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Speed controller efficiency of the TSR based MPPT of a variable speed wind power system

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Abstract—This paper compares the usefulness of linear and nonlinear control laws applied in MPPT based on the TSR algorithm in the wind power system. The main idea of this paper is to show the improvement brought by the higher order sliding mode control based on Supertwisting compared to the conventional PI to mitigate the chattering phenomenon, cancellation of the hyperlink between the controller parameters and the mathematical model of the system and the reduction of the sensitivity to external disturbances. The results obtained confirm the effectiveness of the proposed control laws during all the operating modes of the variable speed wind power system in extracting the available maximum aerodynamic power.

Keywords—maximum power point tracking; tip speed ratio; PI controller; sliding mode control; supertwisting

I. INTRODUCTION

Variable speed wind systems can adjust the speed of rotation during changes in wind speed using a partial scale power electronic converter. This concept is based on a double fed induction generator (DFIG) configuration (Figure 1). In this topology, the DFIG rotor is connected to the power grid through partial rate power converters called machine side converter (MSC) and grid side converter (GSC), while the stator of the DFIG is directly connected to the grid through a transformer. The MSC has the role of controlling the rotor currents, torque and rotor speed of the DFIG, while the GSC controls the power flow between the grid and the DFIG rotor [1], [2].

In order to improve the control performance of the wind energy conversion system, we will investigate two control strategies. We take into account the nonlinearities of the model. The first method uses the conventional PI controller, the second is based on a higher order sliding mode control [3].

The first order sliding mode control has many advantages, such as high robustness and simple design, but faces some drawbacks such as the chattering phenomenon due to the existence of a discontinuous term caused by the sign function in the control input, which contributes to additional heating of the electrical elements and windings and leads to high mechanical stress, thus limiting the practical implementation [4]. Several literatures has proven that higher-order sliding mode can reduce chattering problems with great efficiency

without having limited control accuracy performance and finite-time convergence properties.[5].

The second-order sliding mode control includes the Supertwisting algorithm among its classes, which is applicable to systems that have a relative degree of 1, this technique acts on the higher order time derivatives of the sliding manifold, [6].

The focus of this work is to improve the efficiency of the MPPT by improving the performance of the speed control loop, and consequently, to increase the production of the generated power.

The sections of this work are presented as: Section II describes the static-dynamic wind turbine model. After, the proposed control techniques were investigated in section three. The results obtained were analyzed and interpreted in the following section. The paper ends with conclusions.

II. THE STATIC-DYNAMIC WIND TURBINE MODEL

The simplified wind turbine model can be generalized to two main sub-models, a static model that defines the available power of the wind system and a dynamic model that describes the mechanical behavior of the aerodynamic system. Along with the diameter and altitude of the wind blades, the power coefficient C_p are major factors in characterizing the energy productivity of the system. This parameter is often given by manufacturers and gives the ratio between the angle of inclination of the blade β and the relative speed of the turbine λ [7].

$$C_p = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) \exp\left(\frac{-21}{\lambda_i}\right) + 0.0068\lambda \quad (1)$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

With:

$$\lambda = \frac{R\Omega_t}{V} \quad (2)$$

Where R is the blade radius, V the wind speed, and Ω_t is the mechanical speed of the system.

The dynamic model shows the opposing forces applied by the aerodynamic torque T_a and the torque of the generator T_{em}

on the turbine shaft passing through the gearbox. The dynamic model with one mass that brought back on the slow shaft is made up of single inertia and a single friction coefficient gathering all the external friction coefficients. The fundamental mathematical relation of this model is given by [8]:

$$J_t \frac{d\Omega_t}{dt} = T_t + GT_{em} - f\Omega_t \quad (3)$$

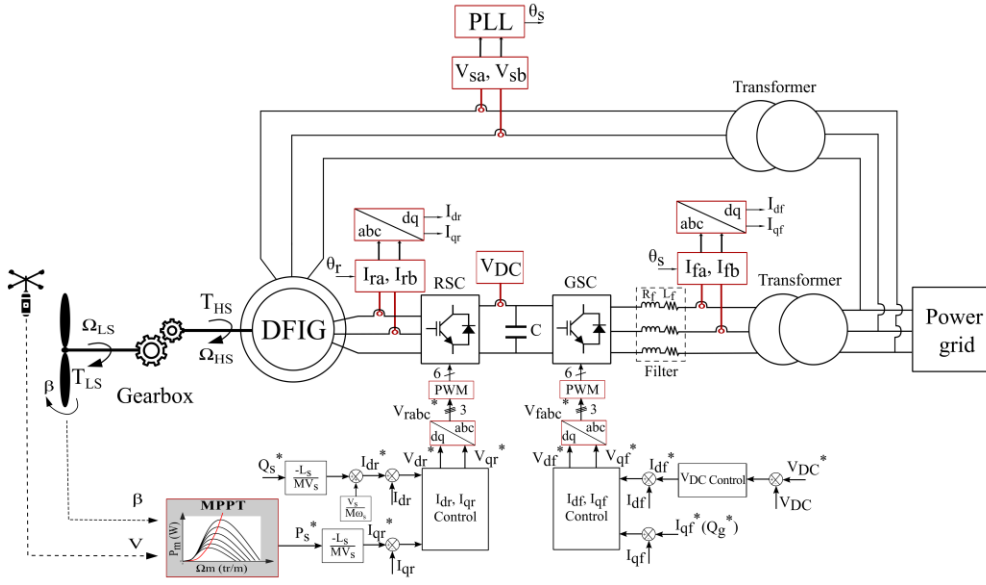


Fig. 1. Control structure of the DFIG - variable speed wind power system

Where J_t is the moment of inertia of the turbine and f is the friction coefficient of the system and G is the gear ratio. Figure 2 shows the distribution of forces applied to the aerodynamic drive shaft.

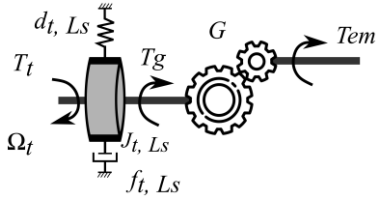


Fig. 2. Dynamic model with one mass brought back on the slow shaft

III. APPLIED TSR BASED MPPT FOR THE WIND POWER SYSTEM

Considering the rotor speed and power output limits of a wind system, the variable speed wind turbine operating zones includes three important zones [2].

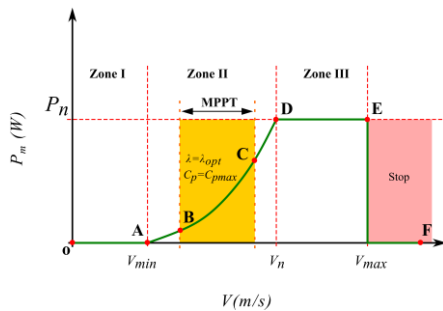


Fig. 3. Operating zones of a variable speed wind turbine

The Tip Speed Ratio (TSR) based Maximum Power Point Tracking (MPPT) is used in wind power systems to maintain the speed ratio λ at its an optimal value, and thus obtain the maximum power coefficient in order to extract the maximum dynamic power available on the drive shaft [9]. The principle of this technique is the adjustment of the rotor speed according to the variation of the wind speed. The rotor speed varies proportionally to the wind speed. The wind turbine is controlled at the optimal turbine speed generated by the controller based on the current wind speed [10].

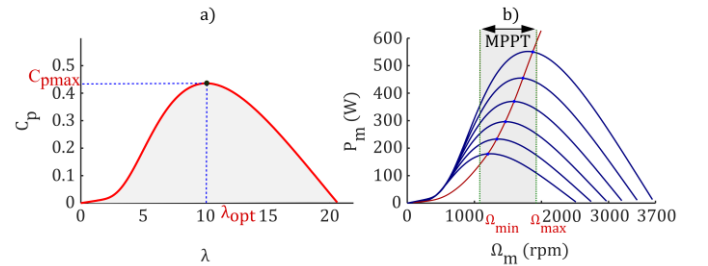


Fig. 4. TSR based MPPT principle, (a) TSR based MPPT principle (b) TSR based MPPT operating zone

A. Applied TSR based MPPT with PI structure

The PI controller is used to reduce the error between the optimal speed reference and the applied speed. The narrow operating mode zones present the big drawback of this algorithm, as well as the additional cost of the anemometer which is very important to provide the best wind speed measurement [11].

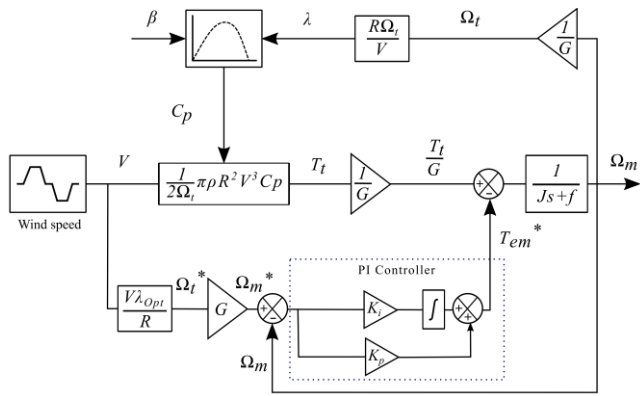


Fig. 5. MPPT based TSR using PI controller

The PI speed controller output impose the electromagnetic torque reference T_{em}^* . The PI controller ensures the convergence of the speed to its reference. The parameters of the PI controller are calculated according to the mechanical characteristics of the generator. Parametric variations of these parameters can limit controller performance

B. Applied TSR based MPPT with SMCST structure

The Super Twisting algorithm is a second-order class of the sliding mode, which has the possibility of reducing chattering problems compared to the sliding mode of the first order, it can be applied directly when the system is of a relative degree of the first, it is applicable to the system which has a relative degree of 1[12]. The algebraic formula for the mechanical speed control law is given by:

$$T_m^* = -\lambda |S_{\Omega_m}|^{0.5} \text{Sign}(S_{\Omega_m}) + \int -\alpha \text{Sign}(S_{\Omega_m}) \quad (5)$$

The general diagram of the SMC Supertwisting speed control technique is simplified in the following figure.

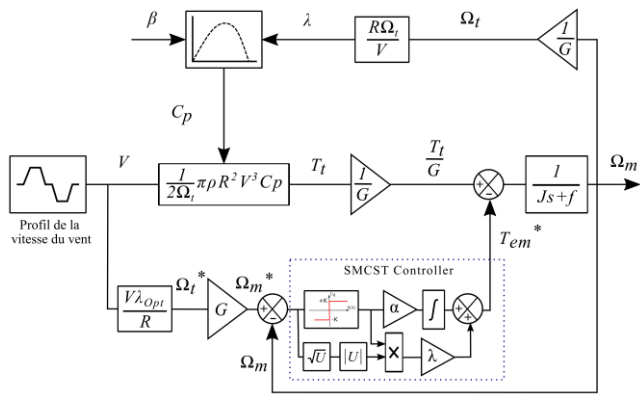


Fig. 6. MPPT based TSR using SMCST controller

IV. RESULTS AND DISCUSSIONS

In this part, we compare, by simulation, the reliability of the proposed control laws for applying the MPPT algorithm based on the TSR principle. The applied wind speed profile (Fig. 7) provides the slow transmutation between the operating

modes, the latter gives good behavior for the control loop robustness test.

All the simulation tests were carried out on a low power wind system, table II gives its nominal parameters.

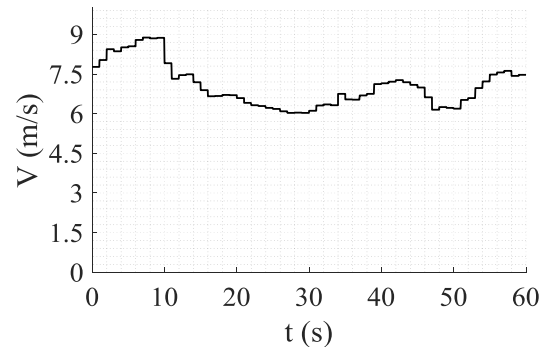


Fig. 7. Applied wind speed profile

Better tracking accuracy is achieved by both controllers (Fig. 8), except for a slight disparity when increasing or decreasing the reference.

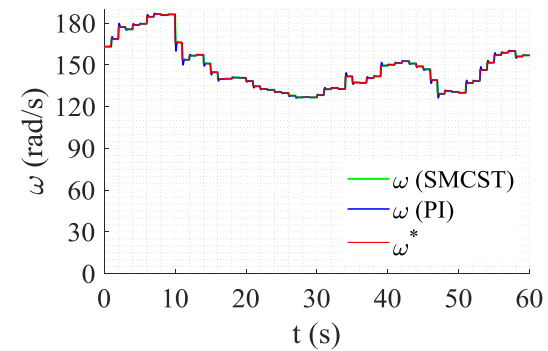


Fig. 8. Tracking accuracy of the speed control loop

The tracking error of the speed control loop is minimized thanks to the performances of the controllers (Fig. 9); thus, they are able to control correctly. However, fluctuations and high loads can lead to an imbalance of the device which require a mechanical system to absorb these noises.

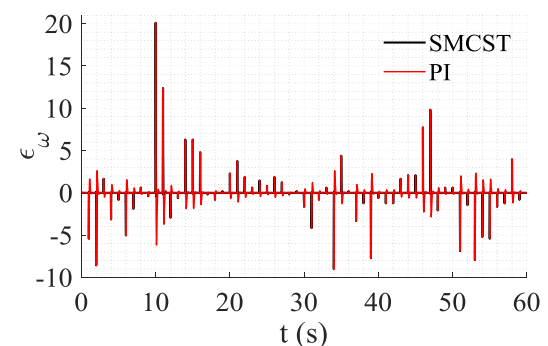


Fig. 9. Tracking error of the speed control loop

The instantaneous changes in the wind speeds generate a sudden variation in the reference torque T_{em}^* to regulate the speed. The quality of the power and the torque (Fig. 10 and

11) is affected. In the case of SMCST controller, this phenomenon is amplified, because of the control law discontinuity. This gives more advantage to the linear controller in this kind of systems.

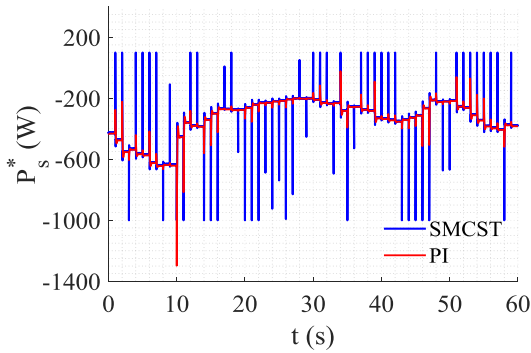


Fig. 10. Resultant active power reference

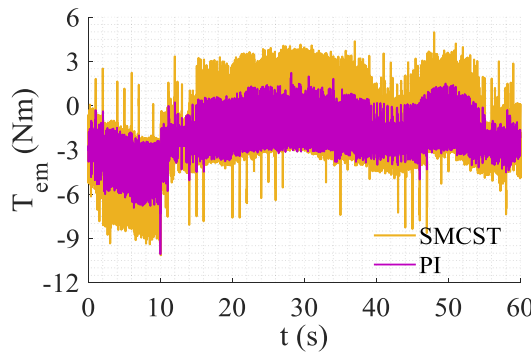


Fig. 11. Resultant electromagnetic torque

The performance of the system control can be quantitatively evaluated using performance indices, such as the Integral Absolute Error (IAE) and the Integral Square Error (ISE). These indices are used for the purpose of quantifying the dynamics of the error between the setpoint and the system output, where:

$$\begin{cases} IAE = \int_0^t |e(t)| dt \\ ISE = \int_0^t (e(t))^2 dt \end{cases} \quad (5)$$

The following table I shows the EAI and ESI values obtained from simulation results. These indices indicate the stability of the system as a function of the accumulation of controller output errors, the closer these values are to zero, the better the control.

TABLE I. CONTROLLERS INDICES

	PI	SMCST
IAE	13.57	22.74
ISE	575	670

In general, the statistical comparison gives a proximity between the indices of the two controllers, with a slight advantage of the linear PI controller.

CONCLUSION

In this paper, a comparative study is conducted to realize the MPPT based on the TSR technique. Linear and non-linear control laws are applied to the speed control loop to manage the extraction of the maximum power.

The effectiveness and applicability of the proposed controllers have been evaluated by simulation tests. The main advantages of the higher order sliding mode control are the good tracking accuracy, the ease of the numerical implementation of the control algorithm, as well as the total independence of the controller gains to the parameter variations of the system. Nevertheless, chattering remains the major disadvantage of this technique which may present physical limitations for real time experimental realization.

The comparison between the results of PI control and those of supertwisting one shows a great resemblance based on the dynamic behavior. However, even if the sliding mode regulation has the advantage of robustness and ease of implementation, the PI controller is distinguished by lower error indices, which explains the wide use of this type of controller in wind power systems and also in other industrial applications. The advantages shown by this paper confirm that conventional PI controllers will be largely sufficient for this type of system.

APPENDIX

TABLE II. WIND TURBINE SIETINGS

Setting	Parameter
Air density	1.225
Gearbox ratio	7
Blade radius	3 m
Nominal speed	1500 rpm
Nominal power	1.5 kW

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