine

Katherin Indriawati[1,*], *Ali* Musyafa[1], *Bambang* L. Widjiantoro[1], and *Anna* Milatul Ummah[1]

[1,2,3,4]Institute of Technology Sepuluh Nopember

Abstract. In relation to improve wind energy production, efforts to increase the extraction of wind energy should be done when there is a decrease in wind power. The decline occurs when there is a change in wind speed. At low wind speed operating range, such as in Indonesia, the controller optimizes power extraction through wind turbine rotor regulation following optimal rotor speed. This study proposed the use of the PI control system as an intelligent control system to solve nonlinearity problem and the setpoint adjustment mechanism to get at the problem of the uncontrolled stochastic driving force input. The PI control is called as a regulatory control while set-point adjustment is known as one mechanism in supervisory level. Thus, that control system is called as the supervisory control. This control had a task to maximize output power of a wind turbine. The technique was applied to a small scale horizontal axis wind turbine operating in wind speed range of 3-11 m/s. The applied optimization algorithm generated an optimum set-point simultaneously when there was a change of wind speed.

1 Introduction

Economic activities has made energy into a key infrastructure requirement in the modern industrial economy. A large energy deficit is expected to occur in the coming 2030s as stated by the energy outlook, the Agency for Assessment and Application of Technology. On the other while, global environmental pollution and climate change issues have encouraged various parties, both government and private, to participate in efforts to reduce the causes of pollution and carbon dioxide emissions. The situation has encouraged Indonesia to face a new era, which called the era of increasing the use of renewable energy sources.

One form of renewable energy source that is environmentally friendly is wind energy. Indonesia has made a fundamental policy specifically for wind energy by establishing wind energy as a source of clean energy and future energy sources. In 2009-2010, the world's installed renewable energy capacity has grown from 250 Giga Watt (GW) to 312 GW, with the highest EBT growth occupied by the Bayu Energy Power Plant (BEPT) of 159 GW in 2009 to 198 GW in 2010. To increase the role and contribution of BEPT to have a big role, so the effort to utilize efficient technology becomes important. Improved technological capabilities to extract wind energy into electricity need to be developed more efficiently, more reliability, more environmentally, and more affordably.

The development of wind energy in Indonesia has become a national energy program handled and developed by LAPAN. Procurement of self-made wind turbines and purchased from European countries, China, Taiwan, and others. The wind turbine has a traditional type of fixed-speed turbine or stall regulation blade fix. This type of wind turbine is more suitable for zones that have stable wind speed and wide range. While tropical wind speeds like Indonesia have a narrow range and fluctuate in the area of 4-6 m/s at night and 3 m/s in the morning until 10.00. Therefore, greater effort is needed to design wind turbines in low wind speed areas (cut-in small) where the chances of a decrease in wind turbine power production are very large. Low wind speed work area will influence cost optimization criteria in wind turbine besides will affect the cost of turbine component [1].

Currently the development of fixed-speed generator technology has shifted to variable-speed generator. The application of controls on wind turbines has been carried out with PI conventional control strategies. In this control strategy requires a detailed knowledge of system dynamics and requires the decline of complex mathematical models [2]. The perfection of conventional control is strongly influenced by system nonlinearity. In addition, in conventional control systems, control areas are divided into several regions that make the system complex and slow [3]. Therefore, nowadays intelligent control system has been developed which is able to produce optimum power as in [4] and [5].

The development of a small-scale wind turbine prototype with variable pitch angle control based on Fuzzy Logic Control (FLC) for low average wind speed has been done by one of the research team even though it has just reached the wind power production stage [6]. The integration of wind turbine and electric generator needs to be developed so that the exploitation of wind energy can be expanded. In this case, the wind energy

* Corresponding author: katherin@ep.its.ac.id

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conversion system built is expected to extract the maximum possible energy in the condition of Indonesian wind farms that have a low average annual speed.

2 Problem Formulation

The characteristics of wind speed and the ability of wind turbines holds the key to successful installation of wind turbine systems. The interaction is a very complex system, but the event can be simplified through aerodynamic torque modelling or aerodynamic power placement. In relation to efforts in increasing wind energy production, efforts to increase the extraction of wind energy should be done when there is a decrease in wind power. The decline occurs when there is a change in wind speed. A suitable control strategy is to keep the value of Tip Speed Ratio (TSR) to stay within the working range of the wind turbine. The optimum TSR value will cause the wind turbine to extract maximum wind power at available wind conditions. Thus, the faced problem is choosing the optimum pitch angle position (to obtain the optimum TSR value) capable of generating maximum power, taking into account the low cut-in value so that the turbine is still capable of generating electrical energy when the wind speed is low. Furthermore, the optimum pitch angle becomes a reference value for the control system that adjusts the pitch angle position.

Power is the energy derivative of time. The wind power that can be captured and extracted by the horizontal axis wind turbine system is further defined as follows [7]:

$$P = \frac{1}{2} \rho_{air} C_p A_r V_w^3 \quad (1)$$

$$P = \frac{1}{2} \rho_{air} C_p(\lambda,\beta) A_r V_w^3 \quad (2)$$

While λ is formulated as follows:

$$P = T_g \omega \quad (3)$$

The relationship between power output of wind turbines and rotor speed of shaft is defined as follows:

$$\lambda = \frac{\omega \cdot R}{V_w} \quad (4)$$

If ω is constant according to the desired setpoint and R blade is constant, then C_p will only depend on V_w and ß. Since V_w can not be controlled and is random, angle ß is used as a manipulated variable to extracted the maximum power output when there is a change in wind speed.

The relationship between the output power generated by the wind turbine, the generator rotor speed and the wind speed is indicated by the curve in Fig. 1.

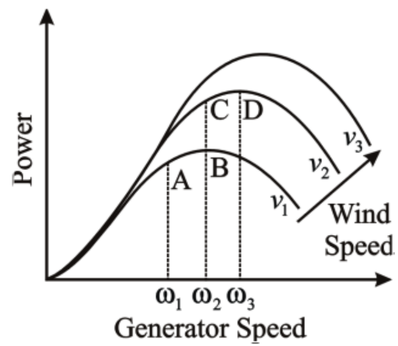

Fig. 1. The relationship between wind speed, generator speed, and the output power of wind turbines [8].

Fig. 1. Shows the presence of a rotor speed (ω) in each work area for a certain wind speed in order to maximize output power of wind turbine. If the wind speed is v_1 and the wind turbines is operated in point A (for the generator speed is ω_1), then for maximizing the output power, the generator speed should be changed into ω_2 in order to the output power is in point B. It also applies to the wind speed v_2 and v_3. When the wind speed is v_2, the wind turbines will be operating in point C, but actually the maximum output power that can be extracted in that wind speed is point D, then the generator speed should be changed from ω_2 into ω_3.

In power optimization, generators also have an important role beside the numerical value of pitch angle in the process of converting mechanical power into electrical power. Maximization of this process is influenced by the output power of turbine and the numerical value of torque generator. In this study the numerical value of torque generator and the pitch angle value are generated by PID control to maximize the electrical power output of wind turbine system.

Based on the above description, then the problem raised in this research is how to develop an intelligent control system based on supervisory control in order to obtain maximum power with minimum maintenance cost through the pitch angle variable as a manipulated variable.

Supervisory control determines the conditions for ordering lower level automation functions or referred to as regulatory control. The hierarchical structure of the power generation system looks in line with the optimization of the supervisory through the determination of the setpoint. Here, the supervisory controller continuously monitors system operating conditions and keeps the system within the specified target domain. Control operation ensures that the goal of system operation is achieved and maintained despite the constraints of uncertainty and resources. It can also act to prevent the system from being in a critical condition or to reduce the consequences of system component failure. Some of the parameters used in this study are as follows:

Table 1. Definition of parameters and their numerical value.

Parameters	Definition	Value	Unit
β_o	Blade pitch angle	0	deg
β_{max}	Maximum blade pitch angle	27	deg
ß/s	Pitch rate	10	deg/s
Cp_{max}	Maximum coefficient of power	0.5	-
λ_{max}	Maximum tip speed ratio	9.95	-
V_w	Wind speed	5-11	m/s
K_{sH}	Stiffness coefficient	80.27	Pu/rad
T_o	The early torque of wind turbine	0.83	pu
F	Friction factor of generator	0.01	pu
ω_{mo}	Rotor electrical frequency	1.2	pu
ω_{max}	Maximum rotor speed	1.2	Pu
ω_{min}	Minimum rotor speed	0.7	pu
P_{mec}	Mechanical power output	400	W

3 Supervisory Control

Supervisory Control (SC) is a wind speed control system. SC has the supervisory level for doing optimization at the generator speed as a setpoint in the simulation of this study in order to be found a fixed blade pitch angle. This angle will be controlled by PI control so that it can produce optimum power output of wind turbine without exceeding the speed limit of the rotor.

The PI control is used to overcome the characteristics of nonlinearity generated by the wind turbine systems. This control uses the proportional parameter and integral parameter (PI control) in the process.

The concept of supervisory control system in this study can be explained through fig. 2.

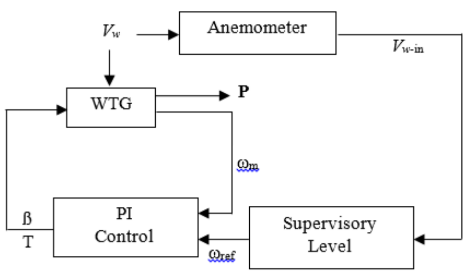

Fig. 2. The concept of supervisory PI control.

Fig. 2. Describes the use of wind speed data to be used as the reference rotor speed at setpoint. The wind speed will be measured by the anemometer and will be used as input at the supervisory level to get the certain generator speed. At this supervisory level there is an optimization of rotor speed to produce maximum power. Then the reference generator speed will be used as input on the PI control system to do the linearization and produce a certain pitch angle and generator torque. This blade pitch angle will change the geometry of the aerodynamic system and become the input of the wind turbine system so that the resulting power becomes optimal. And the torque will change numerical value of generator rotational speed.

3.1. Supervisory Control

The proposed setpoint adjustment is based on extremum seeking (ES) algorithm. This is an dynamic optimization algorithm that does not need mathematical model of electrical power as objective function. Here the power is wanted to be maximized by regulating turbine speed. Furthermore, using this method, any wind speed measurement is not necessary but only the electrical power measurement is required.

ES algorithm finds an optimizing turbine speed as a setpoint value ω_{ref} for the unknown time varying cost function $J(\omega_{ref},t)$ which is defined as:

$$J = -\frac{1}{P_0}(\hat{P} - P_0)^2 + P_0 \tag{8}$$

where P_0 is rated electrical power and $\hat{P}$ is estimated electrical power.

The ES algorithm consists of a highpass filter, a sinus signal, two lowpass filters, an integrator, and a dynamic compensator which are arranged as shown in Fig. 5. A highpass filter, a sinus signal, and one of two lowpass filters are used to extract a signal that is proportional to the gradient of the cost function J with respect to the optimizing variable ω_{ref}. Then the integrator and the compensator drive the gradient to zero and thus achieve the optimal value. The remain lowpass filter has a function to improve steady state tracking of the optimal parameter ω_{ref}.

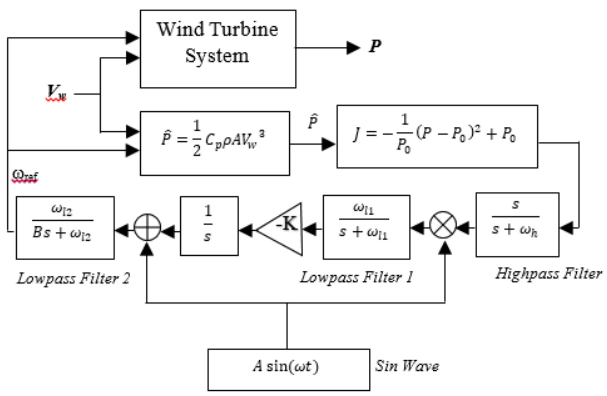

Fig. 6. The structure of setpoint adjustment in supervisory control.

From fig. 6. we know that for designing the supervisory control, there are parameters that must be required. They are the determination of ω_h value on the highpass filter, ω_{l1} on lowpass filter 1, ω_{l2} and value of B on lowpass filter 2, amplitude (A) and angular frequency (ω) in the function of signal generating (sinusoidal signal), and numerical value of negative gain.

The value of parameters are ω_h=1, ω_{l1}=0.01, ω_{l2}=1, B=1, A=0.1, ω=1, and K=3.7.

4 Simulation Results

This paper present design of supervisory control to maximize output power of wind turbine system by modelling system using MATLAB-SIMULINK software. The used rated wind speed in the system is 11 m/s. The results of simulation are as follow fig. 7., fig. 8,., and fig. 9.

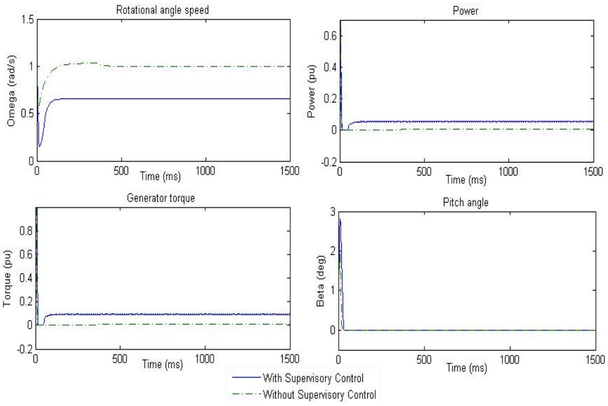

Fig. 7. The results of simulation at below rated wind speed.

The figure shows result of rotational angle speed, output power, generator torque and pitch angle at the time with supervisory control and without supervisory control. The fixed line shows the presence of supervisory control in the wind turbine system. The dots line shows result of wind turbine system without controlling method.

At the below rated wind speed, wind turbine speed will has small rotational angle speed. It makes wind turbine extract small power. Then in the certain wind speed, wind turbine system will not be suitable for generating the power. By applicating supervisory control method, it will make wind turbine system generate output power optimally at above and below rated wind speed.

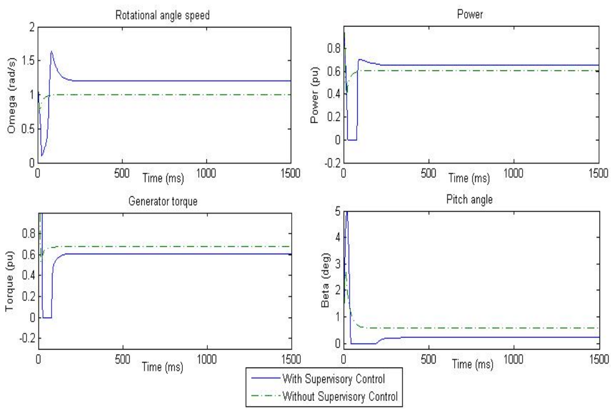

Fig. 8. The results of simulation at rated wind speed.

Fig. 8. shows the presence of increasing output power in wind turbine system by supervisory control. At the same wind speed, wind turbine system without supervisory method just generate smaller power. This process is followed by presence of decreasing torque value and pitch angle.

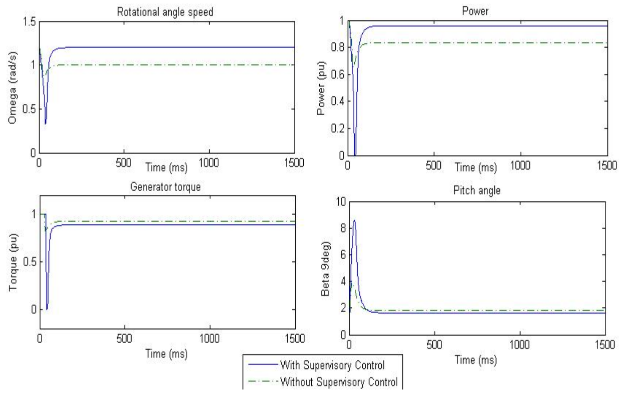

Fig. 9. The results of simulation at above rated wind speed.

Fig. 9. shows the performance of supervisory control in generating output power of wind turbine system optimally at above rated wind speed. The increasing of wind speed will affect in generating power. The rotational angle value will be increasing to generate power maximally.

If we view from the generator torque graph. This value is influenced by PID control. Parameter of Kp and Ki must be required. This numerical value is generated by tunning. At the same time, the value of pitch angle is controlled by PI controller. The PI control can minimize error in the system.

4 Conclusion

The proposed supervisory control system was proven to be successful in increasing the electrical power output of the small scale wind turbine. The supervisory level choose the optimum pitch angle position (to obtain the optimum tip speed ratio) that was capable of generating maximum power by using extremum seeking method. And the PI controller was able to handle nonlinearity behaviour of wind turbine.

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