A Comparative Experimental Investigation of MPPT Controls for Variable Speed Wind Turbines

Original Scientific Paper

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Abstract – *This work presents an experimental comparative investigation between Maximum power point tracking control methods used in variable speed wind turbines. In order to enhance the efficiency of the wind turbine system, the maximum power point tracking control has been applied for extracting and exploiting the maximum available wind power. Furthermore, two maximum power point tracking controls have been analyzed, developed, and investigated in real-time using Dspace. The first was optimal torque control without speed control, whereas the second was with speed control. The maximum power point tracking control performance comparison has been performed in a real-time experimental validation to illustrate the advantages of these control on the real wind energy system. The results have been achieved and discussed, where the power efficiency improvements appeared in the transit time and in the steady-state as well. In addition, the proposed optimal torque control for maximum power point tracking with speed control decreased the response time and oscillations, while it increased the power to an interval of 12,5% to 75% compared to that of strategy without speed control in the steady-state and transit state, respectively.*

Keywords: *Wind energy conversion system (WECS), Maximum power point tracking (MPPT), Optimal Torque Control (OTC), Real time control, Dspace*

1. INTRODUCTION

Nowadays, modern life and technology development has greatly increased the electrical energy demand. This is mainly due to the strong relationship between life quality and the energy consumption level. This leads to an ever-increasing of fossil sources demand. However, these later know a gradual depletion and cause environmental and pollution problems [1, 2]. Currently, there are serious large movements toward free solution energies that are more sustainable, renewable and environment-friendly [3-7]. The wind energy takes an important class among these renewable energies [8-11]. It knows a high growth and use over the world in recent years [12-17]. A large installation capacity is noticed (733GW: onshore 698GW and 35GW offshore) and with an annual increase of 9% expected between 2021-2030 [18]. However, the intermittence criteria of this energy requests a high technology mastering to answer load needs and to benefit as far as possible from this energy [19]. Recently, the wind energy has been focused on higher efficiency and robustness with a lower cost [4, 20, 21]. Several studies have been performed to increase the efficiency of the Wind Energy Systems. For this reason, variable speed wind turbines were adopted instead of those of fixed speed to apply the Maximum power point tracking control when the available power is less than the rated generator power, and pitch angle when it becomes over the rated power to protect the generator from over power [22-24]. Thus, wind turbines can optimize the produced energy with a better quality [25-32]. This paper is focused in MPPT operation mode. Different control algorithms were applied to extract the maximum power [33-43]. They can be classified according to the control technique or to whether or not the use of the wind speed sensor. Perturb and observe (P&O) method is among the famous used techniques [44, 45]. It is easy to set up and can reach the maximum power points without the need to wind turbine parameters. However, during rapid wind speed variations, it is liable to diverge and lose the maximum power point. Even for slow variations, this command lacks precision because its power always oscillates around the maximum point, which can generate oscillations that generate noise and disturbances of the torque. In addition, this MPPT method has less efficiency and presents the difficulty of optimizing the test step [9]. Other techniques were based on the knowledge of the power curve characteristics as a function of the rotor speed. These characteristics are obtained from several tests either to store them in a 'Lookup table' or approach them with a mathematical function. However, this method loses its precision in the case of variations in turbine parameters due to climatic conditions changing on blades. Besides, the turbine characteristics are often not available (from the factory) to avoid an additional cost. For these reasons, other MPPT control strategies will be presented in this paper. MPPT based on the control of the electromagnetic torque (Optimal Torque Control (OTC) without speed control), and Optimal Torque Control with speed control which is based on the adjustment of the mechanical speed in a way to maximize the power coefficient; therefore maximizing the converted electromagnetic power; [24, 25, 39, 46-48]. Although the previous works were achieved in simulations [36,49], in this work, both later proposed MPPT controls have been analyzed, investigated, and implemented in a real-time wind turbine simulator. The experimental results will be discussed and compared to choose the best method.

Below are the main contributions of this paper:

Firstly, comparison between both proposed MPPT approaches using several tests scenarios that prove the superiority of the OTC with speed control. Secondly, confirming the comparison using real time tests and validations. Thirdly, improvement of the WECS yield and performances such as response time. Fourthly, reducing of overshoot and torque vibration in the system. The rest of this paper is organized on six sections: Section 2 starts by modelling of the wind turbine characteristics. Then the analysis of the OTC MPPT without Speed Control. Followed by the study of the OTC MPPT with Speed Control. The fifth section is reserved to the real time MPPT results; also, this part discusses results and comparisons between MPPT controls in order to improve the yield of the real wind turbine. Finally, the main findings and the suggestions for future work are outlined in Section 6.

2. WIND TURBINE MODELLING

The total wind power that flows through the blades sweep area can be written by [31, 50-53]:

$$P_m = \frac{1}{2}\rho A v_1^3 \tag{1}$$

With $$A = \pi R_t^2 \tag{2}$$

The produced mechanical power is expressed as [24,54]:

$$P_t = \frac{1}{2} C_p(\lambda)\rho A v_1^3 \tag{3}$$

The tip-speed is defined as the ratio between the linear speed before and after blades, as given [55,56]:

$$\lambda = \frac{\Omega_t R_t}{v_1} \tag{4}$$

The power coefficient value C_p is depending on the design of the wind turbine; The equation of C_p is non-linear as it is given by [5]:

$$C_p(\lambda,\beta) = \left(0.5 - 0.0167(\beta-2)\right)\sin\left[\frac{\pi(\lambda+0.1)}{18-0.3(\beta-2)}\right] - 0.00184(\lambda-3)(\beta-2) \tag{5}$$

Fig. 1 shows the power coefficient as a function of the speed ratio for various pitch angle values:

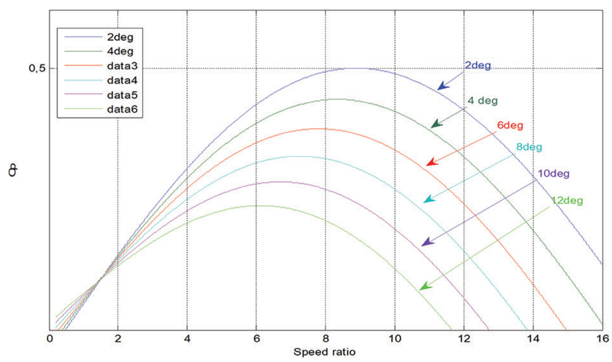


Fig. 1. $C_p(\lambda, \beta)$ Characteristics for various values of β

It can be seen that the value of the power coefficient $C_p(\lambda, \beta)$, and consequently the power are inversely proportional with the pitch angle values. For this reason, the pitch angle control increases its value only to limit the surplus power. On the contrary, when the wind power is less than the nominal power, β value should be maintained fixe at its smallest degree (β=2) to fully exploit the wind energy [2, 27, 57]. Hence, the power coefficient reaches its maximum value at a particular optimal speed ratio λ_{opt}, which is determined from the blade design. This λ_{opt} is corresponding to the maximum power value for each wind speed, Fig.1. So, as a result, to maximize the wind energy, λ should be maintained either at λ_{opt}, or regulate Ω_t at Ω_{ref} which is expressed as following [57]:

$$\Omega_{ref} = \frac{\lambda_{opt} \cdot v_1}{R_t} \tag{6}$$

All these show the use interest of the Maximum Power Point Tracking (MPPT) strategy in order to reach and track the maximum power point whatever the variation of wind speed. This explains the existence of various MPPT strategies to maximise the captured wind power. Most of them are based on the optimal torque or the speed controller. In the next part, the developed Optimal Torque Control MPPT controls without and with Speed Control will be detailed and investigated with a comparison of their performances in real-time case [3].

3. OPTIMAL TORQUE MPPT CONTROL WITHOUT SPEED CONTROL

The Optimal Torque MPPT without Speed Control strategy is based on the rotor speed measurement and the subsequent determination of the desired generator power (or torque). The principle of this control is to impose and adjust the generator torque to its reference torque according to different wind speeds [25]. The OTC Method without Speed Control requires the knowledge of the optimal turbine characteristics $C_{p\text{-}Max}$ and λ_{opt}.

The main advantage of this control method is presented in its simplicity, where it avoids the use of regulators. Moreover, it does not need any wind speed measurement, which avoids the additional cost and failures of the anemometer.

This method is based on the assumption that the wind speed and consequently, the rotor turbine speed varies a bit in the steady operation. Hence, the exerted torque on the shaft is considered null in this case, [2]:

$$T_{mec} = J.\frac{d\Omega_{mec}}{dt} = 0 \tag{7}$$

Also, the resistive torque due to viscous frictions is considered null. So:

$$\begin{aligned} T_{mec} &= T_g - T_{em} - T_f = 0 \\ \Rightarrow T_{em} &= T_g = \frac{T_{aer}}{G} \end{aligned} \tag{8}$$

The reference torque leads to apply and obtain the MPPT control is given by, [2, 33, 48]:

$$T_{em-ref} = K_{opt}.\Omega_{mec}^2 \tag{9}$$

Where:

$$K_{opt} = \frac{1}{2}\frac{C_{p\max}}{\lambda_{opt}^3}\rho\pi R_t^5 \frac{1}{G^3} \tag{10}$$

The goal of the Optimal Torque Control MPPT Method without Speed Control strategy is to pick up the maximum power from the wind. Hence, the curve connects the peaks of these curves that generate the maximum power point (MPP) for different wind speeds and follows the corresponding peaks of maximum power operation. It means the following of path of the power shown in Fig. 2, given by [43]:

$$P_{opt} = P_{Max} = \frac{1}{2}C_{p\_opt}(\lambda_{opt})\rho A v_1^3 \tag{11}$$

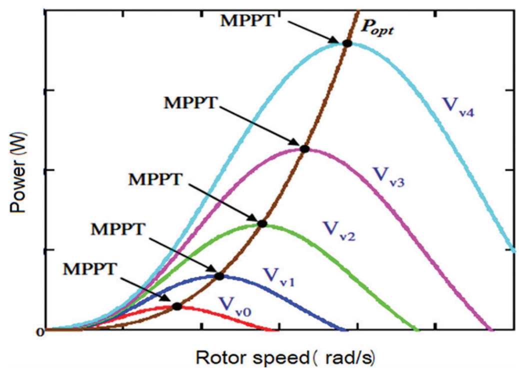


Fig. 2. Wind power characteristics

Although the simplicity of this control, its dynamic is late, especially in the case of fast wind speed variations, because it is an open-loop control. Therefore, the following control overcomes this drawback.

4. OPTIMAL TORQUE MPPT CONTROL WITH SPEED CONTROL

The Optimal Torque MPPT Control method with speed control is used to maximize the captured energy from the wind. It is based on the wind speed measurement in order to calculate the reference rotor speed. The speed controller regulates the rotor speed by controlling the generator torque (and therefore maximizing the electrical power) according to the optimal pre-specified speed λ_{opt}. In this case, the motor torque should be equal to its reference value:

$$T_{em} = T_{em-ref} \tag{12}$$

The reference of the electromagnetic torque T_{em_ref} allows making the mechanical generator speed equal to the reference speed Ω_{ref} by the relation below, [58, 59] :

$$T_{em-ref} = C_{ass}\left(\Omega_{ref} - \Omega_{mec}\right) \tag{13}$$

The reference wind turbine speed that corresponds to the optimal value of the specific speed λ_{opt} and the maximum of power coefficient $C_{p\text{-}Max}$ is given by :

$$\Omega_{tur-ref} = \frac{\lambda_{opt}.v_1}{R_t} \tag{14}$$

By developing the proportional-integral PI controller, the torque becomes:

$$T_{em-ref} = \left(\frac{K_i + K_p S}{S}\right)\left(\Omega_{ref} - \Omega_{mec}\right) \tag{15}$$

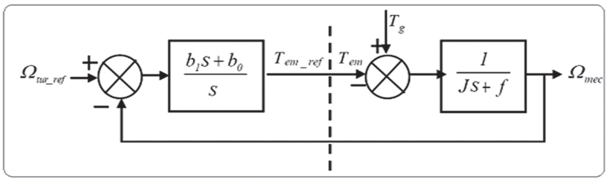


Fig. 3. Diagram block of the speed control

By neglecting losses, the electric output is considered equal to the aerodynamics power.

5. REAL TIME MPPT RESULTS

The tests were carried out in real-time on a test bench where the wind turbine was replaced by an emulator based on an asynchronous machine. This later was controlled in a way to behave such as the real wind turbine when it reacts with the wind speed. The wind turbine emulator was directly coupled with a Permanent Magnet Synchronous Generator (PMSG). The control algorithms have been implemented in a computer equipped with Control Desk software, which receives measurements (current, voltage, rotor speed…) and sends control signals into hardware devices via Dspace card based on DSP micro controller, as shown in Fig. 4 and Table.1 [60-62].

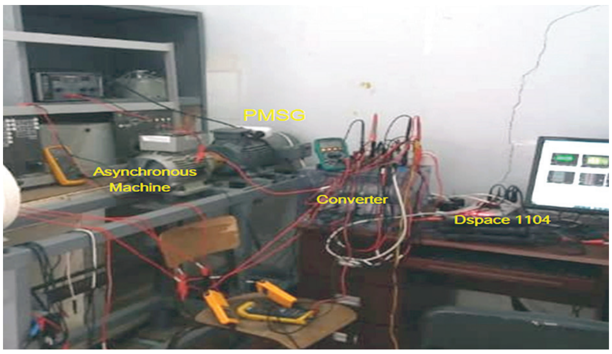
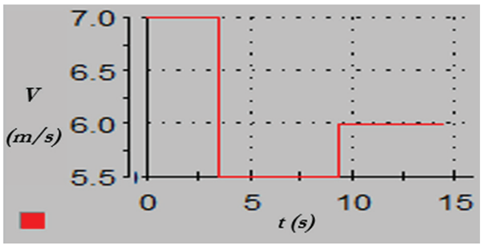


Fig. 4. Wind turbine emulator system in the test bench

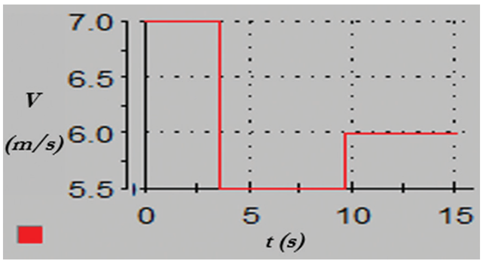
Table 1. Wind energy system parameters

Parameters	Values
Number of blades	3
Blade Radius	0.3m
Air density	ρ =1.225 [kg m-1]
PMSG nominal power	$P = 3kW$
Effective nominal power (line to line)	Vn = 400 V
Number of pole pairs	p = 1
Frequency	fs = 50Hz
Nominal torque	T = 9,5N. m
Nominal speed	3000 tr/min
Asynchronous motor nominal power	$P = 3kW$
Effective nominal power (line to line)	Vn = 400 V
Number of pole pairs	p = 2
Frequency	fs = 50Hz
Power factor	0.85
Nominal speed	1425 tr/min
Converter current RMS	30A
Converter Max DC voltage	750V
Converte Max AC voltage	440V

In order to test and choose the best MPPT strategy performances, the same step shapes of the wind profile in Fig. 5 have been applied for both OTC MPPTs.

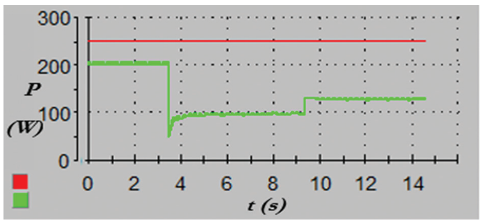


(a) OTC without speed control

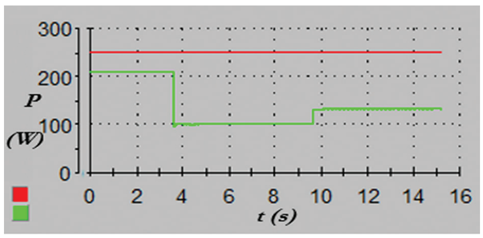


(b) OTC with speed control

Fig. 5. Wind speed profile (m/s)

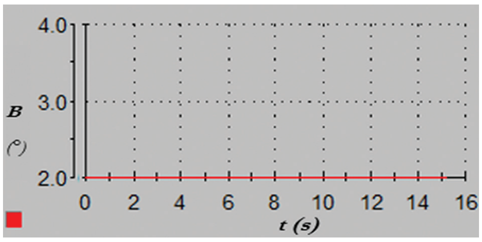


(a) OTC MPPT without with speed control

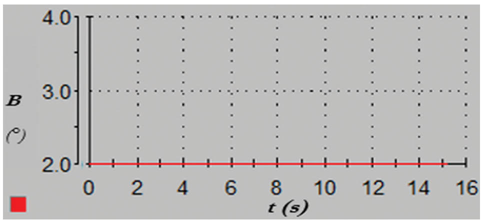


(b) OTC MPPT with speed control

Fig. 6. Wind turbine power (green color) nominal power (red)

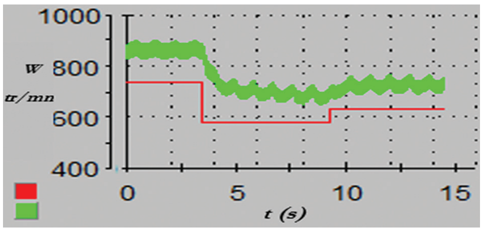


(a) OTC MPPT without speed control

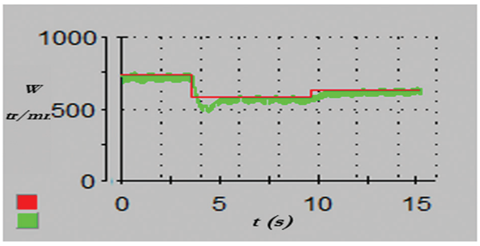


(b) OTC MPPT with speed control

Fig. 7. The Pitch angle

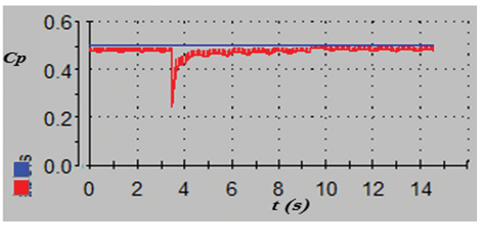


(a) OTC MPPT without speed control

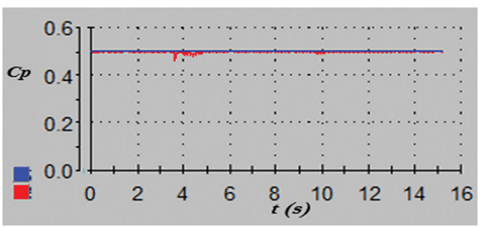


(b) OTC MPPT with speed control.

Fig. 8. Rotor speed (green color) with reference speed (red color)

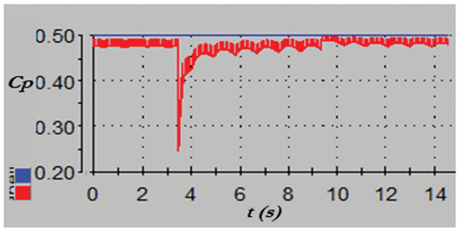


(a) OTC MPPT without with speed control

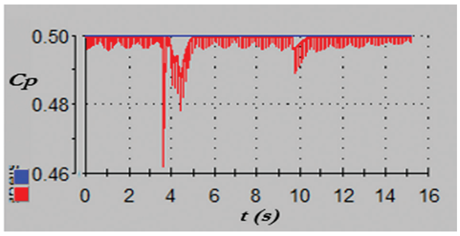


(b) OTC MPPT with speed control

Fig. 9. Power coefficient

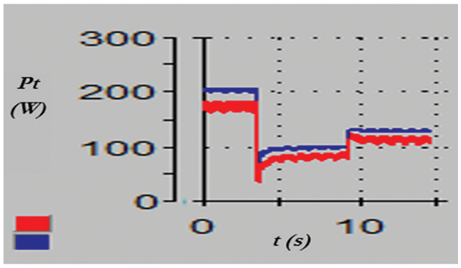


(a) OTC MPPT without with speed control

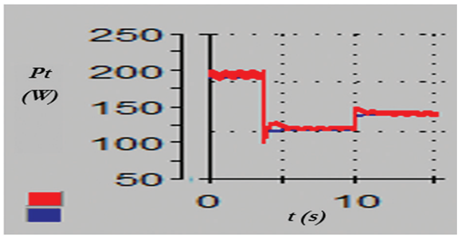


(b) OTC MPPT with speed control

Fig.10. Zoom-in of the power coefficient



(a) OTC MPPT without with speed control



(b) OTC MPPT with speed control

Fig. 11. The wind turbine power: produced (red color), maximal (blue color)

5.1. EXPERIMENTAL RESULT ANALYSIS

In order to confirm the choice of the MPPT control, the wind turbine was put under the same conditions in both cases of MPPT controls. The imposed values of the wind profile were steps of 7m/s, 5.5 m/s, and 6m/s, respectively, as is shown in figures (Fig. 5. a and Fig. 5. b).

Note that the wind turbines power is always lower than its nominal value (250W) in both cases, which requires the operation of the wind turbine at MPPT mode to harvest the maximum available power, figures (Fig. 6. a and Fig. 6. b). Therefore, the setting angle must be maintained at its minimum value ($\beta_{min} = 2$), figures (Fig. 7. a and Fig. 7. b).

Fig. 6. a and Fig. 6. b show that the produced power in the case of the speed control is more stable and

more important in transient mode, especially during the wind speed step variations.

In the case of OTC MPPT with speed control, it is noticed that the speed follows very well its reference, figure (Fig. 8. b). Therefore the power coefficient is well adjusted to its maximum value, figures (Fig. 9. b and Fig. 10. b). It can be also seen that the wind speed is variable. However, the power coefficient is virtually constant at its highest value. consequently harvesting the maximum available power as it is shown in figure (Fig. 11.b); this is from one hand. On the other hand, in the case of OTC MPPT without speed control, the rotational speed is not set at its reference value because it is an open-loop control. Moreover, the power coefficient is slightly lower than its maximum value, which leads to obtain a lower power compared to that of OTC MPPT with speed control, as it is clearly seen in the comparison between the figures (Fig. 10.a and Fig. 10.b), (Fig. 11. a and Fig. 11. b). When the wind speed is 7m/s, it is observed that the power is 175W in OTC without speed control; whereas, in OTC with speed control, the power is maximal, being 200W, which represents an improvement of 25W. When the wind speed changes from 7m/s to 5.5 m/s, Cp and the power decrease to 0.25 and 25W respectively in OTC without speed control. However, in the case of OTC with speed control Cp and the power decrease respectively only till 0.46 and 100W, an improvement of 75W. Based on the comparison, it is clear that the OTC MPPT with speed control is better than that without speed control in the transient state and even in the steady-state, which leads to harvest more power gain and justify the cost of the wind speed sensor, which can be recovered. Moreover, the oscillations during speed variations are reduced in the case of OTC MPPT with speed control. These performances can also be improved by using other speed controllers such as Fuzzy logic control [39], [53].

6. CONCLUSIONS

This paper suggested an experimental comparative investigation between two Optimal Torque MPPT Controls. The first was without Speed Control; whereas, the second was with Speed Control. In order to compare between the performances of each one, both controls have been tested under the same conditions and a similar shape of wind profile. The advantages and disadvantages of each strategy have been discussed.

The validity of the both MPPT controls has been verified by using a wind emulator controlled by Dspace in real time. It was found that the OTC without Speed Control is cheaper and simplest. However, the OTC with speed control was better in its dynamic performances, especially in the case of fast wind speed variations, which leads to harvest more energy and cover the cost of the wind speed sensor. In addition, the proposed OTC MPPT with speed controller decreased the steady-state and improved the oscillation, response time and also it increases the power to an interval of 12,5% to 75% compared to the OTC MPPT without speed control. Furthermore, it has been demonstrated that the applied control strategies can boost the effectiveness of the real wind turbine. This MPPT control encourages its implementation in a real wind turbine under a real wind speed.

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