Design of a MPPT controller for permanent magnet synchronous generator driven wind turbine

Truong Viet Anh1,*, Huynh Quang Minh2, Vo Hoai Thuong3

ABSTRACT
Wind and other renewable energies are more and more developed all over the world, especially in countries with high wind potential such as Vietnam, to replace fossil energy, which would be exhausted in the near future. One important characteristic of wind turbines is that at each different wind speed, there exists a working point, represented by the rotation speed and the mechanical power at the crankshaft of the wind turbine, at which the maximum mechanical power is obtained, called maximum power point (MPP). Therefore, when the wind speed changes, this working point must be changed to be able to extract the maximum power from the wind to improve the total efficiency of the wind turbine system. This, in a wind energy conversion system (WECS), is assigned to the maximum power point tracking (MPPT) controller. In this paper, a MPPT controller is proposed, based on an improved Perturb and Observe (P&O) algorithm, for wind turbines using permanent magnet synchronous generator (PMSG), to maximize energy without measuring the wind speed and power characteristics of the wind turbine. An experimental model is also designed and tested in laboratory conditions, in which two coefficients $K_1$ and $K_2$ are used in turn when the working point is far or close to the maximum power point. The experimental results show that the proposed MPPT controller allows the extraction of maximum power from wind turbines under variable wind speed without determining the wind speed and characteristics of the wind turbine system.

Key words: wind turbine, permanent magnet synchronous generator, maximum power point tracking, perturb and observe, AC/DC converter, DC/DC converter

INTRODUCTION
In recent years, the use of renewable energy resources is more and more increased due to the increasing need for energy and the shortage of traditional energy sources in the near future1. The literature review shows that, renewable energy systems are not cost competitive against conventional fossil fuel power systems. However, the need for cleaner power and improvements in alternative energy technologies gives good potential for widespread use of such systems.

Community facilities such as rural hospitals, schools, telecommunication and water pumping stations can contribute significantly to the welfare of people and rural development. Renewable energy systems have demonstrated the potential to provide support in some of the basic infrastructure needs in remote and urban areas. One of the interesting utilisations of the renewable energy in community development is to electrify remote villages and rural areas located so far from power stations and distribution networks which are uneconomical to install. Recent research and development in renewable energy sources have shown excellent potential, as a form of supplementary contribution to conventional power generation systems. In order to meet sustained load demands during varying natural conditions, different energy sources and converters need to be integrated with each other for extended usage of alternative energy. Therefore, it is necessary to construct a system capable of generating maximum power under these constraints3.

The wind energy conversion system (WECS) incorporated in the proposed scheme consists of a wind turbine coupled to a permanent magnet synchronous generator (PMSG). An AC/DC power electronic interface with diode bridge rectifier and a DC/DC boost converter are used for maximum power tracking. An improved P&O method is proposed to avoid the instable effect of original one. There are two types of MPPT controller for wind turbine: indirect and direct. Indirect MPPT controllers are based on the knowledge of the generator's power characteristic, which is usually not available with a high degree of accuracy and also changes with rotor aging and require wind speed measurement1. On the other hand, direct MPPT controllers are independent from the knowledge of the generator curve, and

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the operating point is independent of climatic conditions. In this paper, a direct MPPT controller for variable speed PMSG driven wind turbine is proposed and tested in laboratory condition to extract maximum power from the wind without any knowledge about generator’s characteristic or load condition.

**APPROACH**

**Wind aerodynamics**

Mechanic power of a wind turbine can be expressed in terms of the air density $\rho$, the blade radius $R_{\text{blade}}$, and is the wind speed $v_{\text{wind}}$:

$$P_m = 0.5C_p\rho\pi R_{\text{blade}}^2 v_{\text{wind}}^3$$  \hspace{1cm} (1)$$

where $C_p$ is the power coefficient. This coefficient is also known as Betz limit. It can be expressed in terms of reduced velocity $\lambda$ and blade angle $\beta$. If $\omega$ is the rotor speed, the reduced speed $\lambda$ is defined:

$$\lambda = \omega R_{\text{blade}}/V_{\text{wind}}$$ \hspace{1cm} (2)$$

A generic equation is used to model the power coefficient $C_p = C_p(\lambda, \beta)$, based on the modeling turbine characteristics described in $^7$:

$$C_p(\lambda, \beta) = 0.5(98/\lambda_i - 0.4\beta - 5)e^{-16.5\lambda}$$ \hspace{1cm} (3)$$

where:

$$\lambda_i = 1/\left[1/(\lambda + 0.08\beta) - 0.035/(\beta^3 + 1)\right]$$ \hspace{1cm} (4)$$

**Electrical system modeling**

The WECS incorporated in our scheme consists of a wind turbine coupled to a PMSG. Since the PMSG produces variable amplitude - variable frequency voltage, additional power electronic devices are required to meet power quality demand. A three-phase diode bridge rectifier is used for the AC/DC conversion. A boost converter (DC/DC) is used to vary the rotor speed by adjusting the converter’s duty cycle (Figure 3).

The dynamic model of PMSG can be represented in the Park’s system using these equations $^{10}$:

$$V_d = -R_s i_d - L_d di_d/dt + \omega L_q i_q$$ \hspace{1cm} (7)$$
The expression of electromagnetic torque in the rotor is given by:

\[ T_e = \frac{3}{2p} \left[ (L_d - L_q) i_q i_d - \lambda_m i_q \right] \tag{9} \]

\[ \omega_c = \omega \cdot R \tag{10} \]

where \( p \) is the number of pole pair, \( \lambda_m \) is the magnetic flux, \( L_d \) is the direct axis inductance, \( L_q \) is the inductance in quadrature, \( R_s \) is the stator resistance and \( \omega \) is the electrical angular frequency.

If the rotor is cylindrical, \( L_d \approx L_q \approx L_s \) so:

\[ T_e = -1.5 pi q \lambda m \tag{11} \]

Relationship between mechanical torque and electromagnetic torque in a wind turbine:

\[ T_m - T_e = J \cdot d\omega / dt \tag{12} \]

where \( J \) is the inertia of the wind turbine.

In PMSG wind generation systems, the output current and voltage are proportional to the electromagnetic torque and rotor speed, respectively:\n
\[ T_e = k_T i_a \tag{13} \]

\[ E = k_e \omega \tag{14} \]

where \( i_a \) is the stator current. On the other hand:

\[ E^2 = V_{WT}^2 + (L_s \omega)^2 \tag{15} \]

\( V_{WT} \) is the generator phase voltage and \( L_s \) is the inductance of the generator.

From (14), (15) we have:

\[ \omega \propto V_{WT} \rightarrow d\omega / dt \propto dV_{WT} / dt \tag{16} \]

Thus, in a variable speed PMSG driven wind turbine, we can vary the output voltage \( V_{WT} \) of the generator (by adjusting the duty cycle of the boots converter) to change the rotor speed \( \omega \). If we can control our system to work at the optimal rotor speed \( \omega_{opt} \), maximum power will be extracted from the wind turbine.

\[ V_q = -R_s i_q - L_q di_q / dt - \omega L_d i_d + \omega \lambda_m \tag{8} \]

\[ \omega_c = \omega \cdot R \tag{10} \]

\[ T_e = -1.5 pi q \lambda m \tag{11} \]

\[ T_m - T_e = J \cdot d\omega / dt \tag{12} \]

\[ T_e = k_T i_a \tag{13} \]

\[ E = k_e \omega \tag{14} \]

\[ E^2 = V_{WT}^2 + (L_s \omega)^2 \tag{15} \]

\[ \omega \propto V_{WT} \rightarrow d\omega / dt \propto dV_{WT} / dt \tag{16} \]

\[ \omega_c = \omega \cdot R \tag{10} \]

\[ T_e = 3/2p \left[ (L_d - L_q) i_q i_d - \lambda_m i_q \right] \tag{9} \]

\[ \omega_c = \omega \cdot R \tag{10} \]

\[ T_e = -1.5 pi q \lambda m \tag{11} \]

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voltage, we can predict the new position of the MPP. That means, when wind speed increases, the new MPP will move to the left of the power curve, and when wind speed decreases, the new MPP will move to the right.

The flow chart of the proposed algorithm is given in Figure 4. This algorithm needs to determine the two experimental constant $k_1$ and $k_2$. When the operating point is far away from MPP, we should use a big variation to reach the MPP more quickly. When our system is working in the MPP and wind speed change, we will use smaller variation to keep the system stable. Thus $k_1 > k_2$ and their value are proportional to the turbine capacity. The $k_1$ and $k_2$ are determined experimentally on physical model shown in Figure 5. The experimental parameters of our proposed controller are given in Table 1.

### Table 1: Experimental parameters

| Parameter | Value |
|-----------|-------|
| $\Delta P_{\text{min}}$ | 0.4 |
| $\Delta P_{\text{max}}$ | 1.7 |
| $x_0$ | 10 |
| $k_1$ | 0.7 |
| $k_2$ | 0.35 |

## EXPERIMENTAL, RESULTS AND DISCUSSION

### Tested system

The wind turbine emulator includes a tunnel and a three-phase motor controlled by an inverter, a wind speed gauge, a 6-bladed turbine system and a PMSG. The wind speed is varied by changing the three-phase...
motor speed through the inverter. The output voltage is rectified by a three-phase diode bridge. These devices were produced by the DE LORENZO group (Italy) in Figures 5, 6 and 7.

To determine the maximum power point for each wind speed of a wind turbine system, an experiment is arranged as shown in Figure 8a and the results are shown in Figure 8b.

**Results and discussion**

At 12.5 m/s wind speed, we tested our system in 2 conditions: without MPPT controller (Figures 9 and 11) and with MPPT controller (Figures 10 and 12). We also use a battery and then a 60W-220V lamp as load, we obtained the following result:

![Figure 9: Results without MPPT controller at 12.5 m/s wind speed with battery load.](image)

With the battery load, when the MPPT is not activated, the charging power is 11.4W, and when the MPPT controller is activated, the charging capacity reaches 15.6W. With the 60W-220V lamp loading without MPPT system, the measured power is 3.9W, after activating the MPPT controller the measured power is now 15.6 W.

Results obtained at different wind speeds with 60W-220V are given in Table 2.

![Figure 10: Results with MPPT controller at 12.5 m/s wind speed with battery load.](image)

Table 2 shows the maximum power supplied by the MPPT unit for lamps similar to the resistor survey results in Figure 8. We can see that with our proposed MPPT controller, when wind speed and load change, the power extracted from our WECS is always maximized.

![Figure 11: Results without MPPT controller at 12.5 m/s wind speed with 60W-220V lamp load.](image)

![Figure 12: Results without MPPT controller at 12.5 m/s wind speed with 60W-220V lamp load.](image)

| V(m/s) | 0 → 10 | 10 → 8 | 8 → 10 |
|-------|--------|--------|--------|
| 14    | 20s    | 7s-8s  | 13s-14s|
| Proposed algorithm | 12s | 7s-8s | 7s-8s |

The P&O algorithm of Badreddine et al. 14 takes more than 20 seconds to achieve MPP while the proposed algorithm only needs 12 seconds in the inception phase. When the wind speed increases from 8m/s to 10m/s, the time to get the MPP of the proposed algorithm is also faster than that in Badreddine et al. 14.
Table 2: Summary of experimental results

| Wind (m/s) | Without MPPT | With MPPT | $P_{\text{max}}$ (W) at Figure 8 |
|-----------|---------------|-----------|---------------------------------|
|           | U(V) | I(A) | P(W) | U(V) | I(A) | P(W) |
| 9.4       | 22.4 | 0.11 | 2.46 | 49.0 | 0.15 | 6.86 |
| 10.0      | 24.9 | 0.11 | 2.74 | 53.0 | 0.14 | 7.42 |
| 10.6      | 26.5 | 0.11 | 2.92 | 61.0 | 0.15 | 9.15 |
| 11.7      | 29.9 | 0.11 | 3.29 | 75.0 | 0.16 | 12.0 |
| 12.5      | 32.5 | 0.12 | 3.90 | 70.8 | 0.22 | 15.6 |

CONCLUSION

In this paper, an adaptive perturbation MPPT controller for WECS is designed and tested in laboratory condition. Without information of wind speed, generator's power characteristic or load condition, control signals were generated to extract maximum power from the wind. Experimental results show that our proposed controller works well to achieve the MPP of the wind turbine system at various wind speeds and load conditions.

ABBREVIATION

MPP: maximum power point
WECS: wind energy conversion system
MPPT: maximum power point tracking
P&O: Perturb and Observe
PMSG: permanent magnet synchronous generator
AC: alternating current
DC: direct current

CONFLICT OF INTEREST

In this paper, there is no conflict of interest.

AUTHORS’ CONTRIBUTION

Truong Viet Anh, Vo Hoai Thuong have contributed in conducting experiments. Huynh Quang Minh has tested experiments. Truong Viet Anh, Huynh Quang Minh wrote the manuscript.

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Thiết kế bộ điều khiển MPPT cho tuabin gió dùng máy phát đồng bộ nam châm vĩnh cửu

Trương Việt Anh1,*, Huỳnh Quang Minh2, Võ Hoài Thương3

Tóm tắt
Năng lượng gió và các năng lượng tái tạo khác ngày càng được phát triển trên toàn thế giới để thay thế dần năng lượng hóa thạch với tốc độ ngày càng nhanh chóng, đặc biệt tại các nước có tiềm năng gió lớn như Việt Nam. Một đặc điểm của các turbine gió là ứng với mỗi tốc độ gió khác nhau, sẽ tồn tại một điểm làm việc được thiết kế bởi tốc độ quay của turbine gió và moment đầu trục turbine (công suất cơ học) hay dòng điện và điện áp (công suất điện) mà ở đó công suất thu được là lớn nhất. Vì vậy, khi tốc độ gió thay đổi, điểm làm việc này sẽ phải thay đổi để có thể trích xuất được công suất lớn nhất nhằm cung cấp hiệu suất sử dụng của turbine gió. Việc này, trong một hệ thống turbine gió được giao cho bộ dò tìm công suất cực đại (MPPT) trong hệ thống chuyển đổi năng lượng gió sang năng lượng điện. Trong bài báo này, bộ điều khiển MPPT dựa trên giải thuật nhiễu loạn và quan sát được đề xuất cho tuabin gió sử dụng máy phát đồng bộ nam châm vĩnh cửu thu được năng lượng tối đa mà không cần đo tốc độ gió và đặc tuyến công suất của tuabine gió. Mô hình vật lý được thiết kế và thử nghiệm trong điều kiện phòng thí nghiệm, giải thuật sử dụng P&O cải tiến với 2 hệ số K1 và K2 được dùng làm latching khi điểm làm việc xa và gần điểm công suất cực đại. Kết quả được mô tả qua một thí nghiệm trên mô hình vật lý, cho phép trích xuất được công suất điện từ turbine gió lớn nhất trong các điều kiện gió thay đổi mà không cần xác định tốc độ gió và đặc tính của hệ thống turbine gió.

Từ khoá: tuabin gió, máy phát đồng bộ nam châm vĩnh cửu, dò tìm điểm công suất cực đại, nhiễu loạn và quan sát, bộ chuyển đổi AC/DC, bộ chuyển đổi DC/DC