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Conference paper

MPPT Optimal Torque Control Strategy for a PMSG-based Wind Turbine Emulator

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ABSTRACT

A wind turbine emulator is a valuable tool, which enables real-time physical simulation of a wind turbine behavior using a dedicated experimental test setup, providing a controlled environment for research and development purposes. One significant advantage of using this tool is its ability to test control algorithms designed to maximize power extraction from the wind turbine. This paper continues previous work on developing a small-scale variable-speed wind turbine emulator based on a Permanent Magnet Synchronous Generator for stand-alone applications (Benhacine et al., 2024). This paper presents enhancements made to the emulator. These improvements facilitate the assessment of a maximum power point tracking control strategy designed to optimize power extraction from the wind turbine.

1. INTRODUCTION

In remote locations where access to the power grid is impossible or not economically viable, distributed generation systems based on renewable energy sources are often utilized (Khare, Nema, & Baredar, 2016; Simoes & Farret, 2008). In particular, small wind turbines with an output power rating of less than 10 kW have proven to be a compelling option to meet the load demands of standalone sites (Alnasir & Kazerani, 2013; Satpathy, Kishore, Kastha, & Sahoo, 2014; Wood, 2011). Furthermore, small wind turbine technology is not yet as advanced as the current development stage of large-power wind turbines. To study and enhance the small wind turbine performance, extensive research is conducted on wind emulator test benches equipped with low-power electric generators. Indeed, wind turbine emulator (WTE) provide a controlled environment for testing and refining control algorithms, offering benefits

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such as real-time simulation, cost-effective development, enhanced safety, and flexibility in exploring different scenarios. They enable developers to optimize control strategies without the need for costly field testing, ensuring improved performance and reliability of wind energy conversion systems. This flexibility enables researchers to explore a wide range of design options and optimize control strategies for specific applications (Abdallah, Arafa, Shaltot, & Aziz, 2018; Benhacine et al., 2024; Benzaouia et al., 2021; Dekali, Baghli, & Boumediene, 2019; Diana, Emerson, Jean, Rafael, & Carlos, 2016; Martínez-Márquez et al., 2019; Moussa, Bouallegue, & Khedher, 2019; Sokolovs, Grigans, Kamolins, & Voitkans, 2014). In particular, WTEs can be used for testing Maximum Power Point Tracking (MPPT) control strategies to extract the maximum available power from the wind turbine. They provide a controlled environment where different MPPT algorithms can be evaluated efficiently, flexibly, and cost-effectively (Hsu, Lu, & Liaw, 2021; Kortabarria et al., 2014; Liu, Locment, & Sechilariu, 2015). On the other hand, these MPPT control algorithms differs in terms of accuracy and time required to reach the desired reference (Dali, Abdelmalek, Bakdi, & Bettayeb, 2021; Hannachi, Elbeji, Benhamed, & Sbita, 2021; Haque, Negnevitsky, & Muttaqi, 2010).

This paper is a continuation of the ongoing work on developing a small-scale variable-speed WTE based on a Permanent Magnet Synchronous Generator (PMSG) for stand-alone applications (Benhacine et al., 2024). The proposed WTE is built with standard industrial components, including a variable speed drive and a programmable logic controller (PLC), and notably operates without a torque sensor, making it a cost-effective, sensorless solution. This paper outlines the enhancements made to the proposed emulator to facilitate the evaluation of control algorithms aimed at maximizing power extraction from the wind turbine. To accomplish this goal, an optimal torque control strategy is deployed on the PLC, employing a proportional–integral controller to effectively track and maintain the reference torque.

2. HARDWARE IMPLEMENTATION OF THE CONTROL STRATEGY

The aerodynamic performance of the Whisper 100 wind turbine and the aerodynamic model were established and detailed in (Benhacine et al., 2024). The developed model forms the basis of wind turbine simulations and helps in the design and control of wind energy conversion systems.

To perform the physical implementation of the aerodynamic performance of the Whisper 100 wind turbine, a laboratory test bench was used. Then an experimental validation an open loop control was studied (Benhacine et al., 2024). The synoptic diagram and the experimental test bench are shown in Figs. 1 and 2 respectively. In the open loop control operating mode, the torque variation of the emulated turbine was achieved by changing the duty cycle of the active switch of the buck converter, which makes it possible to change its dc input voltage, which in turn permits to change the rotational speed.

In this study, the experimental validation with the laboratory test bench will be verified for the closed loop control mode.

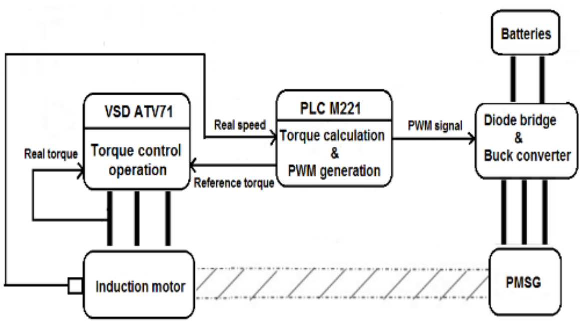

Fig 1. Block diagram of the experimental test bench

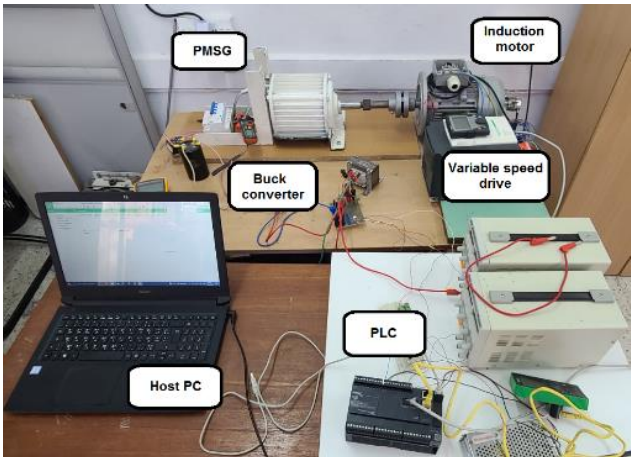

Fig 2. Photograph of the experimental test bench

From the results discussed in Benhacine et al. (2024), it was shown that the torque value varies according to the operating point. That is, the torque of the emulated turbine is not controlled. However, introducing a closed loop control for the torque can lead to tracking and extracting the optimal torque from the emulated wind turbine, this will permit the wind turbine to operate in the Maximum Power Point Tracking (MPPT) mode, as will be shown in this paper.

This control strategy, designed to regulate the electromagnetic torque at an optimal value, is referenced as MPPT optimal torque (OT) control strategy. To maximize the power extraction from the wind turbine, the wind turbine must operate at the optimal power coefficient (C_{p_opt}). To maintain this condition, the rotor speed must be kept at the optimal tip-speed ratio (λ_{opt}). As wind speed changes, the rotor speed should be adjusted accordingly. Therefore, the optimal torque (T_{opt}) can be calculated at the optimal operating point defined by the pair (C_{p_opt}, λ_{opt}) and is derived from the optimal power (P_{opt}) as follow (Haque et al., 2010):

$$P_{opt} = \frac{1}{2}.\rho.S.C_{p\_opt}(\frac{w_{t\_opt}R}{\lambda_{opt}})^3 = K_{opt}w_{t\_opt}^3 \quad (1)$$

where $K_{opt} = \frac{1}{2}.\rho.S.C_{p\_opt}.(\frac{R}{\lambda_{opt}})^3$ and $w_{t\_opt} = \frac{\lambda_{opt}}{R}V_w$

Hence, the optimum torque T_{opt} is given by

$$T_{opt} = \frac{P_{opt}}{w_{t\_opt}} = K_{opt}w_{t\_opt}^2 \quad (2)$$

In order to operate the torque control strategy in a closed-loop manner, the values of the rotor speed and the real torque are estimated with the VSD and send to the PLC, as illustrated in Fig. 3. Hence, the difference between the optimum torque calculated from Eq. (2) and the real torque modulates the duty cycle of the active switch via a Proportional-Integral (PI) controller.

This approach offers the advantage of controlling the input voltage of the buck converter through a PWM signal generated by the PLC, wherein a PI control is programmed to achieve and maintain the optimum torque. The configuration of the PI controller inside the PLC is facilitated through a PID

Graphical Assistant within the EcoStruxure Machine Expert Basic software, as depicted in Fig 4. This dynamic graphic updates according to the configuration, aiding in visualizing the construction of the PID function.

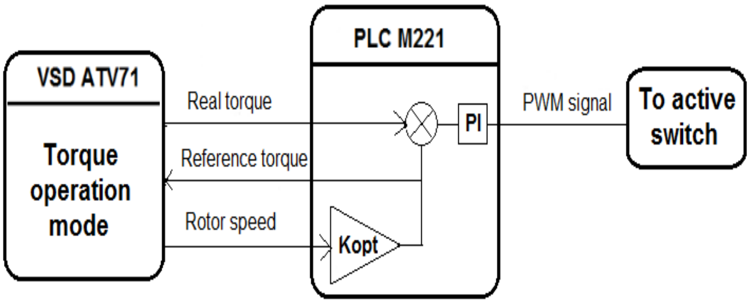

Fig 3. Functional diagram of the MPPT OT control strategy

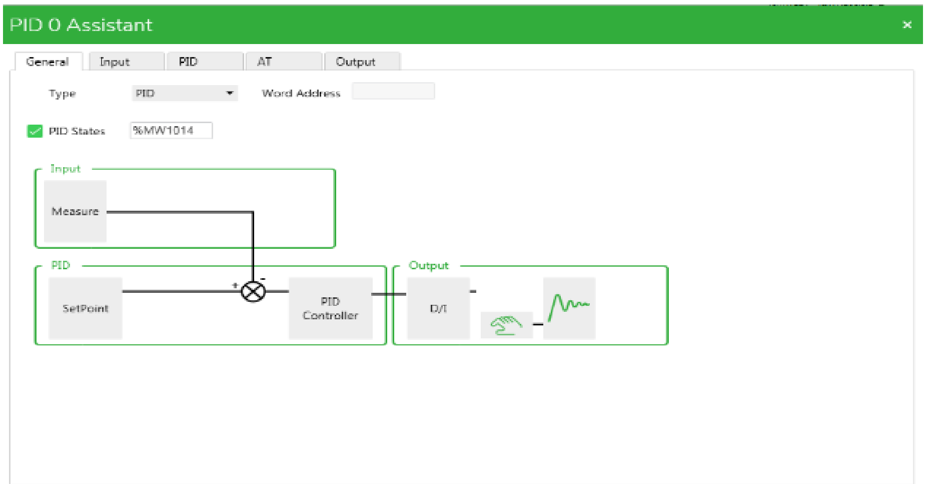

Fig 4. Screen of the PID Graphical Assistant

3. RESULTS AND DISCUSSION

The proposed optimal torque control strategy is evaluated under variable wind speed conditions ranging between 5 m/s and 6.5 m/s, as depicted in Fig. 5.a. Observation of Fig. 5.b and Fig. 5.c. reveals that the controller attempts to follow the desired torque and power reference values. Although there are slight deviations between the actual and reference values, these differences remain small, primarily due to suboptimal tuning of the PI controller parameters. Meanwhile, the rotor speed continuously adapts to variations in wind speed, as illustrated in Fig. 5.d.

Furthermore, the results presented in Fig. 5.e. demonstrate a close alignment between the experimental operational points and the theoretical turbine's mechanical power curves (dashed lines) across varying wind speeds. This alignment reflects the attainment of the optimal operating point defined by the pair $(C_{p\_opt}, \lambda_{opt})$, which enables maximum power extraction from fluctuating wind conditions.

Specifically, the power coefficient is noted as 0.42 and the tip speed ratio as 5.7, as indicated in Fig. 5.f and 5.g, respectively. The (C_p, λ) curve illustrated in Fig. 5.h also confirms these results. These findings validate the efficacy of the proposed torque control strategy.

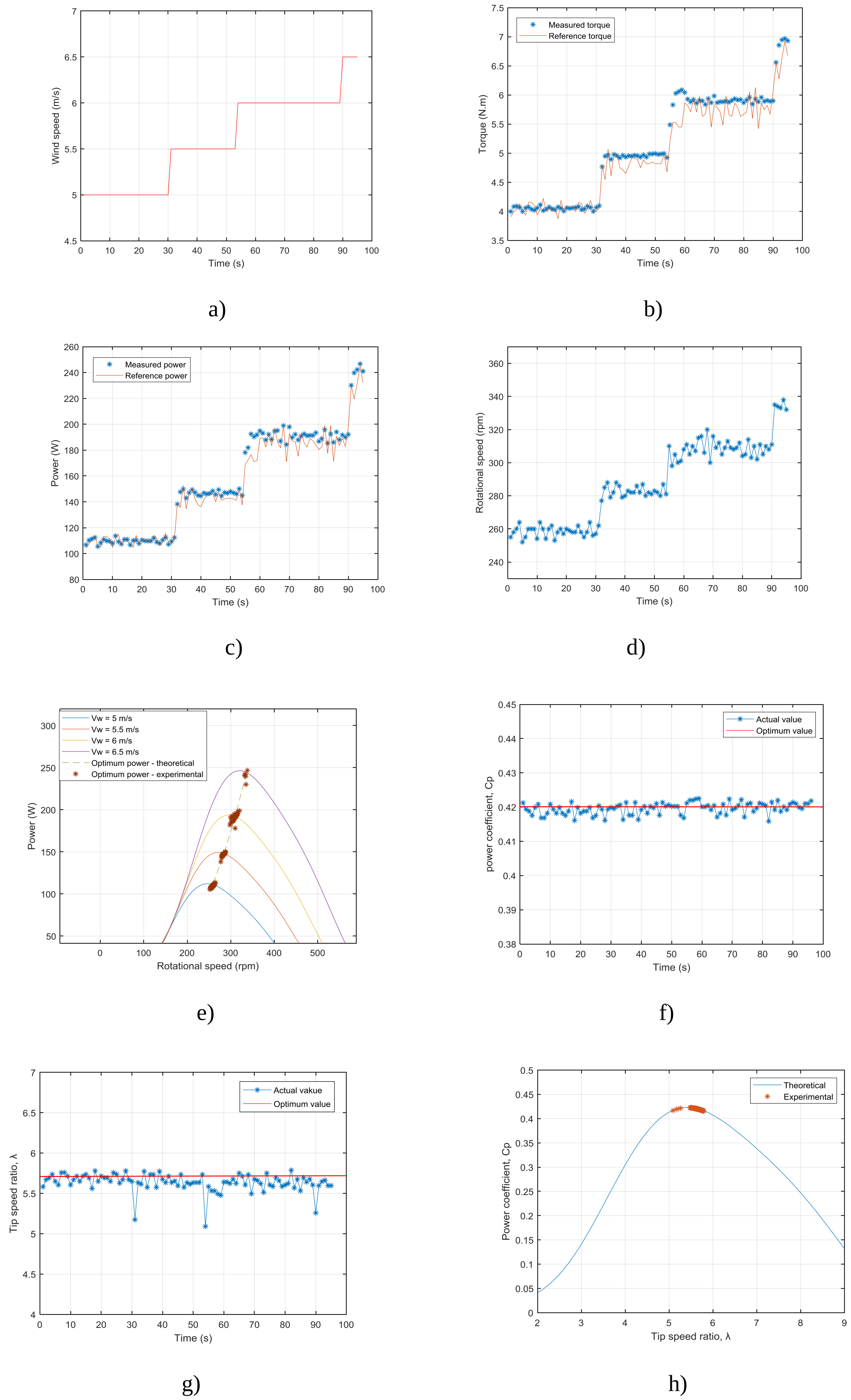

Fig 5. Performances of the proposed MPPT OT control strategy: a) Wind speed profile, b) Mechanical torque, c) Mechanical power, d) Rotational speed, e) Power-speed curve, f) Power coefficient, g) Tip speed ratio and h) Power Coefficient-Tip speed ratio curve

4. CONCLUSION

In this research paper, an MPPT optimal torque control strategy is proposed and implemented on the PLC that maximizes power extraction from the wind turbine. The advantage of the proposed approach is that the integrated control functions within the PLC eliminate the need for additional electronic boards. This proposed approach as well as the user-friendly design of test bench makes it ideal for academic needs, particularly for electrical engineering and wind energy conversion courses.

NOMENCLATURE

R	Blade radius [m]	V_w	Wind speed [m/s]
S	Surface swept by the turbine [m^2]	ρ	Air density [kg.m^{-3}]
P_{opt}	Optimal power [W]	λ_{opt}	Optimal Tip speed ratio
T_{opt}	Optimal torque [W.s. rad^{-1}]	C_{p_opt}	Optimal wind turbine power coefficient
W_{t_opt}	Optimal wind turbine angular speed [rad/s]		

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