MAXIMUM POWER POINT TRACKING CONTROL SCHEME FOR MICRO-WIND TURBINE SYSTEM

Ho Nhut Minh*, Nguyen Trong Huan*, Van Tan Luong+

* Học Viện Công Nghệ Bưu Chính Viễn Thông Cơ Sở Thành Phố Hồ Chí Minh

+ Trường Đại học Công nghiệp Thực phẩm Thành Phố Hồ Chí Minh

Abstract **-** In this paper, a maximum power point tracking (MPPT) scheme is proposed for permanent magnet synchronous generator (PMSG) wind turbine systems. With this method, an adaptive compensation control is considered to improve the system dynamic response and therefore more energy yield can be extracted from the wind turbine, depending on a trade-off between the system dynamic behavior and the transient load of the drive train. The effectiveness of the proposed methods is verified by simulation results for the 3.2[kW]-PMSG wind turbine system.

Keywords **-** Maximum power point tracking, permanent magnet synchronous generator, torque control, wind turbine.

I. INTRODUCTION

These days, variable-speed wind turbine systems have been widely used in field applications. The operation range of variable-speed system is wide and provides 10%-15% higher energy capture from the wind turbine, when compared to the fixed-speed wind turbine systems [1]. Also, the initial installation cost for variable-speed system increases since the power converter is required. However, this cost can be compensated due to the enhanced capability of the energy capture.

Several different methods such as power signal feedback control, perturbation and observation (P&O) control, tip-speed ratio control, and optimal power control have been suggested to regulate the maximum output power of the wind turbine system in the low speed region. For the power signal feedback control, the MPPT method is not difficult to implement without wind speed measurement. Also, the method is stable since the data in the look-up table is obtained by the real test [2], [3]. However, it is not easy to get the field data. Also, a P&O control method has been applied for maximum power point tracking (MPPT) [4], [5]. This algorithm has been widely used in searching for maximum power values due to its simplicity. Furthermore, the use of the P&O does not require wind speed information and turbine parameters, and it is faster and more efficient in searching the maximum point of power. However, its disadvantage is that oscillations are produced under steady-state conditions because of constant duty cycle changes [4]. As for the tip-speed ratio control, the rotational speed is regulated to keep the tip-speed ratio to be optimal [6]. This method is simple. However, the performance of the tip-speed ratio control depends on the accuracy of the wind speed measurement. On other way, the optimal power control can regulate the generator power to its optimal value which corresponds to the optimal tip-speed ratio and rotor speed [7]. With this method, the power reference is proportional to the cubic of the rotor speed. Although this method is simple and effective, the study on the system dynamics, which is done in frequency domain, proves that its MPPT speed is low. Also, when the turbine operates at the low wind velocity, the MPPT bandwidth is narrow. Thus, energy produced is reduced and this affects electrical users. [1]

In this paper, a MPPT control method is proposed for PMSG wind turbine system. With this method, an adaptive compensation control has been applied, from which the bandwidth of the MPPT is significantly increased. Thus, transient performance of the MPPT control is also improved. Simulation results for a 3.2[kW] PMSG wind turbine system are provided to verify the validity of the proposed control strategy.

II. SYSTEM MODELING OF WIND TURBINE SYSTEMS

The configuration of the PMSG wind turbine system is shown in Figure 1, in which the machine-side converter controls the MPPT and grid-side converter regulates the DC-link voltage.

Contact: Ho Nhut Minh,

Email: minhho@ptithcm.edu.vn

Received: 15/10/2020, Revised: 10/12/2020, Accepted: 28/01/2021.

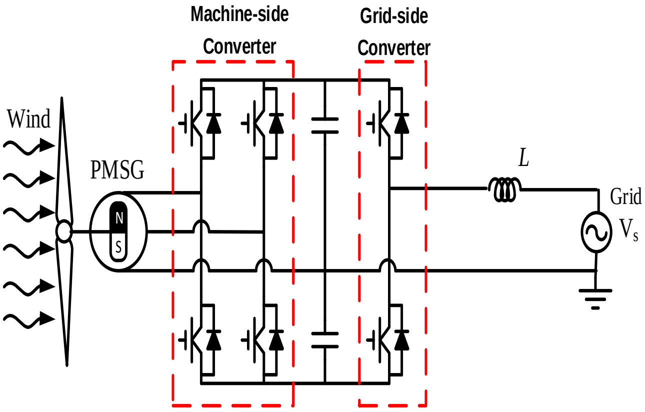


Figure 1. *Circuit configuration of small wind turbine system with PMSG.*

The turbine power of the wind turbine (P_t) is determined as [8]

$$P_t = \frac{1}{2}\rho\pi R^2 C_p(\lambda) V_w^3 \qquad (1)$$

Where ρ is the air density [kg/m^3], R is the radius of blade [m], V_w is the wind speed [m/s], and $C_p(\lambda)$ is the power conversion coefficient which is a function of the tip-speed ratio, in which the tip-speed ratio is defined as [8]

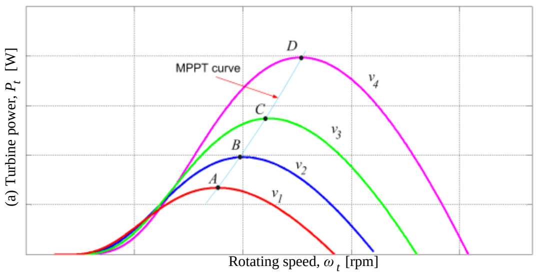
$$\lambda = \frac{\omega_t R}{V_w} \qquad (2)$$

The $C_p(\lambda)$ is expressed as

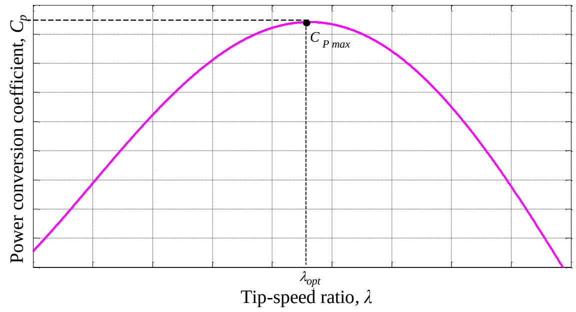
$$C_P(\lambda) = \frac{1}{2}\left(\frac{116}{\lambda - 0.035} - 4.8\right)e^{\left(\frac{-21}{\lambda - 0.035}\right)} \qquad (3)$$

The turbine torque is expressed as

$$T_t = \frac{0.5\rho\pi R^5 C_p(\lambda)}{\lambda^3}\omega_t^2 \qquad (4)$$



(a)



(b)

Figure 2. *Wind turbine characteristics. (a) $P_t - \omega_t$ curve. (b) $C_p - \lambda$ curve.*

As illustrated in Figure 2, the wind turbine is characterized by the ($P_t - \omega_t$) and ($C_p - \lambda$) curves. The power conversion coefficient reaches its maximum value ($C_{p\max}$) at the optimal tip-speed ratio (λ_{opt}), as shown in Figure 2(b). Also, the wind power conversion system has to operate at the λ_{opt} to maximize the C_p.

The relation between the torque and the rotor speed is expressed as [9], [10]

$$T_t - T_g = T_J = J_t\frac{d\omega_t}{dt} + (B_t + B_r)\omega_t \qquad (5)$$

Where T_J is inertial torque of the rotor, J_t is the combined inertia of the turbine and generator, B_t is the damping coefficient of turbine, B_r is the intrinsic speed feedback of the turbine and T_g is the generator torque.

III. PROPOSED MPPT CONTROL

Figure 3 shows the MPPT control block diagram for the conventional control method and the proposed control method, respectively. First, the turbine speed is estimated. Then, the torque reference divided by the torque constant (k_t) commands the rotor q-axis current reference (I_{qse}^*). This MPPT control block diagram can be seen in the corresponding part in Figure 3.

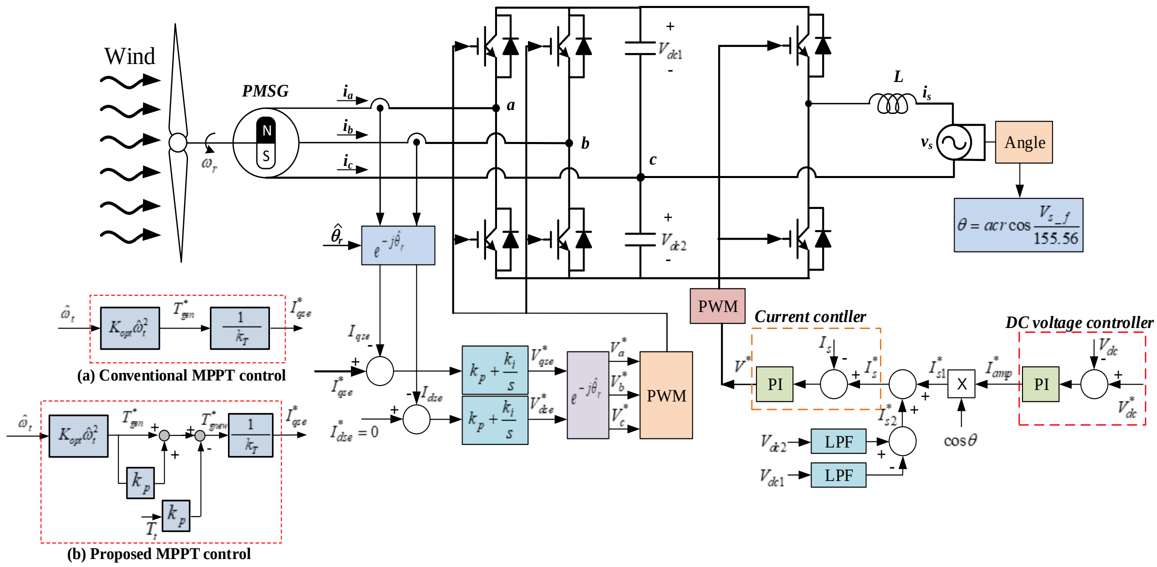


Figure 3. MPPT control block diagram. (a). Conventional MPPT control. (b). Proposed MPPT control

III.1. TURBINE SPEED ESTIMATION

A sensorless control method is applied, depending on rotor flux observer and induced electro-motive force. As can be seen from Figure 4, the stator flux (λ_s^s) is obtained from the stator voltage (v_s) and current (i_s). Then, the cut-off frequency (ω_0) of a high-pass filter is properly chosen to be one-third of the generator rated speed. Also, to remove a delay problem caused by the filter, the magnitude component, $\sqrt{\hat{\omega}_p^2+\omega_0^2}/\hat{\omega}_p$, and phase component, $e^{(\phi-\pi/2)}$, are multiplied with the function of λ_s/v_s, for compensation, in which $\phi = \arctan(\hat{\omega}_p/\omega_0)$ is the phase angle. Next, the flux linkage λ_f, is calculated from the d, q-axis rotor flux, λ_{df}^s and λ_{qf}^s, from which the rotor position angle is obtained as [11]

$$\hat{\theta}_r = \arctan\left(\lambda_{qf}^s / \lambda_{df}^s\right) \quad (6)$$

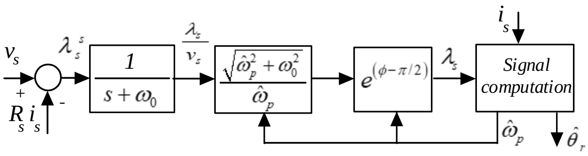


Figure 4. Block diagram of generator speed estimation.

By integrating the term of $\cos(\hat{\omega}_p t)$ in [t_0, t_1] and calculating the approximate area for the integration, $\int_{t_0}^{t_1}\cos(\hat{\omega}_p t)dt$, the estimated speed is obtained as

$$\hat{\omega}_p = \frac{\sin\hat{\theta}_{r1}-\sin\hat{\theta}_{r0}}{(\cos\hat{\theta}_{r1}+\cos\hat{\theta}_{r0})T_s/2} \quad (7)$$

where $\hat{\theta}_{r1}=\hat{\omega}_p t_1$, $\hat{\theta}_{r0}=\hat{\omega}_p t_0$, and T_s is a sampling time.

A low-pass filter is applied to reduce the speed ripple at the high frequencies to get the average generator speed, $\hat{\omega}_r$. The estimated turbine speed, $\hat{\omega}_t$, is obtained from $\hat{\omega}_r$.

III.2. MPPT METHOD

For a conventional MPPT controller, when the C_p reaches $C_{p\max}$ and the λ reaches λ_{opt}, the torque reference is obtained from (4) as follows

$$T_{gen}^* = K_{opt}\hat{\omega}_t^2 \quad (8)$$

where $K_{opt} = 0.5\rho\pi R^5 C_{p\max}(1/\lambda_{opt})^3$.

To increase the annual energy yield, an improved MPPT control strategy is applied, in which the adaptive compensation gain (k_p) is added to the controller to determine the transient performance of the MPPT control. Thus, the new torque reference (T_{gnew}^*) is obtained as

$$T_{gnew}^* = K_{opt}\hat{\omega}_t^2\left(1+k_p\right)-k_pT_t \quad (9)$$

It can be seen from (9) that k_p is used as an adaptive compensation, to improve faster performance of the turbine speed. Thus, more extracted energy can be captured.

Hence, the relation between the torque and the rotor speed for the proposed MPPT method is expressed as

$$T_t - T_{gnew}^* = J_t'\frac{d\hat{\omega}_t}{dt} + \left(B_t'+B_r'\right)\hat{\omega}_t \quad (10)$$

where $J_t' = J_t/(1+k_p)$ and $B_t'+B_r' = \left(B_t+B_r\right)/(1+k_p)$.

As illustrated in Figure 5, the proposed MPPT controller is considered when there is the step change of wind velocity from V_{w1} to V_{w2}. Due to the inertia of the wind power generation system, the generator speed cannot follow the sudden speed change immediately. For a conventional MPPT controller, the torque reference T_{gen}^* is obtained from (8) during the transient state. However, as the wind velocity is changed to V_{w2}, the optimal torque is located at point *B*. The solid trajectory between A and B is not really optimal one. The dynamic response for turbine acceleration at point *B* will be relatively slow (see dash line). On the other hand, by using the proposed MPPT controller, due to the adaptive compensation, the new torque reference will be smaller than that of the conventional optimal torque (conventional MPPT) controller to increase the torque difference for accelerating faster to point *B*. Thus, during the period of the wind speed variation, the amount of the extracted wind energy is significantly increased by using the proposed MPPT controller.

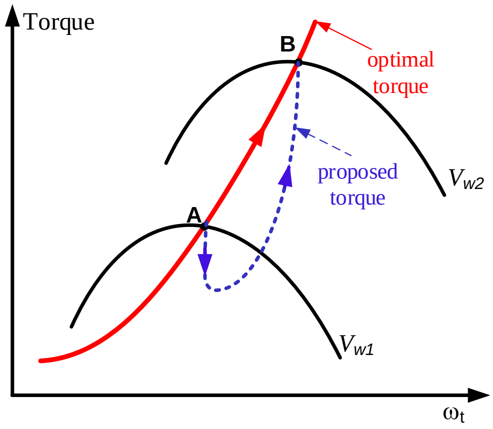


Figure 5. Turbine torque versus rotor speed

III.3. OPTIMIZED CONTROL OF SYSTEM DYNAMICS

As aforementioned, the proposed MPPT control method can make the maximum power point tracking speed much faster than that of the optimal one. The acceleration effect of the wind turbine is mainly generated by the gain (k_p). Thus, the k_p should be optimized through optimizing the bandwidth of the control system.

Using small signal analysis to (5) at the operating point *M* (V_{wM}, ω_{tM}), the system dynamics can be achieved as a first-order system:

$$\left(T_s s+1\right)\Delta\omega_t = 0 \qquad (11)$$

where

$$\begin{cases} T_s = \dfrac{J_t}{B_t + B_r + 2K_{opt}\cdot\omega_{tM} - K_{rr}} \\ K_{rr} = \dfrac{\partial T_t}{\partial \omega_{tM}} = \dfrac{1}{2}\rho\pi R^3 V_w^2\left(\dfrac{\partial C_p(\lambda)}{\partial\lambda}\dfrac{\partial\lambda}{\partial\omega_{tM}}\right) \end{cases}$$

(11)

$\partial C_p(\lambda,\beta)/\partial\lambda$ and $\partial C_p(\lambda,\beta)/\partial\beta$ in (11) are approximately zero when the system operates around the maximum power point and below the rated wind speed, respectively. Thus, the cut-off frequency of the control system dynamics can be obtained as

$$\omega_c = \frac{2K_{opt}}{J_t}\left(1+k_p\right)\omega_{tM} \qquad (12)$$

From (12), adaptive compensation gain k_p which can give faster MPPT speed, is achieved as

$$1+k_p = \left(\frac{J_t}{2K_{opt}}\right)\frac{\omega_c}{\omega_{tM}} \qquad (13)$$

According to van der Hoven spectrum, the ω_c can be selected between 0.01 [cycles/h] and 1000 [cycles/h], corresponding to the bandwidth range from $2.7\cdot10^{-6}$ [Hz] to 0.28 [Hz] [12]-[14]. The ω_c should be set to be wide enough to extract more energy from the wind turbine. In this research, ω_c is suggested to be 0.264 [Hz] (950 [cycles/h]).

IV. SIMULATION RESULTS

To verify the effectiveness of the proposed method, the simulation has been carried out using the PSIM software for a 3.2[kW]-PMSG wind turbine. The parameters of the wind turbine and generator are listed in Table 1 and 2, respectively.

Table 1. Parameters of wind turbine

Rated power	3.2[kW]
Blade radius	1.22838 [m]
Air density	1.225[kg/m^3]
Max. power conv. coefficient	0.35
Optimal tip-speed ratio	10.6
Cut-in speed	3[m/s]
Cut-out speed	25[m/s]
Rated wind speed	15.8 [m/s]
Blade inertia	0.021 [kg.m^2]

Table 2. Parameters of generator

Rated power	3.2 [kW]
Rated flux	0.468 Wb
Moment of inertia	0.021 [kg.m^2]
Stator resistance	0.49 [Ω]
Stator inductance	5.35[mH]
Number of poles	6

Figure 6 and 7 shows the dynamic responses of the conventional MPPT method and the proposed method, respectively when the wind speed changes from 10 m/s to 14 m/s at 6 sec and back to 10 m/s at 7 sec. The power conversion coefficient (C_P) which is shown in Figure 4(b), is recovered to C_{Pmax} in 0.3 sec after there is a sudden drop at 7 sec during the wind speed changes. Meanwhile, it takes about 0.2 sec for the proposed method (Figure 7(b)). Compared with the conventional MPPT method, the C_P variation gives the faster response during the step-wise wind speed change. As can be illustrated in Figure 6(c), the generator torque also varied, and then, reaches a steady state after 0.5 sec. However, for the proposed method as shown in Figure 7 (c), this value shows faster performance than that of the conventional MPPT one. Also, the actual turbine power and the maximum turbine power are shown Figure 6(d) and 6(d), respectively. For both the conventional and the proposed MPPT methods, the actual turbine power is 1000 W at the wind speed of 10 m/s and reaches abot 2800 W at at the wind speed of 14 m/s. However, the actual turbine power in the proposed MPPT method reaches a steady state after just 0.15 sec, compared with the conventional MPPT one. As can be seen from Figures 6 (d) and 7 (d), the proposed MPPT control method gives good performance. It is evaluated with the proposed MPPT method, the energy production is 0.4 % larger than that of with the conventional MPPT control method. As the rotor speed changes as quickly as the wind speed, more turbine power can be generated. The turbine speed is well estimated, as shown in Figure 6(e) and 7(e) without using speed sensor.

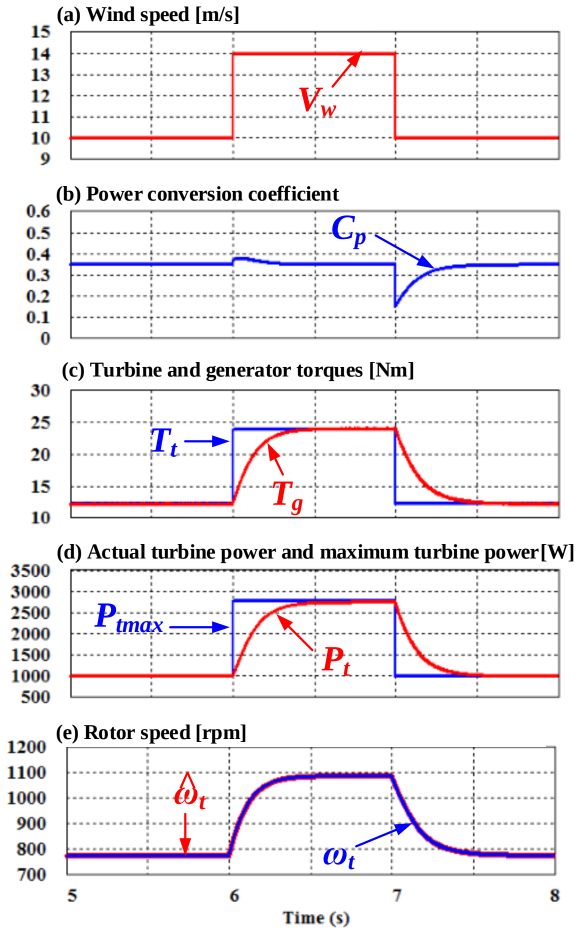


Figure 6. *Performance responses of conventional MPPT method in stepwise wind speed (a) Wind speed (b) Power conversion coefficient (c) Turbine and generator torques (d) Actual turbine power and maximum turbine power (e) Rotor speed.*

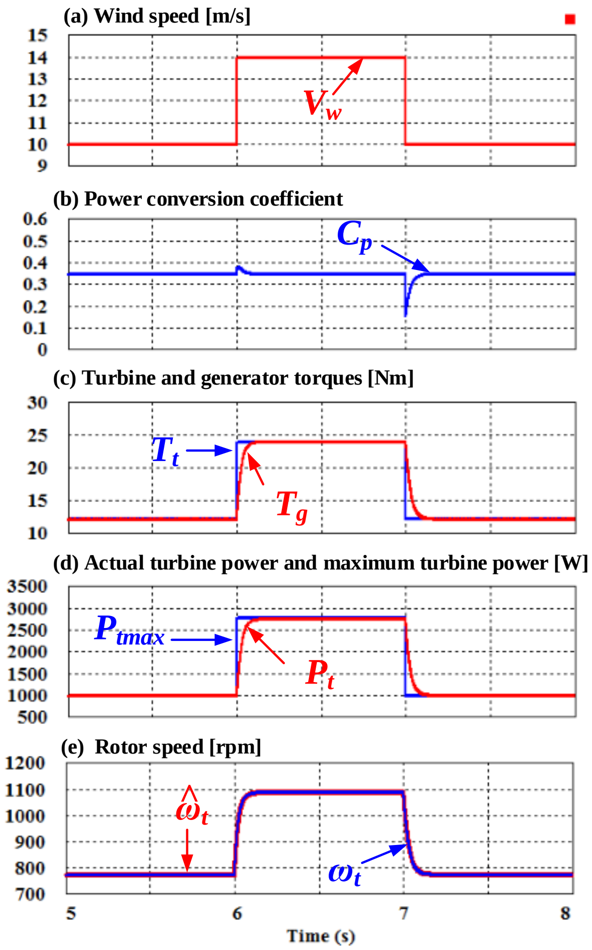


Figure 7. *Performance responses of proposed method in stepwise wind speed (a) Wind speed (b) Power conversion coefficient (c) Turbine and generator torques (d) Actual turbine power and maximum turbine power (e) Rotor speed.*

V. CONCLUSION

This paper has proposed an improved MPPT method for PMSG wind turbine systems considering the inertia torque. Through adding the adaptive compensation gain to torque, the bandwidth of the MPPT is greatly increased, from which the rotational speed is increased to improve the faster dynamic performance. For this, the amount of energy produced from wind turbine system can be annually increased (the energy production in the MPPT proposed method is 0.4 % larger than that of with the conventional MPPT control method). The validity of the control algorithm has been verified by simulation results for a 3.2[kW] PMSG wind power system.

REFERENCES

[1] Wang Q. and Chang L. (2004), An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems, *IEEE Transactions on Power Electronics*, vol. 19, No. 5, pp. 1242-1249.

[2] Ermis M., Ertan H. B., Akpinar E., and Ulgut F. (1992), “Autonomous wind

energy conversion systems with a simple controller for maximum-power transfer", Proceedings on Inst. Electric. Eng. B, vol. 139, pp. 421-428.

[3] Barakati S. M., Kazerani M., Aplevich J. D. (2009), Maximum power tracking control for a wind turbine system including a matrix converter, *IEEE Transactions on Energy Conversion*, vol. 24, pp.705-713.

[4] Farhat S., Alaoui R., Kahaji A., Bouhouch L., Ihlal A. (2015), "P&O and Incremental Conductance MPPT Implementation", *International Review of Electrical Engineering*, Vol. 10, No. 1, pp. 116–122.

[5] Ramadoni S., Indah S. (2019), "Performance Improvement for Small-Scale Wind Turbine System Based on Maximum Power Point Tracking Control", *Energies*, Vol. 12, No. 3938, pp. 1-18.

[6] Hua G. and Geng Y. (2006), A novel control strategy of MPPT tracking dynamics of wind turbine into account, *in Proceedings of IEEE Power Electronics Specialist Conference*, pp. 1-6.

[7] Cardenas R. and Pena R. (2004), Sensorless vector control of induction machines for variable-speed wind energy applications, *IEEE Transactions on Energy Conversion*, vol. 19, No. 1, pp.196-205.

[8] Morimoto. S, Nakayama. H, Sanada. M and Takeda. Y (2005), Sensorless output maximization control for variable-speed wind generation system using IPMSG, *IEEE Transactions on Industry Application*, vol. 41, No. 1, pp. 60-27.

[9] Nguyen T. H. , Hosani K. A., Sayari N. A., (2016), "Grid integration improvement for single-phase inverters of small wind turbines under distorted voltage conditions", *International Journal of Electrical Power & Energy Systems*, Vol. 87, pp. 144-153.

[10] AKHMATOV, V. (2005), Induction generators for wind power, *Multi-Science Publishing Company*.

[11] Van T. L., Truong T. H., Nguyen B. P. N. T., and Trang T. T. (2013), "Nonlinear Control of PMSG Wind Turbine Systems", *Lecture notes in electrical engineering*, Vol. 282, pp.113-124.

[12] LUBOSNY, Z. (2003), Wind turbine operation in electric power system, *Springer-Verlag Berlin Heidelberg*, New York, Chap. 5.

[13] Bianchi F. D., Battista H. D. and Mantz R. J. (2007), Wind turbine control systems. *Germany: Springer*.

[14] Fernando D. Bianchi, Hernan De Battista, and Ricardo J. Mantz (2007), Wind turbine control systems, principles, modeling and gain scheduling design, *Springer*-Verlag London Limited.

[15] Leon F., David I. (2008), Renewable energy in power system, *John Wiley & Sons*.

CHIẾN LƯỢC ĐIỀU KHIỂN PHÁT CÔNG SUẤT CỰC ĐẠI CỦA HỆ THỐNG TUA BIN GIÓ CÔNG SUẤT NHỎ

Tóm tắt: Trong bài báo này, chiến lược tìm điểm phát công suất cực đại (MPPT) được đề xuất trong hệ thống tua bin gió dùng máy phát điện đồng bộ nam châm vĩnh cửu (PMSG). Với phương pháp đề xuất này, điều khiển bù thích nghi được xem xét để cải thiện đáp ứng động của hệ thống và do đó nhiều năng lượng hơn được trích ra từ tua bin gió, tùy thuộc vào sự cân bằng động giữa hệ thống và tải của bộ truyền động. Hiệu quả của các phương pháp đề xuất được xác minh bằng kết quả mô phỏng cho hệ thống tua bin gió dùng máy phát PMSG công suất 3,2 [kW].

Từ khóa - tìm điểm phát công suất cực đại, máy phát đồng bộ loại nam châm vĩnh cửu, điều khiển mô men, tua bin gió.

Ho Nhut Minh was born in Vietnam in 1987. He received his undergraduate degree in 2010, major in Electronics & Telecommunications Engineering from University of Technical Education of Ho Chi Minh City. In 2014, he received the Master of Telecommunication Engineering Degree from Posts and Telecommunications Institute of Technology, Ho Chi Minh City Campus. He is working at Department of Electrical and Electronic Engineering, Posts and Telecommunications Institute of Technology, Ho Chi Minh City Campus, VietNam.

Nguyen Trong Huan was born in VietNam in 1986. He received his undergraduate degree in 2010, major in Electrical and Electronics Technology from University of Technical Education of Ho Chi Minh City. In 2014, he received the Master of Telecommunication Engineering Degree from Posts and Telecommunications Institute of Technology, Ho Chi Minh City Campus. He is working at Department of Electrical and Electronic Engineering, Posts and Telecommunications Institute of Technology, Ho Chi Minh City Campus, VietNam.

Van Tan Luong was born in Vietnam. He received the B.Sc. and M.Sc. degrees in electrical engineering from Ho Chi Minh City University of Technology, Ho Chi Minh city, Vietnam, in 2003 and 2005, respectively, and Ph.D. degree in electrical engineering from Yeungnam University, Gyeongsan, South Korea in 2013. Currently, he is working at Department of Electrical and Electronics Engineering, Ho Chi Minh city University of Food Industry. His research interests include power converters, machine drives, wind power generation, power quality and power system