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Extremum Seeking based Supervisory Control for a Variable Speed Variable Pitch Wind Turbine Benchmark

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ABSTRACT

The extraction of wind energy should be conducted especially for decline condition in wind power in order to intensify electrical power production. This paper introduced the use of supervisory control scheme which consists of a regulatory control level and a supervisory level. The first level has a function to keep the wind turbine system produces maximum power in safety manner using two PI controllers which track any reference rotor speed. The latter level is used to adjust the speed setpoint to its optimum value. Here the dynamic optimisation problem is solved by using the extremum seeking algorithm which is then compared with using the reference formula. The proposed method was applied in simulation to a small scale horizontal axis wind turbine operating in region II of wind speed condition.

Keywords: wind turbine generator, supervisory control, extremum seeking, optimization, rotor speed.

I. INTRODUCTION

Recently, energy has become an important utility needs in the modern industry. Wind energy is one shape of green renewable energy source that has been established as a future energy source. Thus, the technology of extracting it should be built into more efficient, reliable, and affordable one.

The main problem of using wind energy source is certainly the availability of wind. There are so many zones that have fluctuate low wind speed and narrow range. Low wind speed condition will affect cost optimization measure in wind turbine, in addition to influence the cost of its component [1]. Because of that, this time the usage of fixed-speed generator technology has switched to variable-speed wind turbine generator.

The use of controls on variable-speed wind turbine has been conducted with conventional control algorithms as in [2]. In conventional control schemes, regulation zone is split into several areas thus the system become complex [3]. At Region II (low wind speed operating region) like in Indonesia, the controller should optimize energy extraction by means of turbine rotor regulation complying its optimal speed as in [4] and [5]. Here advanced control strategy can be used to enhance wind power capture because this strategy might be applied easily to those installed turbines, so it is a more cost-effective way for energy capture enhancement. In [4], the torque control gain was adjusted based on the average power coefficient measuring result. While in [5] the appropriate torque control value was selected using a model-based approach. However, both works were limited to maximization of rotor power using variable speed but fixed pitch scheme, and also without addressing the electrical power conversion. Indeed, variable speed variable pitch scheme has ability to perform well in wide range wind speed and has better result in power quality [6].

This paper discusses an alternative approach to achieve the maximization of ultimate power generation by using variable speed variable pitch scheme and by incorporating the conversion from rotor power to the electrical power generally. At Region II, the controller is in charge of optimizing power extraction. While at high wind speed operating range, the controller limits power extraction by changing the geometry of the aerodynamic system following a maximum rotor speed (as an optimum value) in order not to overload the system. The proposed strategy is a supervisory control system which is known as one of advanced control strategy methods.

The use of supervisory control for power generation systems have been conducted by several researchers, such as on thermal generation system [7], fossil energy [8], and geothermal power plant [9]. In supervisory control, the determination of reference value is done at the supervisory level. In this case an optimization approach is used to generate an optimum reference value. A commonly known technique in case of power generation is maximum power point tracking (MPPT) which can be done using several ways. Initially, the commonly used method is perturbation and observation (P&O). Another method is the extremum seeking algorithm in where the optimization method is converted into control problem to make zero gradient [10]. Thus, this algorithm is also called as extremum seeking control (ESC). In [11], the comparative study between the used methods in optimization of photovoltaic system was conducted. The study result shows that ESC scheme is more robust and efficient than other online optimization methods such as P&O in [12]; [13] and ripple correlation control (RCC) in [14]; [15]; [16]; [17]. The application of ESC for wind energy conversion have been conducted by some researches such as [18]; [19]; [20]; [21]. They used ESC on different control methods except supervisory control scheme.

In this paper, ESC is proposed for the determination of the optimum reference value at the supervisory level in the supervisory control scheme of wind turbine generator system. As study case, it considers a wind turbine benchmark which consists of blade and pitch systems, drive train, generator and converter. The incorporation between wind turbine and generator is necessary in order to extend of the usage of wind energy. The strategy was implemented in simulation to a small scale horizontal axis wind turbine.

II. PROBLEM FORMULATION

The time derivative of energy is known as power. The capture and extraction process of the wind power in the horizontal axis wind turbine system is formulated as follows [22]:

$$P_a = \tfrac{1}{2}\,\rho_{air}\, C_p(\lambda,\beta)\, A_r\, V_w^3 \tag{1}$$

where

ρ_{air} = air density

A_r = blade impact area

V_w = wind speed

C_p is the nondimensional power coefficient whose value in this paper is approached using this experiment equation [23]:

$$C_p(\lambda,\beta) = 0.645\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp\left(\frac{-21}{\lambda_i}\right) + 0.00912\,\lambda \tag{2}$$

where

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

$\lambda = \dfrac{\omega_t}{V_w} R$ = tip speed ratio

ω_t = turbine shaft speed

R = blade length

The relationship between wind power with turbine torque T_t and turbine shaft speed (blade rotation) is shown by the following equation

$$P_a = T_t\, \omega_t \tag{3}$$

A mechanical model of the wind turbine system is assumed having a two-mass system character, i.e. drive train (blade-rotor) and generator. By ignoring the gearbox and the bearing / seal attenuation, the mechanical model used is:

$$J\frac{d\omega_t}{dt} = T_t - T_m \tag{4}$$

where

$$T_m = D_m(\omega_t - \omega_g) + K_{sh}\int(\omega_t - \omega_g)\,dt$$

= the input mechanical torsion of generator

J = moment inertia of the whole mechanical system

ω_g = generator speed

D_m = mutual damping

K_{sh} = stiffness constant

In the steady state condition, the turbine speed is the same with the generator speed, or $\omega_t = \omega_g = \omega$. In the dynamic condition, the generator speed equation is:

$$J_g\frac{d\omega_g}{dt} = T_m - T_g - F\omega_g \tag{5}$$

where

J_g = moment inertia of the generator

F = friction factor

T_g = the generator electrical torsion

This paper considers a separately excited DC generator whose field winding is excited by an external independent source. Thus, it consists of field circuit and armature circuit. The dynamic model of both circuits can be stated in the following transfer function:

$$\frac{I_a(s)}{V_f(s)} = \frac{K_f\ \omega_g}{(sL_a + R_{tot})(sL_f + R_f)} \tag{6}$$

with

I_a = armature current

V_f = field voltage

L_a = armature inductance

R_{tot} = total resistance in the armature circuit

L_f = field inductance

R_f = field resistance

K_f = field constant

In the case of variable-speed operations, the armature current is controlled using power electronics such as converter by manipulating field voltage V_f so that it loads the generator with a certain torque T_g, that is:

$$T_g = K_f I_f I_a \tag{7}$$

where I_f is field current. Thus, the electrical power output of the generator is:

$$P = T_g \omega_g \tag{8}$$

For the certain pitch, the relationship between the turbine output power, the rotor speed and the wind speed are shown in Fig. 1. If pitch is constant, then power coefficient C_p is only be influenced by V_w and ω. Since V_w cannot be regulated, ω is chosen as a manipulated variable to extract maximally the power output while the wind speed varies. The turbine speed should be changed from ω_1 into ω_2 for maximizing the output power (in point B) at the wind speed of v_1. When the wind speed turns into v_2, then the generator speed should be changed from ω_2 into ω_3. Thus, the maximum power is obtained in the optimal value of ω.

In the high wind speed condition, because the turbine speed is limited in its maximum value related to its physical constrain, then λ becomes low. In order to keep C_p in its maksimum value, β needs to be controlled. Furthermore, the pitch control can be used to keep the turbine speed and power output in theirs maximum value, thereby increasing the reliability of the wind turbine.

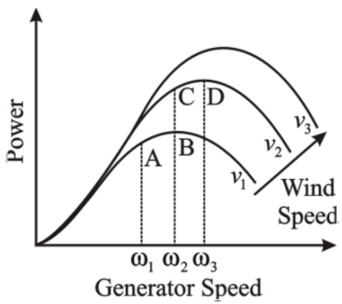

Fig. 1. The correlation of wind speed, rotor speed, and the output power of wind turbines [24].

In power optimization, the control system has a task to keep turbine speed and then generator speed are in the optimal value. This paper considers two manipulated variables for this task, i.e. the torque generator and the pitch angle. Both variables are driven by using proportional – integral (PI) controller. Thus, the studied control system in this paper requires a converter and a motor as actuators, as well as a speed sensor to measure the real generator speed.

As the WTG operates frequently in the low wind speed condition, it assumes that there is no fault in the pitch motor but there is a fault in the converter. The converter fault can make the wind turbine generator system does not work well and furthermore the system can be damaged when it is stopped suddenly. It can also cause damage to the machine due to setting the rotor brakes to stop blade’s position in the desired position at maximum pitch rate. Meanwhile sensor fault will certainly lead to a wrong decision, which may be harmful the safe operation of the whole system. Therefore, it is often possible to use redundant sensors to improve the overall reliability of the measurement system. But it needs more cost.

The remains problem is how to make both controller can work together in order to maximize the power output of the turbine generator system with minimum maintenance cost. This paper studies the implementation of supervisory control mechanism to solve that problem.

III. SUPERVISORY CONTROL

In supervisory control, the condition for regulatory control is supervised and its operating point is determined. The power generation system looks having parallel structure with the optimization of the supervisory, that is by way of setpoint adjustment. Here, system operating conditions are monitored continuously by the supervisory controller. Furthermore it keeps the system within the specified target operation and ensures that the goal is reached in spite of the constraints of uncertainty and resources are exist.

The proposed scheme of supervisory control system could be interpreted through Fig. 2. The output power will be measured and will be used as input at the supervisory level. This unit generates the optimum value of the turbine speed which is then set as reference speed. Next the reference rotor speed should be considered as input on the regulatory control to produce an appropriate pitch angle and generator torque. This blade pitch angle can modify the aerodynamic geometry of the system, whilst the generator speed may be altered by the generator torque. Both variables become the input of the wind turbine generator (WTG) system.

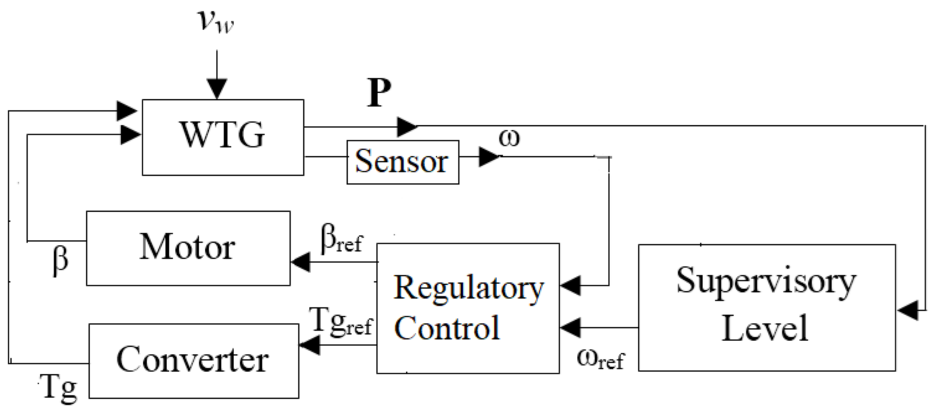

Fig. 2. The mechanism of the supervisory control.

III.1 Regulatory Control

In optimization point of view, the control system sees service to maintain the rotor speed and then generator speed are in their optimal setpoint value. Here, it considers two manipulated variables, namely the torque generator and the pitch angle. Both variables are regulated by using proportional – integral (PI) controllers as a regulatory control system.

In order to know the real operation of the system, the rotor speed must be measured. The drift of the present measured speed ω with the reference speed ω_{ref} is called as tracking error, which should be reduced by two PI controllers. Both controllers work simultaneously: the torque controller works in the low wind speed region and the pitch controller performs in the high wind speed region. The transfer function in the frequency domain of the PI-controller are given by

$$G_C(s) = K_P \frac{T_I s + 1}{s} \qquad (9)$$

where proportional gain K_P and integral gain T_I must be selected in order to get the best speed response.

III.2 Setpoint Adjustment

The supervisory level has a task to adjust setpoint of the turbine speed ω_{ref}. Here it is needed the optimization algorithm to find an optimum value of the turbine speed in order to get the maximum power. The proposed setpoint adjustment is based on extremum seeking (ES) algorithm which is a modified version of the algorithm in [25]. This is a dynamic optimization algorithm that nearly does not need mathematical model [26]. This algorithm considers finding an optimizing variable in an online optimization problem the generally time varying cost function. In this study, the electrical power is clearly as an objective function. Here the power is wanted to be maximized by regulating turbine speed. Thus, the turbine generator speed is an optimizing variable. Furthermore, using this method, the wind speed measurement is not necessary but only the electrical power measurement is required.

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

$$J = -Q(P - P_o)^2 + P_o \qquad (10)$$

where P_o is maximum electrical power that can be generated by the turbine generator, P is measured electrical power at time t which is a function of ω, and Q is a positive constant.

This function realizes the optimization variable ω without measuring the wind velocity v_w so that J can be maximized when v_w is smaller than the maximum wind velocity and can stay at the maximum point (i.e. the maximum electrical power) when v_w is larger than the maximum wind velocity. The maximum wind speed is the largest value of the wind speed that the WTG system still responds to.

Thus the problem optimization is formulated as

$$\omega_{ref} = \arg \min_{\omega \in \Re} J(\omega, t) \tag{11}$$

The ES algorithm consists of a high pass filter, a sinus signal, a low pass filter, an integrator, and a dynamic compensator which are arranged as shown in Fig. 3. A high pass filter, a sinus signal, and a low pass filter are used to extract a signal that is proportional to the gradient of the cost function J with respect to the optimizing variable ω. Here, dc component or low frequency component is suppressed by the high pass filter and the multiplication of the high pass filter output signal by sinus signal creates an estimate of the gradient of the cost function. Next the effect of dynamic part of the gradient estimate signal is reduced by the low pass filter. Then the integrator and the compensator drive the gradient to zero and thus achieve the optimal value as ω_{ref}. Stability analysis of the ES algorithm has been discussed in [21].

Thus, for designing the supervisory level, there are some parameters that must be determined. They are ω_h value on the high pass filter, ω_l on lowpass filter, amplitude (A) and angular frequency (ω_s) in the sinusoidal signal, and gain K. There is no formula to determine all those parameter. However ω_s should be small enough in comparison with the slowest dynamic of the controller system.

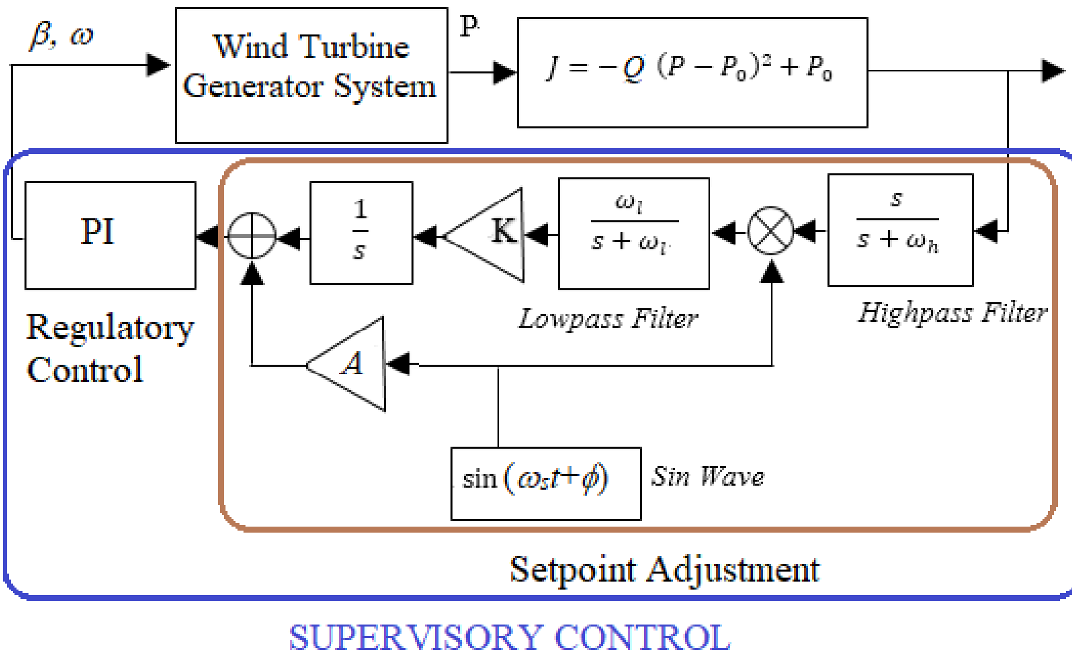

Fig. 3. The structure of setpoint adjustment in supervisory control.

IV. SIMULATION RESULTS

The maximum power of the wind turbine generator system is 400 W for wind speed of 11 m/s. The simulated system is represented as per unit (pu) system. Some of the model parameters used in this study are listed in Table 1.

Table 1. Definition of model parameters and their value.

Parameters	Definition	Value	Unit
$ß_{min}$ - $ß_{max}$	Minimum and maximum blade pitch angle	0 - 27	deg
ß/s	Pitch rate	10	deg/s
Cp_{max}	Max. power coefficient	0.5	-
λ_{max}	Maximum tip speed ratio	9.95	-
V_w	Wind speed	3-14	m/s
K_{SH}	Stiffness coefficient	80.27	pu/rad
T_0	The initial torque of turbine	0.83	pu
ω_{min} - ω_{max}	Minimum and maximum rotor speed	0.5 - 1.2	pu
H	Inertia constant of generator	0.685	pu
F	Friction factor of generator	0.01	pu
H_{all}	Whole inertia constant	4.32	pu
D_{mutual}	Mutual damping	1.5	pu

The control gains of the pitch control are $K_{p,\beta}$ = 0.1 and $K_{i,\beta}$ = 0.5, while the control gains of the torque control are $K_{p,T}$ = 3 and $K_{i,T}$ = 0.1. The parameters for the cost function are P_0 = 0.9 pu, Q = 0.5. The value of the ES parameters are ω_h = 2, ω_l = 8, A = 0.001, ω_s = 0.001, ϕ = 5π, and K = 4.55.

Aiming to analyze the superiority of the ES algorithm in determining the optimum reference value, this study employed the reference model equations [27] as a comparison, i.e.

$$\omega_{ref} = -0.67P^2 + 1.42P + 0.51 \quad (12)$$

In this paper, there are three type controls compared, namely the PI control without setpoint adjustment (the conventional control), the supervisory control using the ES, and the supervisory control using the reference formula. The conventional control using a fixed speed reference at 1 pu. Furthermore, there are six simulations for this study comparison, each of them represents two wind speed condition changes (step changes), involving low (5 m/s), moderate (7 m/s), and high speed condition (11 m/s).

The comparison result is shown in Table 2. In the low and moderate wind speed conditions, the wind turbine benchmark system using conventional control is unable to generate electrical power as the controller could not make the system having the rotor speed value at the setpoint value (1 pu). It is because that the extracted wind energy is lower than the required one related to provide the rotor speed of 1. Hence the generator speed becomes zero, so the generated power is non-existent. In other word, the setpoint value is not appropriate for the lower and moderate wind speed condition, and thus it must be modified. This problem is solved by the supervisory control. Furthermore, in the high wind speed condition, the output power of the conventional control system is less than the supervisory control system. This is because the conventional control system maintains the rotor speed at 1 pu (its setpoint) while the supervisory control system provides 1.2 pu (the maximum rotor speed) for the ES and 1.14 pu for the reference formula. At wind speed of 11 m/s, the rotational speed generated by the system with the conventional controller is slower than that of supervisory control, as well as the largest overshoot. The presence of high overshoot could trigger the occurrence of damage to the generator because it exceeds the maximum working limit. So the utilization of supervisory level provides an optimal rotor speed in each wind speed condition thus the wind turbine generator benchmark system could produce electrical power even in the low wind speed.

The output responses for this condition as shown in Fig. 4 for the rotor speed and Fig. 5 for the pitch angle. Due to the small wind speed, the pitch movement could not be clearly observed. But, for wind speed of 11 m/s which is happened before 500 second, the pitch moves to 0.2 degrees.

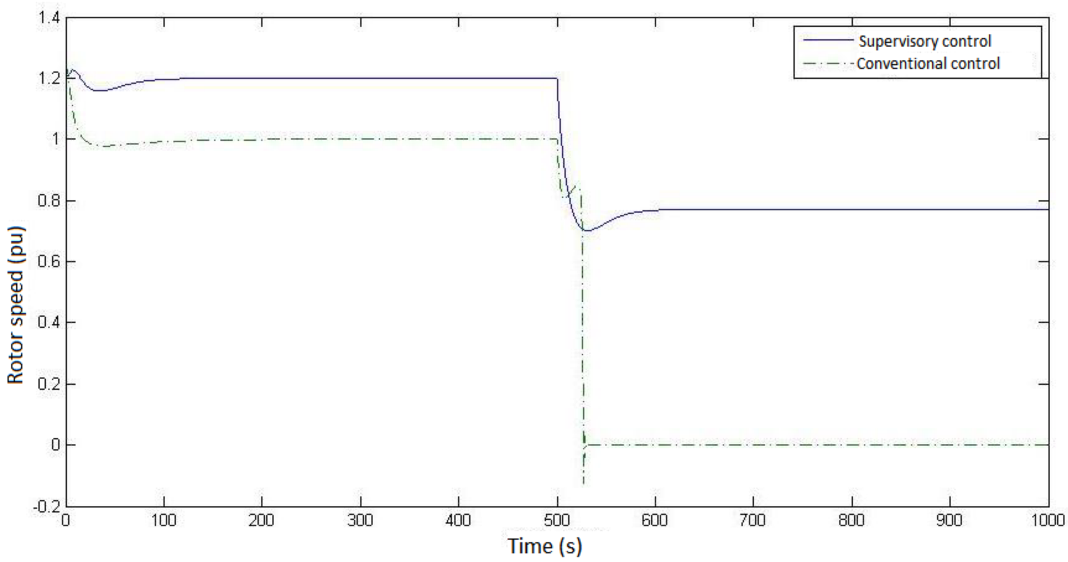

Fig. 4. The rotor speed for wind speed decrement from 11 m/s to 5 m/s

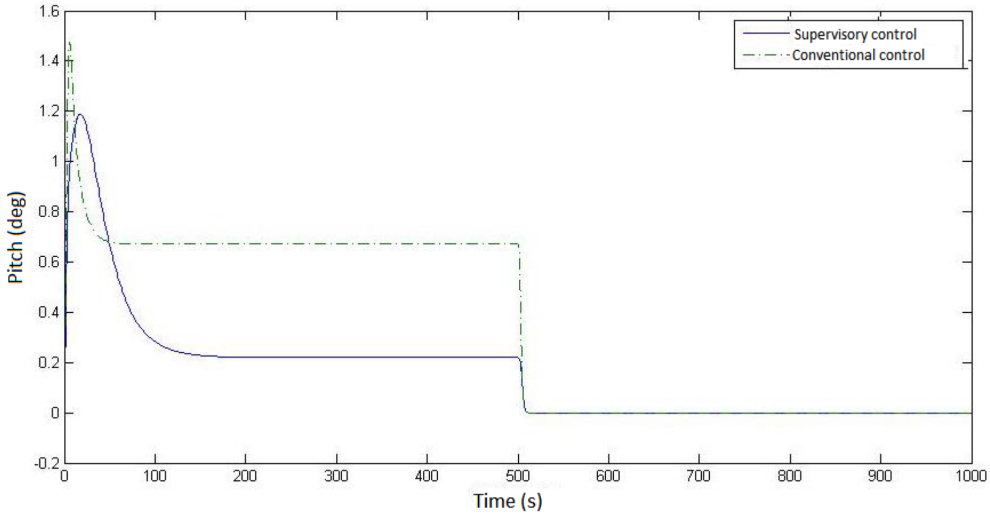

Fig. 5. The pitch angle responses for wind speed decrement from 11 m/s to 5 m/s

Fig. 6 and Fig. 7 show that the supervisory control provides the optimum power coefficient or C_p value (0.5 for wind speed of 11 m/s) even though the wind speed changes dynamically (changing in both up and down). So that the extracted power could reach the optimum value. The C_p value generated by supervisory control system is greater than conventional control system. Due to the change in wind speed from 11 m/s to 5 m/s and vice versa, there is decreased slightly in 500 seconds. However, for the steady state condition, the C_p is maintained as close as possible at 0.5 (or the optimum value for wind speed of 5 m/s), that is 0.43.

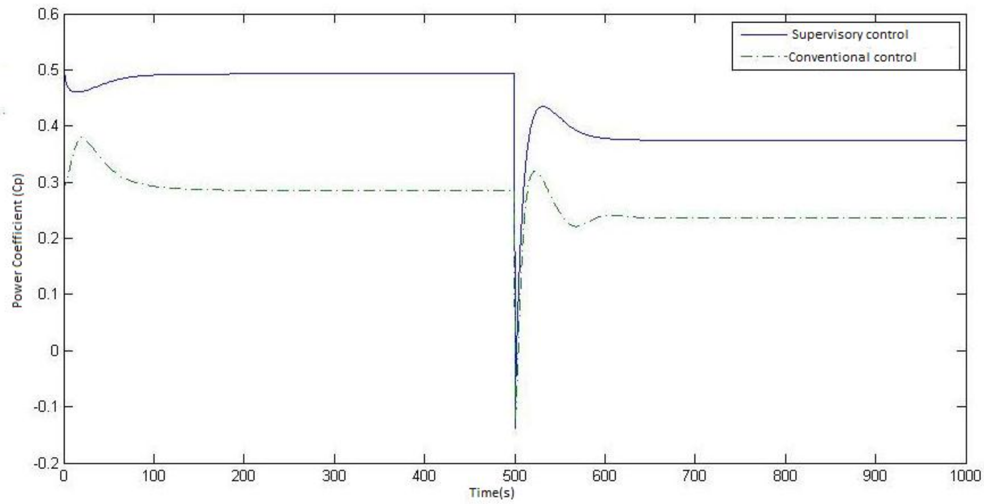

Fig. 6. The power coefficient responses (Cp) for wind speed decrement from 11 m/s to 5 m/s

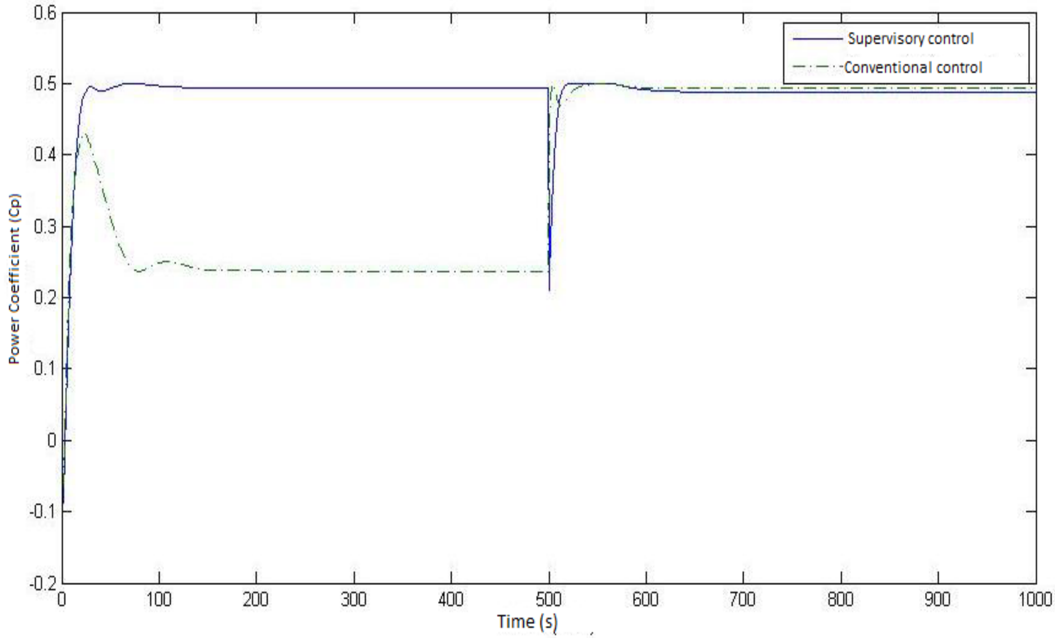

Fig. 7. The power coefficient responses (Cp) for wind speed increment from 5 m/s to 11 m/s

This study is also conducted to compare the performance of two dynamic algorithm in the supervisory level, i.e. the ES and the reference velocity formula as described above. As shown in Table 2, both algorithms provide the different rotor speed value for each wind speed condition, thus the system delivers the output power even at low wind speed. However, both algorithms generate the different rotor speed value. The ES algorithm could produce higher set point than the reference formula, hence the wind turbine generator output power of the first system is greater than the second one. This indicates that the performance of the ES algorithm is better than the reference formula. The responses of both algorithm is clearly expresses in Fig. 8 – 11, which show the changes in the resulting power value, the rotor speed value, the torque value and the pitch response, respectively. Fig. 8 and Fig. 9 proves that the supervisory control system using the ES algorithm has higher value than the one using the reference formula. Meanwhile, Fig.10 shows that the generator torque (as the one of the two manipulated variables) generated by the supervisory control system using the ES algorithm is slightly lower than the other one. And Fig. 11 shows that the pitch angle (as the second manipulated variable) does not move at low wind speed (5 m/s). The pitch angle movement appears after 500 seconds due to the increment of wind speed to 11 m/s.

Table 2. Comparation between performance of Extremum Seeking and Reference Formulas Algorithm

Wind Speed Change (m/s)	Algorithm Type	Final Value			
		Power (pu)	Speed (pu)	Torsion (pu)	Pitch Angle (deg)
5 to 7	Conventional	0	0	0.05	0
	ES	0.169	0.73	0.256	0
	Reference	0.139	0.99	0.154	0
5 to 11	Conventional	0.60	1	0.67	0.6
	ES	0.652	1.2	0.604	0.22
	Reference	0,646	1.14	0.626	0.33
7 to 11	Conventional	0.60	1	0.68	0.7
	ES	0.652	1.2	0.604	0.22
	Reference	0.646	1.14	0.626	0.33
11 to 5	Conventional	0	0	0,02	0
	ES	0.059	0.59	0.115	0
	Reference	0.042	0.77	0.061	0
11 to 7	Conventional	0	0	0.05	0
	ES	0.169	0.73	0.256	0
	Reference	0.157	0.90	0.193	0
7 to 5	Conventional	0	0	0,02	0
	ES	0.059	0.59	0.115	0
	Reference	0.032	0.84	0.043	0

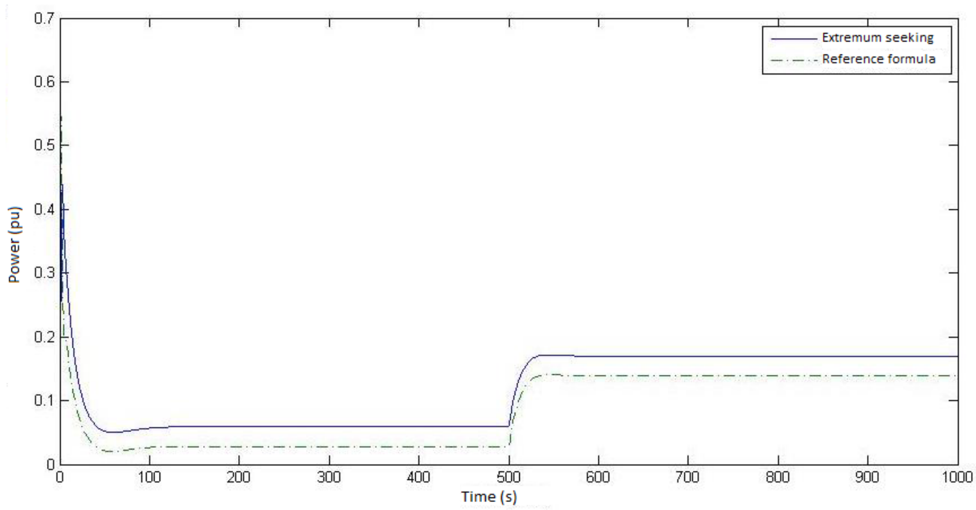

Fig. 8. The output power responses of the supervisory control system for wind speed increment from 5 m/s to 7 m/s

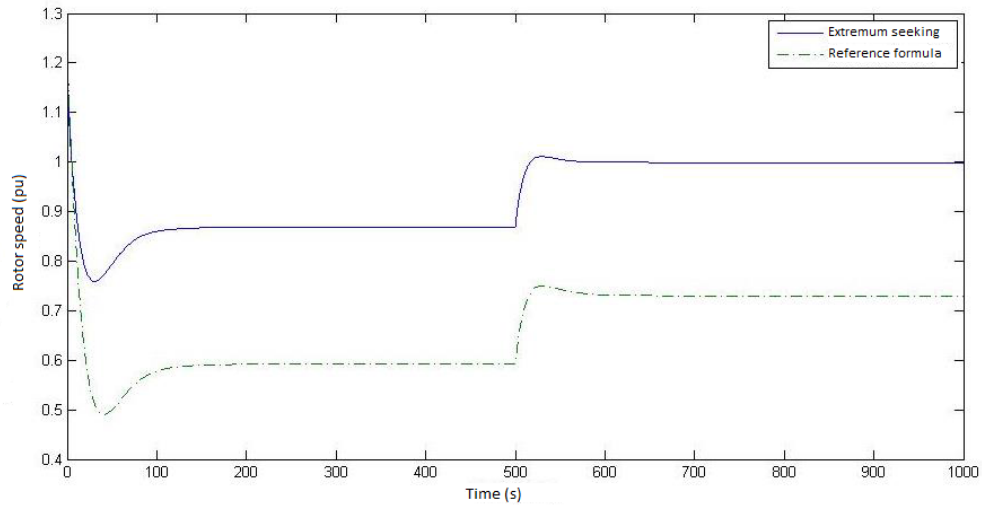

Fig. 9. The rotor speed responses of the supervisory control system for wind speed increment from 5 m/s to 7 m/s

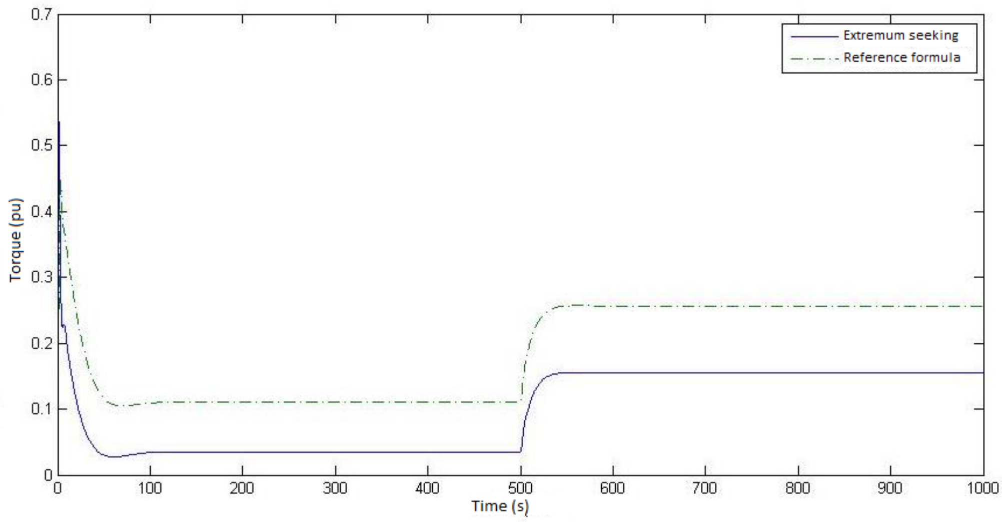

Fig. 10. The generator torque responses of the supervisory control system for wind speed increment from 5 m/s to 7 m/s

Based on the response performance indicators including rise time, settling time, maximum overshoot and steady state error, the ES algorithm has better performance than the reference formula, as stated in Table 3. Error steady state for both algorithms are almost the same, which is close to zero. Meanwhile, the settling time of the ES algorithm is smaller than that of the reference formula, which means that ES algorithm is able to provide faster response. The maximum overshoot value of both algorithms do not exceed to the maximum allowed overshoot (<5%). But, they have different overshoot value. The maximum overshoot of the ES algorithm is smaller than the one of the reference formula, which means that the ES provides more safety operation than the reference formula.

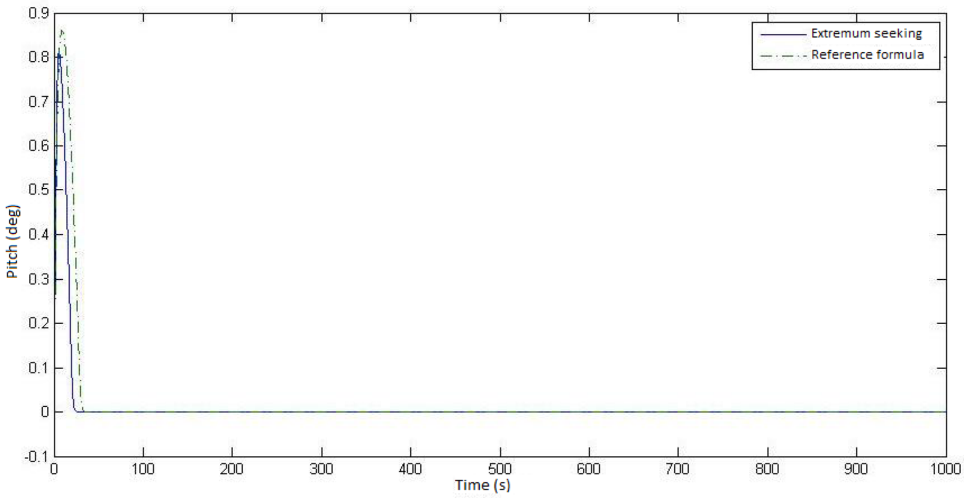

Fig. 11. The pitch angle responses of the supervisory control system for wind speed increment from 5 m/s to 7 m/s

Table 3. The performance indicators of the rotor speed responses of the supervisory control

Wind speed (m/s)	Algorithm Type	Response Characteristics		
		Rise time (s)	Settling time (s)	Overshoot (%)
5 – 7	ES	30	146.6	0.42
	Reference	40	213.5	0.53
5 – 11	ES	26	160	-
	Reference	32	210	1.05
7 – 11	ES	24	180	-
	Reference	27.5	170	0.6
11 – 5	ES	28.5	152	2.7
	Reference	21	133.5	2.01
11- 7	ES	30	163	0.4
	Reference	30	120	0.55
7 – 5	ES	40	146	0.18
	Reference	38	110	0.31

V. CONCLUSION

This paper proposes the supervisory control scheme for wind turbine benchmark system. The simulation results showed that the proposed method is proven to perform well in maximizing the electrical power output of the small-scale wind turbine generator system. The supervisory level chooses the optimum rotor speed to reach the maximum value of the power coefficient so that it is able to produce maximum power. Moreover, the supervisory level which applies the extremum seeking algorithm has been proven having better performance than the supervisory level using the reference formula, both in terms of power generated and in terms of dynamic response. The next study is to apply this scheme in more detail to a wind turbine generator system with a converter circuit in order to develop a supervisory control module which is embedded in wind turbine generator system.

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