Wind Turbine Power Limitation using Power Loop: Comparison between Proportional-Integral and Pole Placement Method

[1*]NorzanahRosmin, [2]Suhaila Samsuri, [3]Muhammad Yusri Hassan, [4]AedeHatibMusta'amal, [5]Faridah Hussin

[1*]Centre of Electrical Energy Systems (CEES), Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia.
[4]Faculty of Education, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia.

[1*] Corresponding author: NorzanahRosmin (norzanah@fke.utm.my). Tel: +607-5557174

The authors would like to thank RMC, FKE and CEES, Universiti Teknologi Malaysia and the Ministry of Higher Education of Malaysia for the financial support provided under RUG(05H18) and FRGS(4F108) to carry out this research.

Abstract

This paper deals with power limitation for a small-sized stall-regulated variable speed wind energy conversion system. Here, a Power Loop Control using a Proportional Integral (PI) controller and Pole Placement method are presented. Control effort is focused to control the generated power and the generator torque corresponding to the wind speed variation above the rated wind speed. A simple tuning method of PI controller for Power Loop Control is briefly explained. For pole placement method, the influence of different damping ratios is shown. Finally, the comparison of the transient response of both methods is demonstrated. From the comparison result, it is found that the pole placement method presents some significant overshoot compared to Power Loop case, but it can reach the steady-state value faster than PI. Using pole placement method, the result shows that system with higher damping ratio presents better transient response.

Keywords: stall regulated, PI controller, pole placement, power limitation, power loop, damping ratio.

1. Introduction

Malaysia is located at 2° 30' North latitude and 112° 30' East longitude. Around this geographic coordinate, the velocity of wind is considerably low. With mean wind speed of around 4 to 5 m/s per year, the application of medium/big size of wind energy generation system in this country is impossible. However, at certain locations such as Kota Belud, Gebeng, Pulau Tioman and Pulau Langkawi, the application of the small-sized wind turbine is feasible. At these locations, the mean wind speed can reach up to 6.1 m/s.

Pitch-regulated wind turbine is very popular nowadays since this type of wind turbine can limiting the power during high wind speed at a rated power without experiencing obvious peak power or stressing the turbine's structure. Due to this advantage, this turbine has a high capital and maintenance cost owing to its complex electronic system (John F. Manwell, Jon. G. McGowan and Anthony L. Rogers,2002). Since Malaysia has low wind velocities, the application of pitch-regulated wind turbine is not practical. Therefore, a low cost wind turbine must be introduced. Stall-regulated wind turbine is the most practical one since this turbine has low cost of construction, less complex due to unaltered blade and of course has less maintenance cost (IulianMunteanu, Nicolaos-Antonio Cutululis, AntonetaIulianaBratcu, Emil, 2008). In general, stall-regulated wind turbine is operated in fixed speed. This leads to suboptimal power generation. Hence, to optimise the wind velocities in Malaysia, the application of variable speed is forecasted will maximizing the generated power and power limitation during rated wind speed can be done smoothly.

Hence, the objective of this paper is to design a control algorithm for a variable speed stall-regulated wind turbine to limit the generated power at a rated value. In this paper, two control methods will be presented. The first method is by using a power loop case with proportional integral (PI) controller, whereby the second method is by implementing pole placement method.

In the scientific literature, PI controller is a classic control theory and very well known in industrial applications due to its cheap price, simplicity and intrinsic robustness properties [2]. Pole placement method is also one of the classic control theories, but, this method has a different theoretical method where the desired pole locations are set and moved in order to achieve the desired system response [3]. In contrast to PI control method, numerous tuning techniques are available, for instance, Good Gain method, Ziegler-Nichols' method including Ultimate Gain method for closed-loop response and the Process Reaction method for open loop response, and etc.

This paper is organized as follows: in section 2 a description of wind turbine model is presented while section 3 describes the proposed power loop with PI controller method and the pole placement method applied to the wind turbine. Section 4 shows experimental results and in section 5 a conclusion is given.

2.0 Wind turbine system model

Figure 1 shows the model of a stall-regulated, variable-speed, wind turbine system. This turbine comprises four sub-models referred to as the wind speed, aerodynamic, drive train and squirrel cage induction generator (SCIG) model.

Fig.1 Wind turbine model

In general, wind power can be calculated by using equation (1) (James F. Manwell et. al, 2002) , (IulianMunteanu et. al, 2008):

$$P \quad = -\rho\pi R \; C \; u \qquad (1)$$

Where

is rotor speed,

is rotor radius,

is wind speed,

ρ is air density

is power coefficient.

From equation (1), it can be seen that the efficiency of useful mechanical power from the wind is depends on the blade profiles. This efficiency of power extracted from the wind is highly depends on the power coefficient. To generate maximum power, power coefficient must be maintained at the peak value. This control goal is applied during low wind velocity. For high wind velocity region, power need to be limited at a constant value. This goal can be achieved by regulating the generator's torque. Generator torque can be regulated during high velocities by reducing the power coefficient by reducing the turbine's tip speed ratio. Tip speed ratio must be optimized at each wind speed. To achieve this, the turbine rotor speed must be restricted at a certain value which is suitable to its current wind speed.

3.0 Methods

In this paper, two different methods how to limit the generated power during high wind velocities is presented. The first method will be explained detail in sub-chapter 3.1, whereby the second method will be explained detail in sub-chapter 3.2, respectively. A plant of wind energy conversion system (WECS) that has a transfer function as written in equation (2) is considered in this work.

$$- = \frac{\cdot \qquad \cdot}{\cdot \qquad \cdot} \qquad (2)$$

3.1 Method 1: Power loop with PI controller

In this method, a power loop with PI controller is presented as illustrated in Figure 2 (IulianMunteanu et.al, 2008). The WECS has an input of the electromagnetic torque, whereby the output is the generator active power, P.

Fig.2 Power loop with PI controller method

Based on the designed PI controller that has been applied for maximizing the generated power during low wind speed in (IulianMunteanu et.al, 2008),the transfer function needs to be factorized in the form of:

$$- = \frac{\cdot(\quad)}{(\ _{\Sigma}\ )(\quad)} \qquad (3)$$

Hence, based on the WECS plant given in equation (2), the transfer function becomes

$$- = \frac{\cdot\ (\ \cdot\qquad)}{([\ \cdot\qquad\cdot\quad]\ \ )([\ \cdot\qquad\cdot\quad]\ \ )} \qquad (4)$$

The obtained transfer function in (4) produces a complex number. So, an adaptation is done where only magnitude part of the complex number will be considered. Thus, the transfer function is modified into equation (5):

$$- = \frac{\cdot\ (\ \cdot\qquad)}{([\ \cdot\qquad)(\ \cdot\qquad)} \qquad (5)$$

By comparing equation (5) with equation (3), all parameters that needed in WECS block as illustrated in Figure 3 are known, where

$= -107.08$

$= \quad = 1.4660$

$_{\Sigma} = 1.4660$

$= 1.0618$

To design the controller, two blocks need to be considered (see Figure 2). In the first block, the time constant is compensated by taking $T = T$. Then, to compute the gain K_p, a suitable equation as written in equation (6) is applied (IulianMunteanu et.al, 2008).

$$= \frac{\cdot\ \Sigma}{\cdot} \qquad (6)$$

By imposing ≈ 0.1 [2], the controller gain and are obtained as

$$= \frac{(1.4660)(1.4660)}{(-107.08)(0.1466)}$$

$$= -0.9339$$

$$= \frac{1}{}$$

$$= \frac{1}{1.466}$$

$$= 0.6821$$

Then, for the second block of the controller, the first controller plant is compensated by having a first-order filter by applyingT as the time constant.

After all the needed parameters (as shown above) have been estimated, these values are placed in the appropriate box in the Simulink model. For PI controller block, the value of K and I represents the parameter values of proportional gain (P) and integral gain (I), respectively. However, before running the program, a linearization analysis needs to be done before doing the tuning process. The purpose of this analysis is to determine whether the operating point specification is successfully met or not, where it can be done by using Control and Estimation Tools Manager in MATLAB Simulink. After the correct operating points have been met, then, the tuning process can be executed. In order to get a good stability response as outlined in the system's requirements, retuning the controller's parameters is necessary to be executed until satisfaction of the results is achieved. There are several tuning techniques are available, for example, Good Gain method, Ziegler-Nichols' method including Ultimate Gain method for closed-loop response and the Process Reaction method for open loop response, and etc. However, in this work, as an alternative, only good gain method is considered during executing the retuning process.

3.2 Method 2: Pole placement

In this second method, the transfer function of the WECS plant in equation (2) is converted into state space form. This state space form is consider as a control system of the plant and is written as (Bilmal K. Bose, 2002)

$$\dot{} = \quad + \qquad (7)$$

$$= \quad + \qquad (8)$$

Where

x˙ is the derivative of state,

x is state vector,

u is control signal,

y is output.

The matrix of A, B, C and D are as below:

$$= \begin{matrix} -0.09324 & 0.09962 \\ -1 & 0 \end{matrix}, \quad = \begin{matrix} 0.00294 \\ 0 \end{matrix}, \quad = [-3853 \quad 3629], \quad = \begin{matrix} 0 \\ 0 \end{matrix}$$

To implement the pole placement method, the control signal, u needs to be written in the form as below:

$$= - \qquad (9)$$

By inserting equation (9) into (7). Thus,

$$\dot{} = \quad + \quad (- \quad)$$

$$\dot{} = (\quad - \quad) \qquad (10)$$

Equation (9) is known as state feedback scheme and matrix K is called as state feedback gain matrix. Figure 3 shows the diagram of the pole placement method. From the figure, it can be seen that the controller gain, K is fedback to the reference, r and now, it's become a new input to the system. Then, with a suitable parameter of the controller gain (-K) that was calculated for each state, the expected output response will be obtained.

Fig.3 Block diagram of control system in state space or pole placement method

To execute the pole placement method, there are several important steps need to be undertaken. The first step that must be done is by checking that the WECS plant is completely state controllable and assumed that all state variables are available for feedback (Brian D.O. Anderson et.al, 1989). Then, for the second step, the appropriate poles' locations need to be identified. In order to get the appropriate poles, the characteristic equation must be created. The characteristic equation is shown in equation (11). To create the characteristic equation, the information of damping ratio and its natural frequency must be identified. This can be gathered by using equation (12) where the relation between the settling time, the damping ratio and the natural frequency is shown in this equation. In this work, a specification was outlined where the settling time is set to be 1 second and the damping ratios are set to be 0.4, 0.5, 0.6 and 0.7.

$$+ 2 \quad + \quad = 0 \qquad (11)$$

$$= \frac{}{} \qquad (12)$$

In the third step, when the desired characteristic equation was obtained, then, a comparison needs to be done between the designed characteristic equation and the plant of the WECS in order to find the controller gain, K. The desired poles can be identified by factorizing equation (11) (Norman S. Nise, 2008). Since there are four different damping ratios were being used, so it will produce four sets of desired poles with same settling time.

4.0 Results and Discussions

4.1 Method 1: PI controller

In this work, power is aimed to be limited at a rated value of 25 kW. Table 1 exhibits the important parameters in designing PI controller that have been calculated using equations (2) to (6). From the executed simulation, by using the calculated data in Table 1, the output represents an underdamped response, as shown in Figure 4. The result represents a significant transient where the response is oscillating before reaching at a steady state value of 25 kW. It's requires approximately 15 seconds to reach the settling time. In terms of wind turbine generator's response, this is a sluggish response. However, this response is based on the first estimation which was involving equation (2) to (6). Since, the result is not satisfied yet, a retuning process must be executed to improve the presented response.

Table 1

Calculated parameter

Fig.4 Result using method 1(before tuning)

After executing a retuning process using Good Gain method, the transient response and the settling time were improved. This can be observed by referring to Figure 5. The proportional gain was increased whereas the integral gain was decreased. The comparison of the proportional and integral gains before and after retuning can be seen in Table 2. As the result, the transient peak can be reduced from 47 kW to 27.5 kW. The oscillations were also have been diminished. The rise time, settling time and percentage of overshoot now are much reduced to 2.22 seconds, 6.47 seconds and 8.15%, respectively, as summarized in Table 3.

Fig.5 Result after retuning

Table 2

Controller parameters

Table 3

Performance and robustness

4.2 Method 2: Pole placement

For pole placement method, the result analyses are done based on the selected settling time of 1 second with different damping ratio, ξ. Table 4 shows the desired poles with different damping ratio of 0.4, 0.5, 0.6 and 0.7.

Table 4

Desired poles for settling time = 1s

From Table 4, the desired poles will be moved farther upper and lower from the zero axes when the damping ratio is decreased. The result for pole placement method with damping ratio of 0.4, 0.5, 0.6 and 0.7 with settling time of 1 s can be depicted in Figure 6. The transient response in this figure shows that the percentage of overshoot for ξ=0.4 is larger than the others. From Figure 6, it is also found that the system with damping ratio of 0.7 represents better response than system with damping ratio of 0.4, 0.5 and 0.6. This is related to the location of desired poles which is when the desired poles are farther upper and farther lower from the zero axes, the percentage of overshoot become bigger. From observation that has been done based on Figure 6, it can be conclude that system with higher damping ratio presents better transient response. Even though all the responses present a significant overshoot peaks at the beginning of the simulation, the responses reached at the steady state value of 25 kW after 1.2 s. However, in terms of safety issue, all these responses may harm the turbine's structures since the overshoot peaks were too high.

Fig.6 Step response with K controller for damping 0.4, 0.5, 0.6 and 0.7

4.3 Comparison between method 1 and method 2

By comparing the response of both methods, results shown that the pole placement method produce too large overshoot when settling time is set to 1 second. In real system implementation, if the overshoot is too large, it will damage the generator and/or turbine's gearbox. The power loop with PI controller method also represents significant transients and overshoots. However, after retuning process, the output depicts a satisfactory result, where transients were diminished whereby the overshoot is only 8.15%. But, for this method, it took a slight longer time to reach the steady state value compared to method 2.

5.0 Conclusions

The power limitation of a stall-regulated variable speed wind turbine system can be limited at a rated value of 25 kW by using both method; power loop with PI controller and pole placement. However, pole placement method produces a significant power overshoot even though the settling time can be achieved faster (in 1.2 second). Power loop with PI controller produces smaller overshoot, but this system has a sluggish response, where the settling time is approximately 6.47 seconds. For power loop case, it is quite difficult to reduce the settling time. However, for pole placement method, some improvement is feasible could be done to reduce the power overshoot by maintaining the fast response time. This however, is topic of on-going research.

References

Bilmal K. Bose, Modern Power Electronics and AC Drives, Upper Saddle River, Prentice Hall PTR, 2002.

Brian D. O. Anderson and John B. Moore, Optimal Control: Linear Quadratic Methods, Englewood Cliffs, New Jersey, Prentice-Hall International, Inc., 1989.

IulianMunteanu, Nicolaos-Antonio Cutululis, AntonetaIulianaBratcu, Emil Ceanga, Optimal Control of Wind Energy Systems, Springer-Verlag London Limited, 2008.

James F. Manwell, Jon G. McGowan and Anthony L. Rogers, Wind Energy Explained: Theory, design and application. West Sussex, England, John Wiley & sons, Lltd., 2002.

John J. D'Azzo , Constantine H. Houpis and Stuart N. Sheldon, Linear Control System Analysis and Design with Matlab, Fifth edition, New York, Basel, Marcel Dekker, Inc., 2003.

Norman S. Nise, Contro System Engineering, Fifth edition, John Wiley & sons, LTD., 2008.

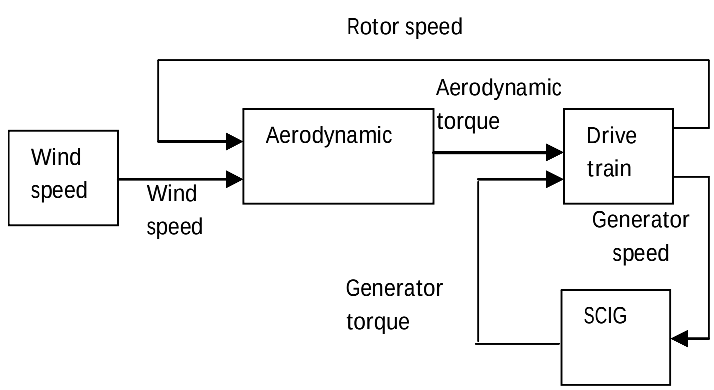

Fig.1 Wind turbine model

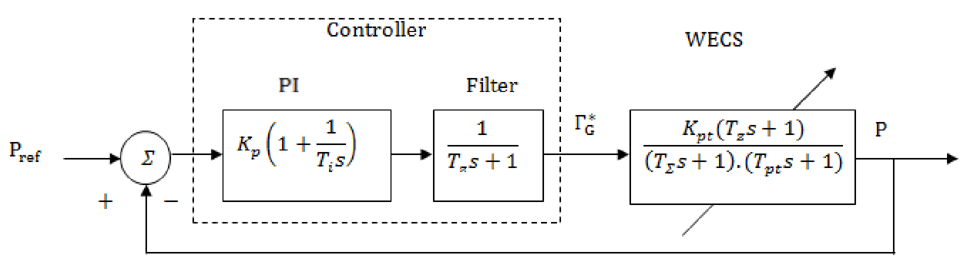

Fig.2 Power loop with PI controller method

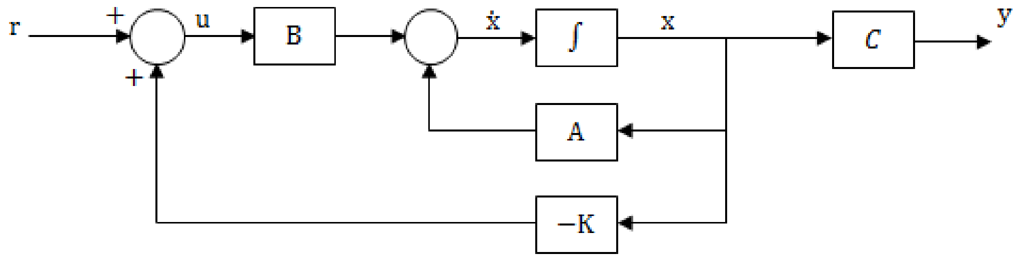

Fig.3 Block diagram of control system in state space or pole placement method

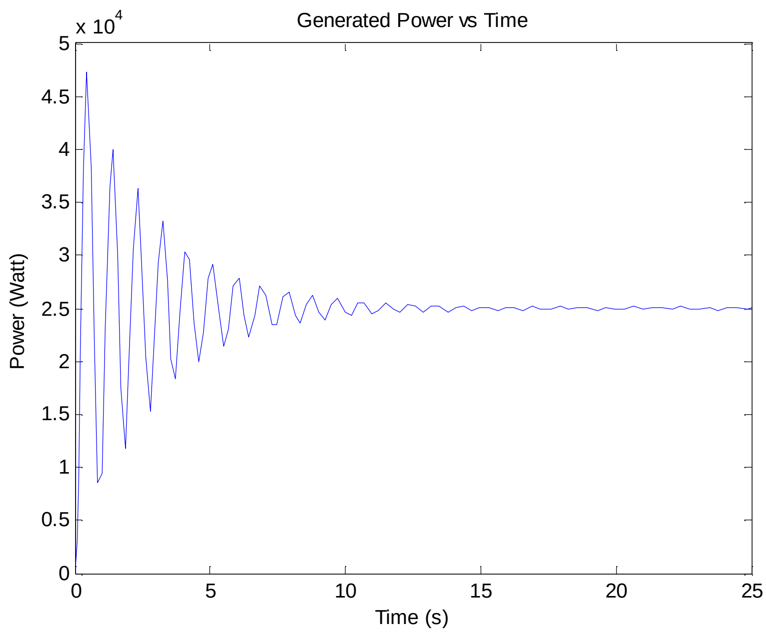

Fig.4 Result using method 1 (before tuning)

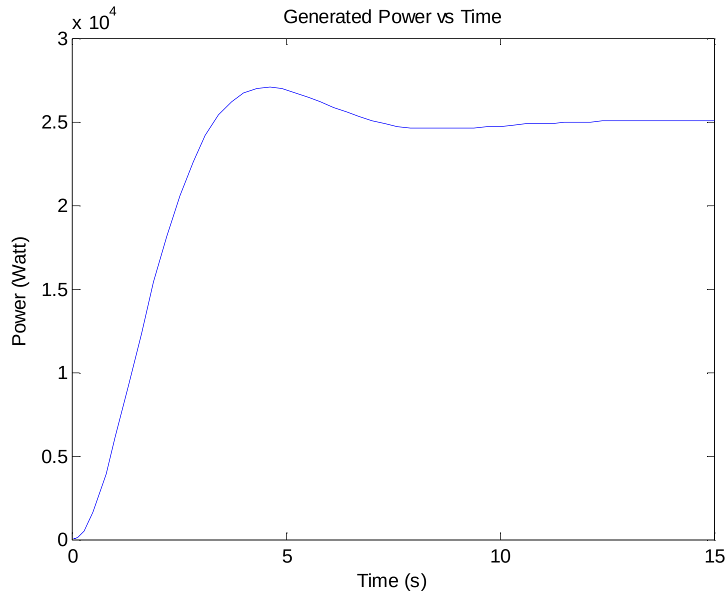

Fig.5 Result after retuning

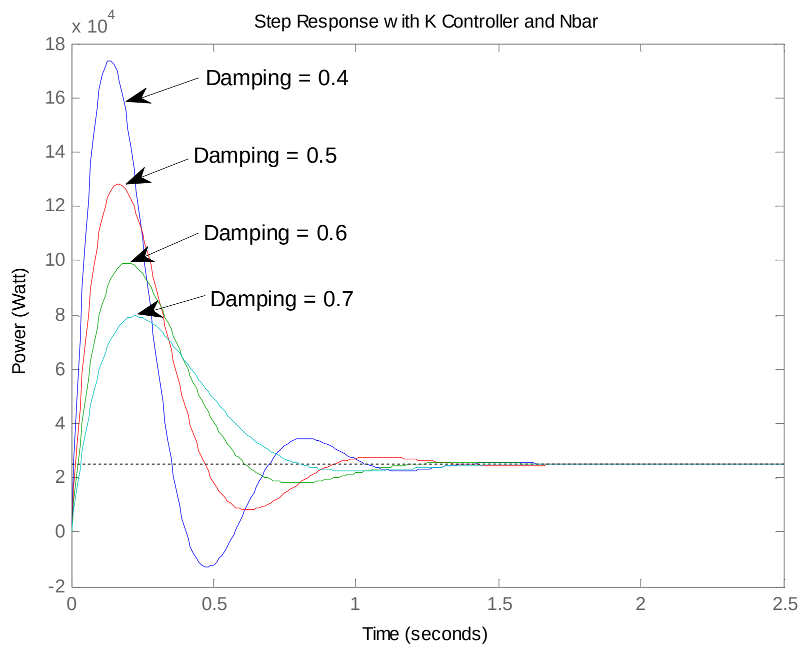

Fig.6 Step response with

Table 1 The total number of residents in Malaysia for year 2000 to 2012

Parameters	Value
	-0.9339
	0.6821
	1.4660
	1.4660
	1.4660
	1.0618
	0.1466

Table 2 Controller parameters

	Before	After
P	-0.9339	-0.01351
I	0.6821	0.45

Table 3 Performance and robustness

	Before	After
Rise time (s)	1.97	2.22
Settling time (s)	8.7	6.47
Overshoot (%)	7.33	8.15
Peak	1.07	1.08
Gain margin (rad/s)	Inf @ Inf	Inf @ Inf
Phase margin (rad/s)	60 @ 0.609	60 @ 0.609
Closed-loop stability	Stable	Stable

Table 4 Desired poles for settling time = 1s

Damping ratio, ξ	Pole, s1	Pole, s2
0.4	- 4 + j9.165	- 4 - j9.165
0.5	- 4 +j6.928	- 4 - j6.928
0.6	- 4 + j5.334	- 4 - j5.334
0.7	- 4 + j4.08	- 4 - j4.08