Power Optimization for a Small-sized Stall-regulated Variable-speed Wind Turbine

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***Abstract*-- This paper focuses on power optimization for a small-sized stall-regulated variable-speed (SS-SR-VS) wind turbine system. In this paper, the behavior of the SS-SR-VS wind turbine during power optimization is demonstrated. The Speed Loop Control method with the assistance of classical Proportional Integral (PI) controller is used. Controller parameter is designed based on the linearization process, and the pole-placement procedure has been applied during the controller tuning. Further improvement is then done by using the Good Gain method. The comparison between these two methods is presented. Results show that the turbine speed, generator speed and hence the generated power can be optimized at the optimum values corresponding to the wind speed variations during power optimization.**

***Index Terms* -- stall-regulated, fixed-regulated, speed loop, variable-speed and power optimization.**

I. Wind Turbine System Control

STALL-REGULATED concept is usually equipped to the wind turbine with fixed speed operation. Hence, only sub-optimal power can be generated during power optimization. Whilst, during power limitation, turbine usually experiences a significant power peaking and a significant stress on the turbine's structures since alteration of the blade geometry is impossible [1]. Hence, for a small-sized wind turbine whereby the power limitation is designed to begin at a lower wind velocity (particularly at location with low wind resource), application of variable-speed concept to the system is forecasted may improve the stall-regulated system performance. In addition, during power optimization, with variable-speed concept, optimal power can be generated during its operation [2]. If such a turbine can be operated successfully, a lower-cost, lighter and affordable wind turbine can be developed, whereby this system is very simple due to unaltered blade pitch.

Small-sized wind turbines are often used for small energy demands, which usually cover home, small farm and small business. Its range may be from 400 watts up to 100 kilowatts [3-4], or might be more [5]. It has a brighter prospect compared to large-sized wind turbine since its requiring lesser wind resources. Therefore, it can be built in many more locations in the world. As claimed in [5], the installation of small-sized wind turbine is cost-effective when installed at the location where the mean wind speed is at least 4.4 to 5.6 m/s at a height of 10 meters above the ground. Malaysia is located at 2° 30' North latitude and 112° 30' East longitude. Around this geographic coordinate, the velocity of wind is considerably low (mean wind speed of around 4 to 5 m/s per annum). 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 [6]. Hence, for locations with low wind resources such as in Malaysia, this application is feasible. It is therefore, to manipulate the free-energy source from the wind, an active research regarding the feasibility of this SS-SR-VS wind turbine performance for Malaysia's application is needed to be performed.

In the literature so far, many works have been studied in terms of the control feasibility of the SS-SR-VS wind turbine application. For example, in [7], study was aimed to gain the maximum power at each wind variation during power optimization by using tip-speed ratio and hill-climbing control methods. Then, in [8], research was focused on the power optimization purpose as well but in this research, fuzzy logic controller was used. Other work which is related with power optimization purpose also can be found in [9] where classical Proportional Integral (PI) controller was used to control the generator speed. In [10], research also discussed how to optimize the generated power on 11-kW wind turbine but work was focused more on the converter issue in order to control the generator speed. In [10] also, digital processor signals (DSPs) and phase-locked loop (PLL) control was used to control the converter's current and voltage. The work regarding converter issue also can be found in [11] where the boost-converter was considered in this research.

Other than that, the scenario from the real experiences regarding small-sized wind turbine also reported and published, such as in [4-5], [7], [10], [12-13], and in many registered websites, for instances, Vestas and Aelos Wind Turbine (Denmark), Fortis WindEnergy (UK, Netherlands, Austrlaia, Denmark, Germany, etc.), Endurance Wind Power (UK), ReDriven Power Inc (UK), Bergey Wind Power (USA), Hummer Wind Power (USA), Urban Green Energy (USA), First Wind Turbine Manufacturing Co. Ltd (China), MicroWind (China), Luminous Renewable Energy (India),

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and many more. From these publications, it is shown that, the research and application of this small-sized variable speed wind turbine seems very important to be looked into in enhancing the problem of world's depletion energy sources and global warming issues, especially in this era.

Hence, to manipulate this energy pollution free source, this research is executed which the objective has been focused to demonstrate the behavior of a small-sized stall-regulated variable-speed wind turbine at the power optimization region. To realize this, a technique known the Speed Loop control method was chosen, whereby the application of variable speed can be applied. In this paper, the content was structured as follows. Section II is about the concept of SS-SR-VS wind turbine control system, section III describes the proposed method. While section IV contains the simulation results and finally, some conclusions and suggestion are given in section V.

II. Wind Turbine Control System

In general, wind turbine is operated in three different regions; low (I), intermediate (II) and high wind (III) velocity's region, as depicted in Fig.1 [14]. In the first region, power is controlled to be optimized where maximum power must be generated as much as possible. In the second region, fixed speed operation will be applied and finally in the third region, power limitation will be taken over. In this study, work will be paid only on the first region (power optimization). To optimize the power, control effort must be aimed to trail the optimum values of the turbine's blade speed corresponding to the wind speeds variations. To achieve this, the power coefficient and the tip speed ratio must be kept at its maximum and optimum value, respectively. This is, however, can be attained by regulating the generator speed corresponding to its optimum speeds.

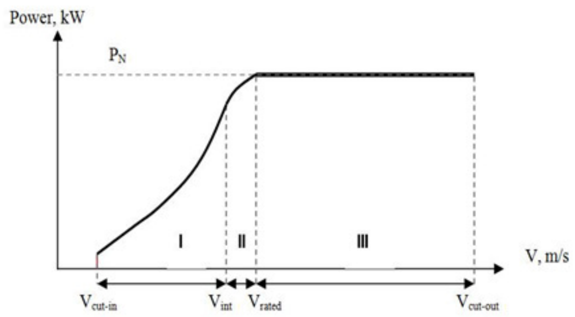


Fig.1. Wind turbine control operation regions

To calculate the maximum power, equation (1) is used [1],[14].

$$P_{aero} = \frac{1}{2}\rho\pi R^2 u^3 C_p(\lambda_{opt}) \tag{1}$$

Where P_{aero} is the aerodynamic power, ρ is air density, R is rotor radius, u is wind speed and Cp is the power coefficient. The aerodynamic efficiency is determined by power coefficient. It is a function of tip speed ratio, λ which defined as the ratio between the peripheral speed of the blades, ω and wind speed, u as shown in equation (2). In this work, the turbine has the maximum power coefficient, C_p and optimum value of tip speed ratio, λ_{opt} as 0.4781 and 5.781, respectively.

$$\lambda = \frac{\omega R}{u} \tag{2}$$

The relation between the power coefficient, torque coefficient (C_Γ) and the tip speed ratio is depicted in (3), whilst the linkage between the aerodynamic/generator torque and the aerodynamic/generator power is represented in equation (4) and (5), respectively.

$$C_\Gamma = \frac{C_p}{\lambda} \tag{3}$$

$$P_{aero} = \Gamma_{aero}\omega \tag{4}$$

$$P_g = \Gamma_g \omega_m \tag{5}$$

The detail characteristics of the wind turbine used in this research is shown in Table I. Since this work is focused for power optimization purpose, the power coefficient will be maintained at 0.4781 and tip speed ratio will be fixed at 5.781.

TABLE I
Wind Turbine Characteristics

Characteristics	Value
Blade rotor	5 m
Generator inertia	0.78 kgm^2
Air density	1.225kg/m^3
Gearbox ratio	12.748
Power output	25kW

III. Method: Speed Loop With PI Controller

In this paper, the Speed Loop control method with PI controller has been used to demonstrate the SS-SR-VS wind turbine behavior. The P and I parameters were designed based on the linearization process and the pole-placement procedure that was proposed in [15]. The simulation model of the proposed Speed Loop control is illustrated as in Fig.2.

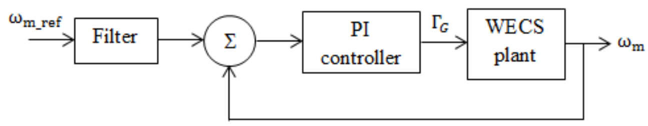


Fig.2. The SS-SR-VS wind turbine plant with the proposed Speed Loop control

As can be seen in Fig.2, the Speed Loop method is proposed in order to track the generator mechanical speed reference signal. The reference signal can be calculated by using equation (1) to (4). The generator torque was chosen as the manipulated input of the wind energy conversion system (WECS) plant model. The WECS plant transfer function is obtained by linearizing the nonlinear model that has been developed by using Matlab Simulink. A simple motion equation has been chosen in order to get the linear transfer function as written in (6). However, before gaining the linear transfer function, the correct operating point (OP) must be chosen to ensure the system is operating in the real physical behavior of SS-SR-VS wind turbine. The load torque is gained from the nonlinear aerodynamic model that has been developed using equation (1) to (5).

$$J\frac{d\omega_m}{dt} = T_L - T_e \tag{6}$$

The WECS plant model then has a transfer function of

$$\frac{\omega_m}{T_g} = \frac{-1.282}{s+0.5244} \tag{7}$$

To apply the pole placement procedure in determining the related parameters, the Speed Loop model that is presented in Fig.3 was referred. From this figure, the detail of the filter time constant, PI parameters and how the transfer function of the WECS plant system is changed by using pole placement procedure is shown.

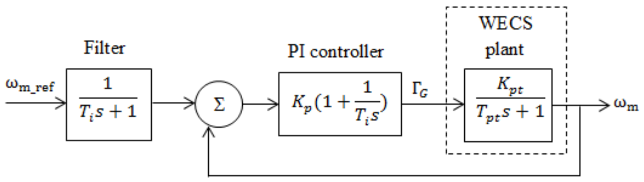


Fig.3. The Speed Loop SS-SR-VS wind turbine model with PI controller details, filter time constant and the zero-pole transfer function.

From Fig.3, the transfer function of the WECS plant is:

$$TF = \frac{K_{pt}}{T_{pt}s+1} \tag{8}$$

By comparing equation (7) and (8), the detail of parameter K_{pt} and T_{pt} can be obtained. By using T_{pt} value, the Integral parameter (T_i) of the PI controller can be calculated by using equation (9). Then, using the calculated T_i and T_{pt}, the proportional parameter of the PI controller can be computed.

$$T_i = \frac{2\zeta}{\omega_n} - \frac{1}{\omega_n^2 T_{pt}} \tag{9}$$

$$K_p = \frac{(T_i T_{pt})}{\omega_n}\omega_n^2 \tag{10}$$

To calculate the T_i and K_p, the information of damping ratio (ζ) and the system natural frequency (ω_n) must be known. By assuming that the ζ is 0.7 whilst the ω_n is equal to 0.4 rad/s, thus, the time constant (T_i) gathered is 0.9173 whereas the K_p is -0.3117.

For the filter block, the T_i time constant can be designed by putting straight away the T_i that has been computed in (9). This filter is included to compensate the zero effect, where the overshoot signal can be limited from the severe state.

A. *Input Model*

Since the focus of this work is to obtain the maximum power during power optimization, only low wind speed region is considered. For a small-sized wind turbine, in this study, turbine is presumed designed with cut-in wind speed at 3 m/s. The turbine will track the maximum power point until wind speed reach at 8 m/s.

By using equation (2), the reference turbine speed (ω) can be computed and then by multiplying the resulted value with the gearbox ratio, the reference generator mechanical speed (ω_m) can be calculated. The detail of this speed reference with the wind speed variations is shown in Table II.

TABLE II
INPUT REFERENCE

Wind speed	Turbine Speed (ω)	Generator mechanical speed (ω_m)
3	3.4686	43.28175
4	4.6248	57.70899
5	5.7810	72.13624
6	6.9372	86.56349
7	8.0934	100.99074
8	9.2496	117.91538

B. *Retuning Process*

After following all procedure mentioned before, a retuning process was still needed to be executed to improve the presented signal responses. A simple method namely the Good Gain method was used in order to establish a better response. The Good Gain method is executed by assistance of Ziegler-Nichols rule [16] as summarized in Table III.

TABLE III
INPUT REFERENCE

Response	Rise time	Overshoot	Settling Time	Steady-state error
K_p	Decrease	Increase	Minor change	Decrease
K_i=1/T_i	Decrease	Increase	Increase	Eliminate

The comparison between the pole placement procedure application and after the retuning process using the Good Gain method is shown in the next section.

IV. Simulation Results

This simulation results section will be divided into two parts. The first part will explain the result of the input reference signal. Then, in the second part, the results of important signals using Speed Loop control with the pole placement procedure will be presented. Yet, in this part also, the result after the retuning process using the Good Gain method is also compared. The important signals that have been paid into attention are the generator speed (ω_m), the generated torque (T_g), the generated power (P_g), the tip speed ratio the (ζ) and the power coefficient (Cp).

A. Input Reference

The reference signal of the generator mechanical speed before the filter and after the designed filter can be depicted in Fig.4. Signal reference shown here covers the wind speed variation from 3 to 8 m/s. The difference between these signals can clearly be observed where with the existence of the time constant in the filter, the latter signal has curved effect. This signal was then used as the model reference signal.

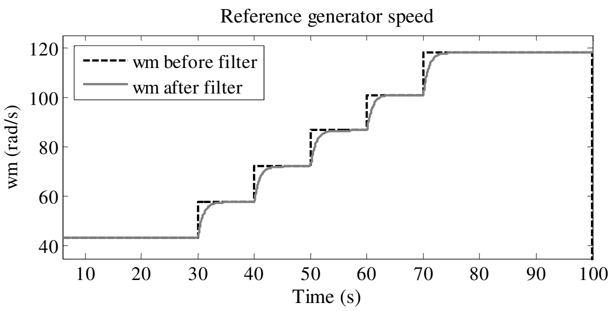


Fig.4. Generator speed reference before and after

B. Results Responses: Speed Loop Control with the Pole Placement Method and the Good Gain Method

The comparison between the generator mechanical speed reference and the actual generator mechanical speed using Speed Loop control with pole placement method is shown in Fig.5.

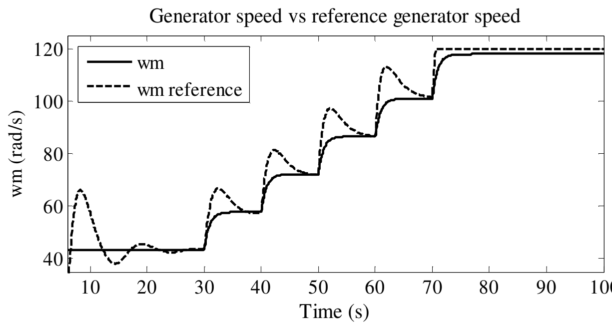


Fig.5. The reference generator mechanical speed versus the actual generator mechanical speed.

From the represented signal in Fig.5, it shows that the resulting speed signal containing a significant overshoot effect (around 80%) and the settling time is reached approximately at 8 seconds. This represents a stressful behavior and a sluggish system response. After the retuning process of the PI parameter is done using the Good Gain method, an important improvement can be observed as depicted in Fig.6. The latter method (after retuning) tracked well the reference signal.

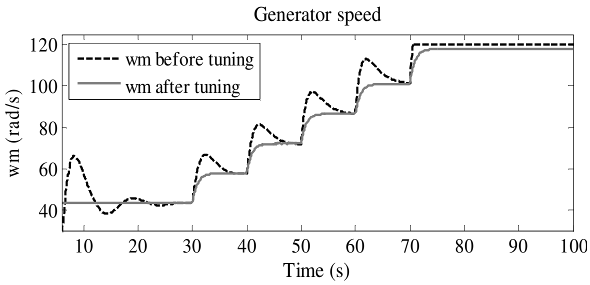
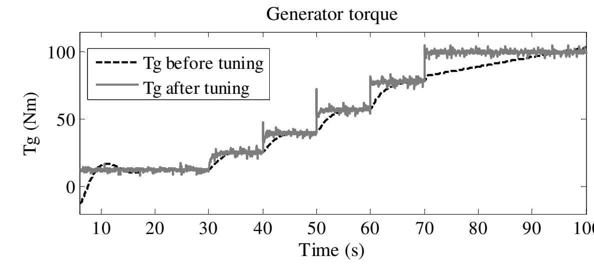
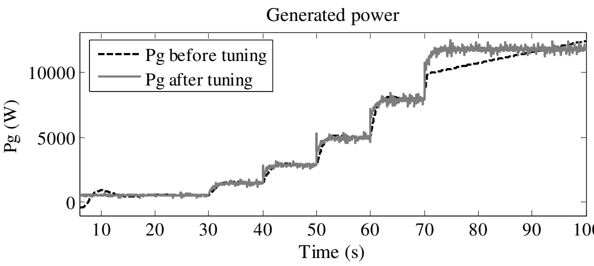


Fig.6. The actual generator mechanical speed; before and after retuning process

Even though the actual generator speed can track well the reference generator signal, the output of the machine's torque and the generated power also must be observed. The resulting signals of the generated torque and the generated power, before and after the retuning processes are shown in Fig.7.



(a)



(b)

Fig.7. (a) The actual generator torque; before and after retuning process, (b) The actual generator power; before and after retuning process,

From Fig.7, signals (generator torque and generator power) before retuning present a good tracking at the beginning of the wind variation from 3 to 7 m/s. But, after 7 m/s, output signals starting to deviate from the reference signal. However, after the retuning process, signals provide better tracking signal compared to before tuning process. From Fig.7(a), even though the generator torque signal (after retuning) has a transient peak at the beginning of each changing step, it's only present an overshoot of less than 10%, and not exceeded the maximum permitted level of 280 Nm.

For the generated power, during power optimization region, power can be generated at the maximum values corresponding to each wind speed variation. This is shown in Fig.7(b) where the generated power can reach at the required steady-state level in less than 3 seconds and the transient peak at the beginning of each step changing also can be reduced below 10%. This shows that the response signals provide a good behavior of SS-SR-VS wind turbine operation. All this only can be achieved if the tip speed ratio can be kept at the optimum value and the power coefficient can be maintained at the maximum value of the power coefficient-tip speed ratio (C_{P}- λ) curve.

Fig 8 exhibits the resulting signals of the tip speed ratio and the power coefficient of the developed system. From Fig.8(a), it can be seen that the tip speed ratio before retuning process present a substantial transient peak of about 100% at the beginning of each input step changing. However, after the retuning process, the tip speed ratio response can be improved whereby this response can be reached at the steady-state level in 3 seconds compared to 8 seconds, before retuning process. However, in terms of the speed response, the latter response will aggressively decelerate the generator speed since the tip speed ratio is adjusted at the left side of the maximum peak of the C_{P}- λ curve (less than 5.781). This is differed with the former action, where the generator speed will slowly accelerate when the tip speed ratio is adjusted at the right side of the maximum peak of the C_{P}- λ curve (more than 5.781). The relation between the C_P and the λ can be depicted from Fig.9.

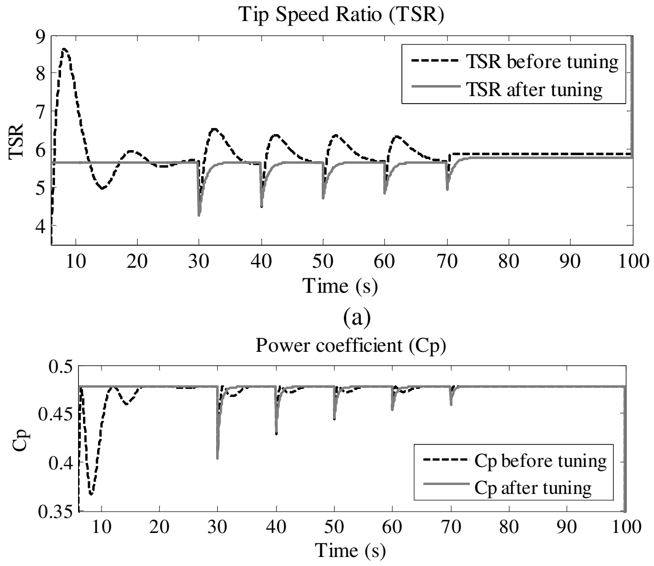


Fig.8. (a) The actual tip speed ratio; before and after retuning process, (b) The actual power coefficient; before and after retuning process.

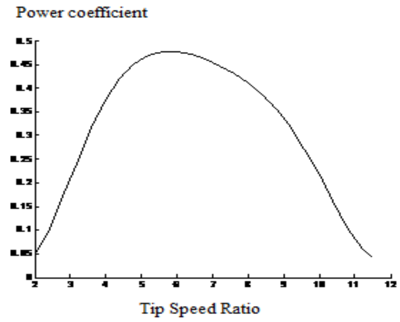


Fig.9. The relation between the tip speed ratio and the power coefficient

However, for the power coefficient (C_P), the response before the retuning process presents better result compared to after retuning process in terms of the percentage overshoot. Nevertheless, in terms of settling time, after the retuning process result presents better time response compared to before retuning process result where the steady-state level of 0.4781 can be reached faster, about less than 2 seconds compared to 5 seconds. The difference parameter of the PI controller before and after the retuning process is shown in Table IV.

TABLE IV
PI CONTROLLER PARAMETERS

	Speed Loop Control Method	
	Pole placement (Before Retuning)	Good Gain improvement (After Retuning)
K_p	-0.3117	-69
T_i	0.9173	0.02941

V. CONCLUSION AND SUGGESTIONS

As the conclusion, the generated power can be controlled at the maximum values corresponding to the wind speed variations by using the Speed Loop control method during the power optimization. The reference signal of the generator mechanical speed can be tracked well by the actual generator speed whereby the tip speed ratio can be maintained at the optimum value of 5.781, and the power coefficient can be kept mostly constant at the peak of the C_{P}- λ curve at 0.4781. The torque also can be limited below the maximum allowable level of 280 Nm. By using the proposed pole placement procedure that was reported in [15], the actual generator speed can reach at the steady-state level around 8 seconds. This, however, represents a sluggish system to wind turbine operation and may interrupt the wind turbine normal operation. Nevertheless, after performing the Good Gain method that was proposed in [16] and explained in section III (*B*), the response was much improved, where the overshoot percentage and the settling time were much reduced. This then presents a normal SS-SR-VS wind turbine behavior whereby the overshoot was had been diminished, and the systems are able acting faster during the wind speed step changes. However, in terms of controller design, Speed Loop control using pole placement procedure is suggested to be used first as a good start in getting the PI controller parameters. Then, the Good Gain method is advised to be used in order to improve further the signal responses. Though this simulation model can represent the behavior of SS-SR-VS wind turbine operation, the key opportunities and challenges to the future market development must be further explored in assessing the feasibility of this SS-SR-VS wind turbine application at the low wind velocity locations. The simulation covering the power limitation issue also needs to be concerned, and this is the topic of on-going research and will be published somewhere in the future.

VI. Acknowledgement

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VII. References

[1] J.F. Manwell, J.G. McGowen, and A.L. Rogers, Wind energy explained: theory, design and application (West Sussex: UK, John Wiley & Sons Ltd, 2002.

[2] N. Rosmin and S.J.Watson, "Power Limitation at High Wind Speed for a Variable Speed Fixed Pitch Wind Turbine using Close-Loop Scalar Control," Renewable Energy & Power Quality Journal (RE & PQJ), no. 8, 2010.

[3] J. Howard. (2012, March 10). Small wind: How much do home wind turbines cost?, LEED Green Associate, Green Competetive Advantage LLC [Online], Available: http://www.green-buildings.com/content/782102-small-wind-how-much-do-home-wind-turbines-cost.

[4] Renewable UK: "The voice of wind & marine energy, Small wind systems," London, UK, UK Market Report, Apr. 2011.

[5] A. Peter, F. Kevin, P. Sarah, R. Heather, S. Angeka and S. Savitt, (2003, September). Permitting small wind turbines: A handbook, learning from the California Experience, USA. [Online]. Available: www.consumerenergycenter.org/erprebate/forms.

[6] N. Rosmin, S. Samsuri and M.Y. Hassan, "A Comparison of Wind Turbine Power Limitation using Power Loop Control and Pole Placement Method," Brunei Darussalam Journal of Technology and Commerce (BDJTC), vol. 6, March 2012.

[7] M. Arifujjaman, M. T. Iqbal and J.E. Quaicoe, "Energy capture by a small wind-energy conversion system," Applied Energy, Elsevier, no. 85, pp. 41-51, 2008.

[8] P. Ghanim, N. Mahinsasa, J. Milutin and L. Pak Sing, "Maximum power point for variable-speed fixed-pitch small wind turbines," 20th International Conference on Electricity Distribution (CIRED), Prague, 8-11 June 2009.

[9] N. Rosmin and S.J. Watson, "Performance analysis of indirect vector control algorithm for small-sized wind turbine induction generator," Journal of Energy Procedia, Elsevier, no. 14, pp. 964-970, 2012.

[10] R. Teodorescu and F. Blaabjerg, "Flexible Control of Small Wind Turbines With Grid Failure Detection Operating in Stand-Alone and Grid-Connected Mode," IEEE Transactions on Power Electronics, vol. 19., n. 5, pp. 1323-1332, September, 2004.

[11] H. Mohd Shafarin, "Small scale wind turbine (synchronous generator)," Final Year Under Graduate Report, Universiti Malaysia Pahang, Malaysia, Nov. 2008.

[12] B. Amy, H. Arlinda, L. Hal, S. Karin, F. Trudy, J. David, V.D. Jereon and S. Joe, "Small wind testing results from the National Renewable Energy lab," Report - NREL/CP-500-45632. Jul. 2009.

[13] P. Migliore, J. van Dam and A. Huskey, "Acoustic tests of small wind turbines," Report – NREL/AIAA-2004-1185, 2004.

[14] N. Rosmin&S.J.Watson, "Speed Control at Low Wind Speeds for a Variable Speed Fixed Pitch Wind Turbine".The Proceedings of Modeling, Identification & Control (MIC), Innsbruck, Austria. 2010.

[15] L.Munteanu.L, A.L.Bratcu, N.Cutululis, E.Ceanga, Optimal Control of Wind Energy Systems, London: Springer-Verlag London Limited, 2008.

[16] Z. Jinghua. (Spring 2006). PID controller tuning: A short tutorial, Mechanical Engineering, Purdue University. [Online]. Available: http://wwwdsa.uqac.ca/~rbeguena/Systemes_Asservis/PID.pdf

VIII. Biographies

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