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Wind Turbine Modeling, Maximum Power Point Tracking (MPPT), and Experimental Validation

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Abstract.
The research presented is driven by the global increase in wind power capacity and the commitment of the scientific community to facilitate its integration into electrical grids. The focus of this study is the modeling of a wind turbine system, beginning with its mechanical components. To ensure the production of power at optimal levels, a control strategy for Maximum Power Point Tracking (MPPT) based on Optimal Torque (OT) has been adopted. The model and control method, developed in Matlab/Simulink, have demonstrated their precision and efficacy through experimental verification using SCADA data acquired from an operational wind turbine.

Key words. Wind turbine modelling, Matlab/Simulink, MPPT, SCADA data, validation.

1. Introduction

The role of a wind turbine is to convert the kinetic energy of the wind into electrical energy. Wind power is a renewable energy source with a number of advantages. It requires no fuel, creates no greenhouse gases, produces no toxic or radioactive waste, and therefore helps combat global warming. It also contributes to better air quality and the fight against global warming.
While the USA and several European countries supported the industrialization of onshore (Denmark, Netherlands, Germany, Spain, among others) and then offshore (UK, Denmark, Germany, Belgium, among others) wind power generation from the early 1980s and 1990s, it is now the Asia-Pacific region, and China in particular, that has dominated the global wind power market for several years, especially in its onshore component. This region accounts for 53% of new capacity (onshore wind) installed in 2018, and 45% of all cumulative capacity installed worldwide at the end of 2018, again onshore, [1].
In 2018, Europe, which developed 59% of the world's new offshore production capacity, was home to 79% of cumulative installed capacity at the end of the same year. China positioned itself in this technology a few years ago and is actively developing it. In 2018, its annual market exceeded that of the UK or Germany, taken separately [2, 3].
The fact that the Asia-Pacific region, and China in particular, will occupy a major in wind power generation sheds new light on the industry and its fundamentals, [4, 5]:
- The incumbent wind turbine (WT) manufacturers (VESTAS, SIEMENS GAMESA, GE, among others) have diversified their manufacturing centers in order to be closer to their new markets, while in 2018 Chinese (GOLDWIND, UNITED POWER, ENVISION) or Indian manufacturers (SUZLON or SENVION consolidated by US investors) were among the top ten suppliers.
- Asia-Pacific is home to the world's leading research and development centres, blade manufacturers, mast builders and the many subcontractors involved in the WT industry;
- This region consolidates the various industrial activities involved in wind power generation (design, construction and assembly of wind energy components), and consequently exerts pressure to drive down the cost of producing a MWh of wind energy.
Enhancing power generation and reducing stress on turbine components represent design goals for

contemporary WTs, achievable through the refinement of control systems. It is, however, a difficult task. The WT aerodynamics have extremely nonlinear features, on the one hand. However, unlike traditional control objectives, wind speed, which is a stochastic quantity that varies in both time and space, is the main external force driving the WT.

To operate a WT at maximum power, it is essential to utilize all of the wind's available power. In this regard, the maximum power point tracking (MPPT) methods are pioneer. Numerous types of MPPT control strategies have been the subject of previous studies, including hill-climb searching (HCS) control [6, 7] (also known as perturbation and observation control), power signal feedback (PSF) control [6, 8, 9], optimal torque (OT) control [6, 10, 11], and Tip Speed Ratio (TSR) control [6, 12]. OT and PSF controls are two of them that are widely utilized, fast, and simple to use [6].

This research just covers OT control because the performance and implementation complexity of these two control approaches are identical [6]. Since access to a real WT is not affordable at any time, the synthesis of a model that reproduces almost the same performance as the real system is very beneficial. It makes the study easier, especially the fault detection, where it is not obvious and common to test and impose a fault on a real WT, while this task becomes doable through a pertinent model. That's why, in this work, the first objective is to make sure that the model used is validated through real SCADA data from a real WT. Then, the second objective is to improve the quality of power production using the OT maximum power point tracking (MPPT) controller, since it is preferred due to its efficiency, simplicity, and speed comparing to other approaches.

The following paper is organized as follows: In Section 2, the principle and modeling of a wind energy conversion system are presented. In Section 3, a maximum power point tracking (MPPT) strategy based on an optimal torque (OT) controller is implemented. The last section is dedicated to experimental validation using SCADA data from a real WT.

2. Wind Turbine Modeling

The wind energy conversion system consists of the turbine, the gearbox and the generator.

The WT captures the wind's kinetic energy and converts it into a torque that turns the rotor blades.

The generator then transforms the mechanical power into electrical power (see Fig. 1).

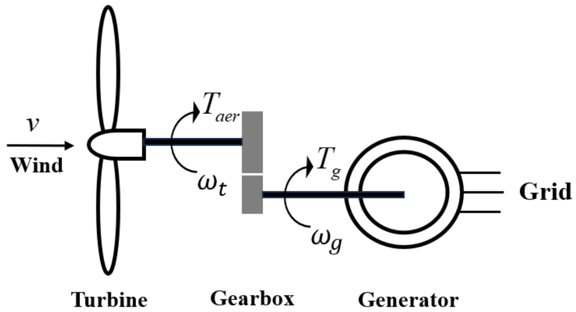

Fig. 1. Wind energy conversion system

The aerodynamic power P_{aer} captured by a WT can be written as follows

$$P_{aer} = C_p(\lambda, \beta)\frac{\rho S v^3}{2} \qquad (1)$$

Where ρ is the air density, v is the wind velocity, $S = \pi R^2$ is the area swept by the rotor blades and R the rotor radius. The aerodynamic torque T_{aer} at the turbine is therefore a function of this power:

$$T_{aer} = \frac{P_{aer}}{\omega_t} = C_p(\lambda, \beta)\frac{\rho S v^3}{2\omega_t} \qquad (2)$$

Where ω_t is the turbine speed and the power coefficient C_p indicates the aerodynamic efficiency of the WT. It depends on the specific speed λ and the blade pitch angle β as shown in Fig.2. It differs from one turbine to another, as it depends on the characteristics of each. This coefficient will be represented throughout this paper by the following analytical equation [13]

$$C_p(\lambda, \beta) = 0.5176(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \qquad (3)$$

Knowing that:

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \qquad (4)$$

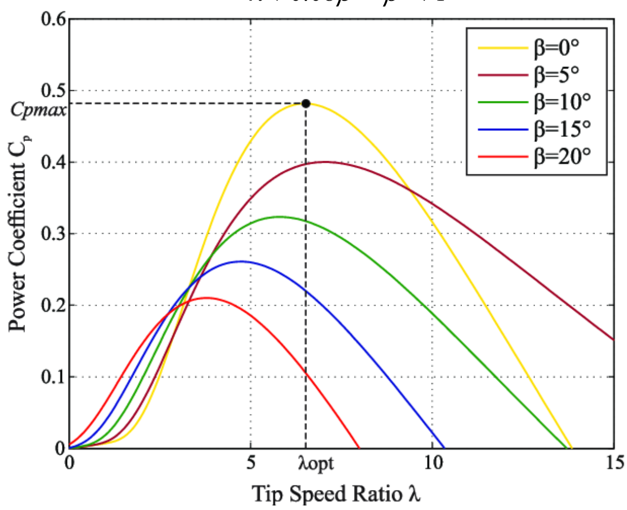

Fig. 2. Power coefficient curves

The generator and turbine are connected by the gearbox. It is used to match the generator's speed to the turbine's speed, and it is frequently represented by the two equations that follow:

$$\omega_t = \frac{\omega_g}{G} \quad ; \quad T_g = \frac{T_{aer}}{G} \qquad (5)$$

Where ω_g is the generator speed, T_g is the generator torque and G is the gearbox gain.

The mechanical shaft is modelled through the following relations:

$$J_g \frac{d\omega_g}{dt} = T_{mec} = T_g - T_{em} - T_{vis} \qquad (6)$$

Where J_g is the generator inertia, T_{mec} is the mechanical torque, T_{em} is the electromagnetic torque and $T_{vis} = f\omega_g$ with f is the coefficient of viscous friction.

The block diagram of the different parts of the WT system is shown in Fig. 3.

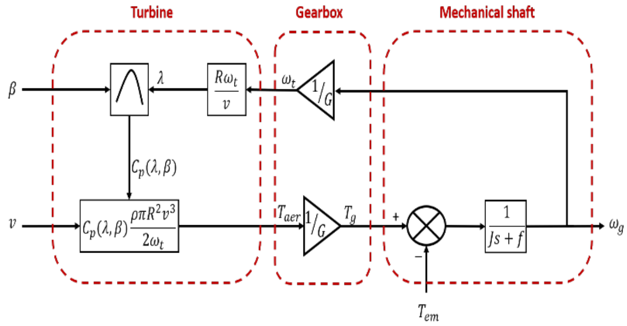

Fig. 3. Block diagram of the wind turbine

Which is equivalent to the following Simulink model (see Fig. 4):

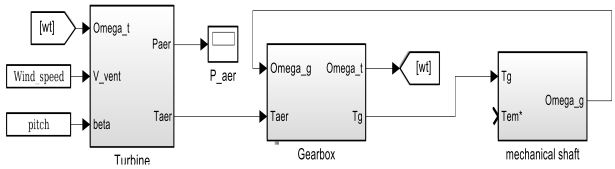

Fig. 4. Simulink model of the wind turbine

In order to improve efficiency and ensure optimal power production, it is necessary to use a control strategy to provide the desired control signal T_{em}^*.

3. Controller objectives

A. Operating regions

The characteristic of a variable-speed WT has four main operating zones, which can be distinguished in Fig. 5. Elaboration of this characteristic is necessary to identify the type of control required by each zone.

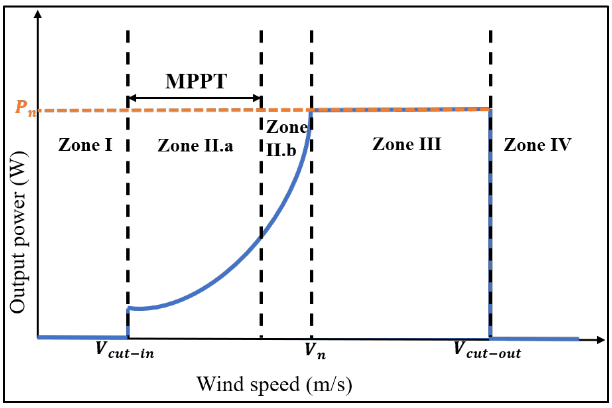

Fig. 5. Operating regions of a variable speed wind turbine

In region I, the turbine cannot start because the wind speed is very low and insufficient (i.e., less than V_{cut-in}), and as a result, the rotational speed and the mechanical power are equal to zero. Once the wind speed exceeds the V_{cut-in} value and remains below a nominal speed V_n, we move to the second operating region, where the objective is to ensure the extraction of maximum power available to have optimal operation by acting on the electromagnetic torque until the wind reaches the nominal speed V_n corresponding to the nominal values of the mechanical power P_n and the nominal rotation speed ω_n. This phenomenon is known as MPPT.

During zone II.b, the wind turbine operates at constant speed. In this region, the turbine speed should no longer be under MPPT control, as its rotation speed can reach around 90% of its rated value, but it must maintain its constant speed until rated power is reached.

In region III, where the wind reaches high speeds above the rated speed, rotation speed and mechanical power must be maintained at their rated values to avoid damaging the turbine. This can be done, for example, by adjusting the WT blades to reduce efficiency (increasing the angle β).

As soon as the wind has reached its maximum value $V_{cut-out}$, the turbine is shut down to prevent it being destroyed. This is the operating mode of zone IV.

The operating modes of a WT may vary depending on the technology and design of the device, but generally, they aim to maximize energy production at least cost by adjusting the rotation speed and angle to the wind conditions.

Control plays an important role in modern WTs. They not only facilitate improved harnessing of the turbine's power capacity but also contribute to the diminution of aerodynamic and mechanical stresses, thereby extending the operational lifespan of the wind turbine components.

The control techniques applied to the wind turbine system are given by the control regions: part-load region (low wind speed) and full-load region (high wind speed).

In the following, we'll start by controlling region II, where the wind is below nominal.

B. Maximum power point tracking (MPPT) control strategy

a. An overview

In recent years, a number of papers have been published that analyze different algorithms and techniques for tracking the maximum power point of wind energy conversion systems (WECs) for different variable speeds. As illustrated in Fig. 6, the techniques are categorized according to the measurement of direct electrical power P_{ele} control (DPC), indirect mechanical power P_{wind} control (IPC), and hybrid in order to obtain the MPPT from WECS.

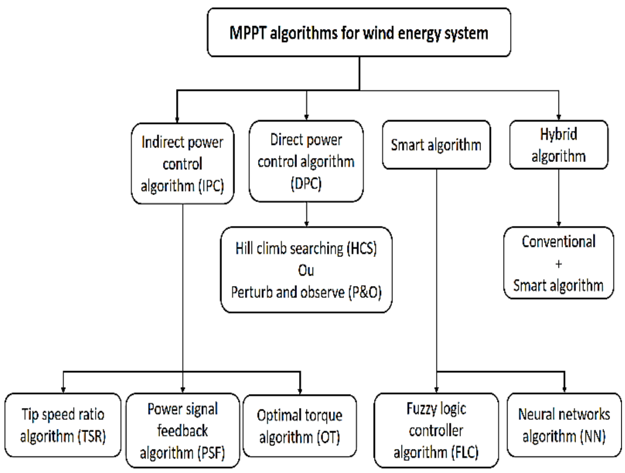

Fig. 6. Classification of different MPPT algorithms

IPC MPPT approaches measure wind speed using anemometers and other sensors. MPPT strategies comprise a variety of algorithms used to control for

WECS, such as the traditional or modified TSR, PSF, and OT algorithms, which use DPC in addition to speed sensors based on capture maximum power point approaches. MPPT methods such as Perturbed and Observed (P&O) or the HCS algorithms do not require wind speed sensors. To overcome the drawbacks of the conventional methods and extract as much energy as possible from WECS, a number of hybrid strategies are available. To optimize the potential of WECS, a range of hybrid algorithms are available that involve the use of intelligent algorithms like neural networks (NN) and fuzzy logic controllers (FLC) [14]. The current generator's torque is controlled by the OT MPPT algorithm, which makes use of optimal torque characteristics for different wind speeds. This approach has the advantages of better tracking speed, simplicity of usage, and increased effectiveness.

Table 1 corroborates and substantiates the selection of this technique for further application in this study.

Table 1. IPC-based MPPT Algorithm Comparison for WECS [15].

MPPT algorithm characteristics	**TSR**	**OT**	**PSF**
Efficiency	High efficiency	High efficiency	Moderate efficiency
Rapidity of convergence.	High	High	High
Complexity	Low complexity	Low complexity	Low complexity
Cost	Very high	Moderate	Moderate
Prior knowledge	Not needed	Needed	Needed
Wind speed measuring sensors.	Yes	No	Yes
Memory requirement	No	No	Yes

b. OT MPPT control strategy applied to the studied wind turbine

The power capture $C_p(\lambda,\beta)$ curve has a unique maximum that refers to the optimal wind power capture (see Fig. 2).

$$C_p^* = C_p(\lambda_{opt}, \beta_{opt}) \qquad (7)$$

Where $$\lambda_{opt} = \frac{\omega_t^{opt} R}{v} \qquad (8)$$

and λ_{opt} is the optimal tip speed ratio, β_{opt} is the optimal pitch angle and ω_t^{opt} is the optimal turbine speed.

The key aim of the MPPT control technique is to get the most power from the wind, and the generator is operated at its highest possible speed. This is done by changing the WT rotation speed when the wind speed is less than the rated value. This ideal speed is reached when the power coefficient is maintained at its maximum value C^*_p as in (7), β is locked at zero and the ratio λ is most effective. To reach this ideal λ, the electromagnetic torque has to be adjusted and approximated using the MPPT strategy and become as in the following equation:

$$T_{em}^* = k_{opt}\,\omega_g^2 \qquad (9)$$

Where $$k_{opt} = \frac{\rho \pi R^5}{2 n_g^3 \lambda_{opt}^3} C_p^* \qquad (10)$$

After adding the MPPT, the model that will be implemented in Matlab/Simulink is schematized as in Fig. 7:

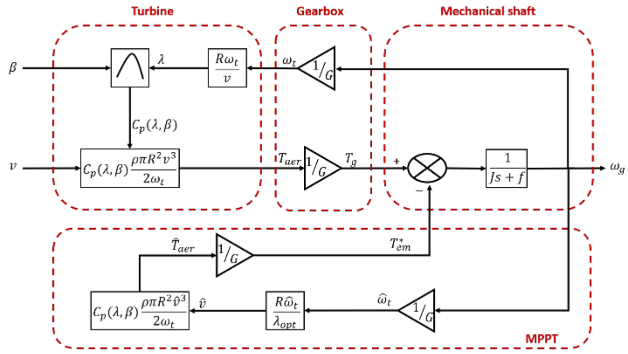

Fig. 7. Wind turbine block diagram with MPPT

According to Fig.8, the power coefficient C_p is kept at its optimal value C_p^* ; 0.45, thereby demonstrating the efficacy of the MPPT controller.

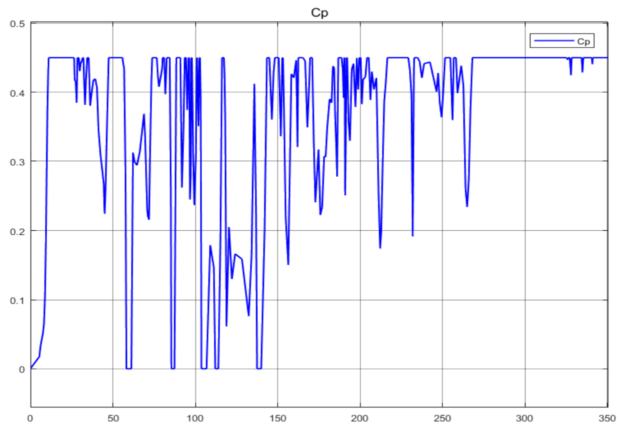

Fig. 8. Power coefficient C_p

4. Validation

The Scada data used to validate the developed model are extracted from the WT located on the campus of the Dundalk Institute of Technology (DKIT) in Ireland (See Fig. 9).

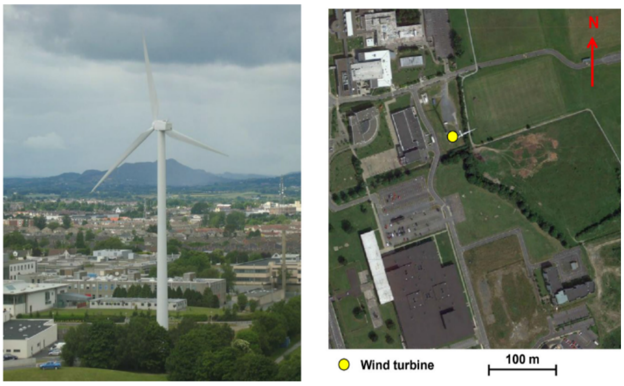

Fig. 9. Real wind turbine location

As inputs for the developed Simulink model, we used the wind speed and pitch angle values of the actual WT, as shown in Fig. 10.

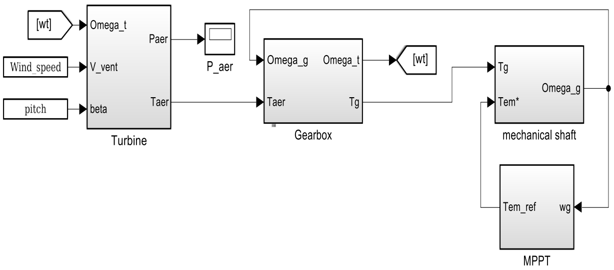

Fig. 10. Wind turbine simulink model with MPPT

The simulation results show the evolution of both the turbine and generator speeds, which are illustrated in Fig. 11 and Fig. 12, respectively.

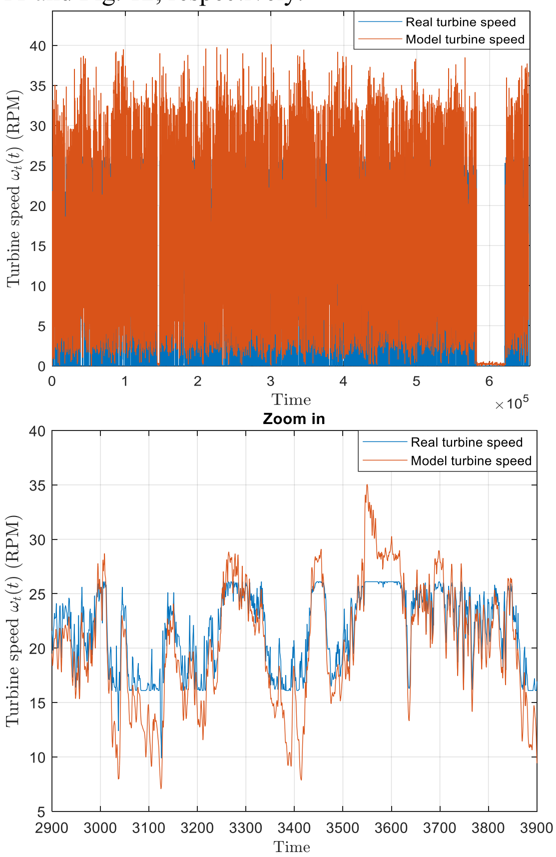

Fig. 11. Validation result of the turbine speed

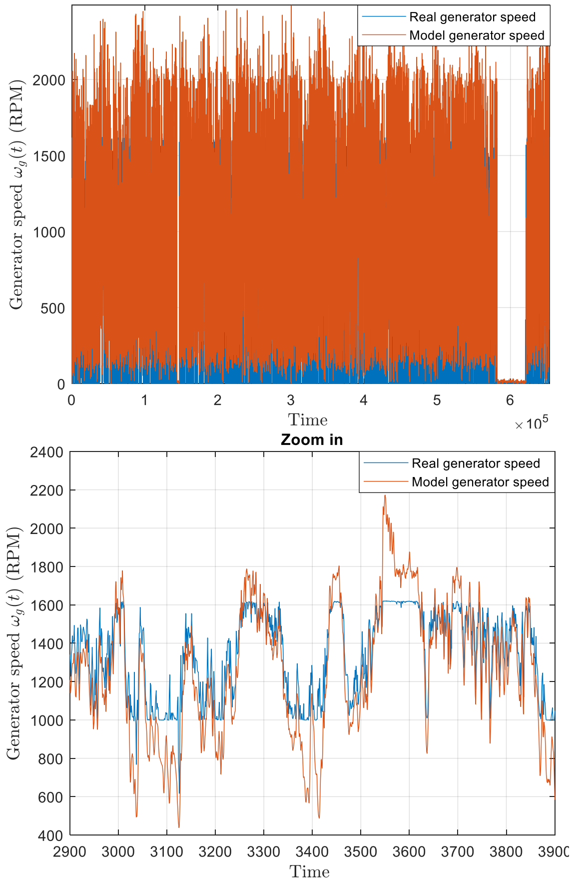

Fig. 12. Validation result of the generator speed

Notably, a gearbox change out occurred between October 4 2018 and July 27 2019, during which no positive electrical power generation was observed, that justifies the data gap around time ~ 6e5 in both Fig.11.a and Fig.12.a, which is equivalent to the period mentioned above. According to Fig.11.b and Fig.12.b, it is worth noting that the real turbine speed and the modelled one gave very close results, which prove the accuracy and the relevance of the model and the efficiency of the MPPT strategy implemented. The same notice for the generator speed.

5. Conclusion

In this study, emphasis is placed on both experimental validation and maximizing power extraction from the available wind speed, as this approach facilitates a closer approximation to the actual dynamics of the system. Consequently, this aids in the enhancement of efficiency and the assurance of optimal energy production. The simulation outcomes attest to the significance of this research, where the validation results show an acceptable error between the modeled and real parameters, and on the other hand, the power coefficient is kept at its optimum values, so the MPPT objective is reached.

Future work includes expanding the model to incorporate the electrical aspects, thereby encompassing the entire system. Subsequently, the objective will be to implement a fault detection strategy to maintain uninterrupted operations and energy production.

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