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Non-linear Control of a Wind Energy Conversion System Based on a Permanent Magnet Synchronous Generator

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- INTRODUCTION
- ARCHITECTURE AND MODLING OF STUDIED SYSTEM
- DEVELOPMENT OF CONVENTIONAL VECTOR CONTROL BASED ON PI CONTROLLER
- DEVELOPMENT OF ROBUST NONLINEAR CONTROL BASED ON SECOND ORDER SLIDING MODE CONTROLLER
- CASE STUDY AND SIMULATION RESULTS
- CONCLUSION

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INTRODUCTION

- The current political, economic and energetic situation is very favorable to renewable energy development. In this context, wind energy is one of the most promising renewable power generations.

- Due to the intrinsic nonlinear characteristic of wind turbine and electric generators, a robust control insensitive to external perturbation is needed to control the production system.

- The objective of this robust control strategy is to insert a control system for pitch angle, to ensure maximum power extraction even for low wind speed, to regulate both the reactive and active power independently and to ensure the operation of system at a unity power factor.

INTRODUCTION

- In this context, this article deals a comparative study between two control strategies applied to a wind energy conversion system to guarantee a robust control strategy which gives a good performance despite the wide range of wind speed variations, of external disturbances and parametric uncertainties of the different components of the wind turbine.

A classical vector control based on PI controllers will be proposed to control our conversion system. The purpose of this command is to show the sensitivity of PI controllers to high large range of wind speed variations and the nonlinearity of the studied system.

To address this problem, a control strategy by sliding mode of higher order was implemented on the basis of the super-twisting algorithm. It has a good performance, because of the insensitivity to external disturbances and to system nonlinearity.

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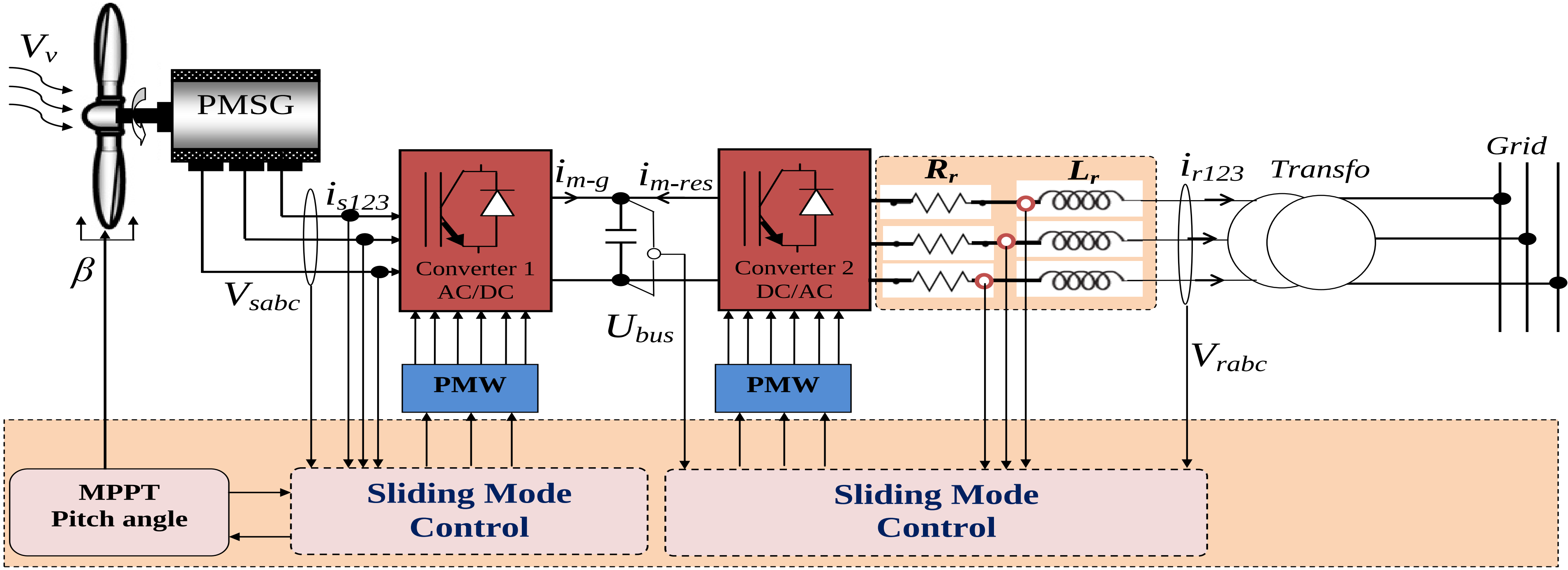
ARCHITECTURE AND MODLING OF STUDIED SYSTEM

Architecture



We consider a wind power generation system, comprising a variable speed wind energy conversion system driving a permanent magnet synchronous generator (PMSG) used as a principal source. This source is connected to a direct current (DC) bus through AC/DC rectifier . The DC bus power is transferred to the electrical grid through a DC/AC inverter and a filter.

ARCHITECTURE AND MODLING OF STUDIED SYSTEM

Wind turbine modeling and control

The aerodynamic power (P_w) that can be extracted from the wind and the aerodynamic torque *Γw* are determined by the following expressions:

$$P_w = \frac{1}{2}\rho\pi R^2 V_w{}^3 C_p(\lambda,\beta)$$

$$\Gamma_w = \frac{P_w}{\Omega_m} = \frac{1}{2}\rho\pi R^3 V_w{}^2 C_p(\lambda,\beta)/\lambda$$

Where Cp(λ,β) is the power coefficient given by (1) corresponding to the aerodynamic performance of the turbine:

$$C_p(\lambda,\beta) = 0.5179\left(98\delta - 0.4\beta + 5\right)e^{-21\delta} + 0.068\lambda$$

$$\delta = \frac{1}{\dfrac{1}{\lambda + 0.089} - \dfrac{0.035}{\beta^3 + 1}} \qquad (1)$$

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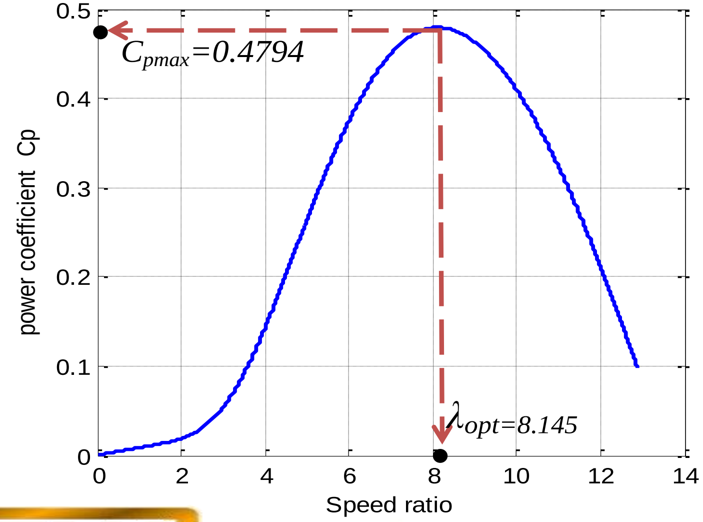
Wind turbine modeling and control

An approximate example of evolution of the power coefficient $C_p(\lambda, \beta)$ according to the speed ratio λ for pitch angle β equal to zero is shown in this Figure. An increase of the pitch angle leads to a decrease in the coefficient C_p. For a given orientation of the blades, the characteristic reaches a maximum for a particular value of the speed ratio. The power coefficient of a wind reflects the proportion of energy from the wind captured by the turbine. Theoretically, it is limited to 0.59, which means that it is possible to extract a maximum of 59% of the kinetic energy in the wind. In practice, it does not exceed 0.49 for the best wind turbine.

In this case, the maximum value of C_p (C_{pmax}=0.4794) is corresponding to the optimal value of λ (λ_{opt}=8.145). (1) gives the expression of the maximum power obtained by using the MPPT strategy:

$$\begin{cases} P_{MPPT} = C_{em-MPPT}\Omega_m & (1) \\ C_{em-MPPT} = \dfrac{1}{2}\dfrac{\rho\pi R^5 C_{p-\max}}{\lambda_{opt}^{\ 3}}\Omega_m^{\ 2} \end{cases}$$



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DEVELOPMENT OF CONVENTIONAL VECTOR CONTROL

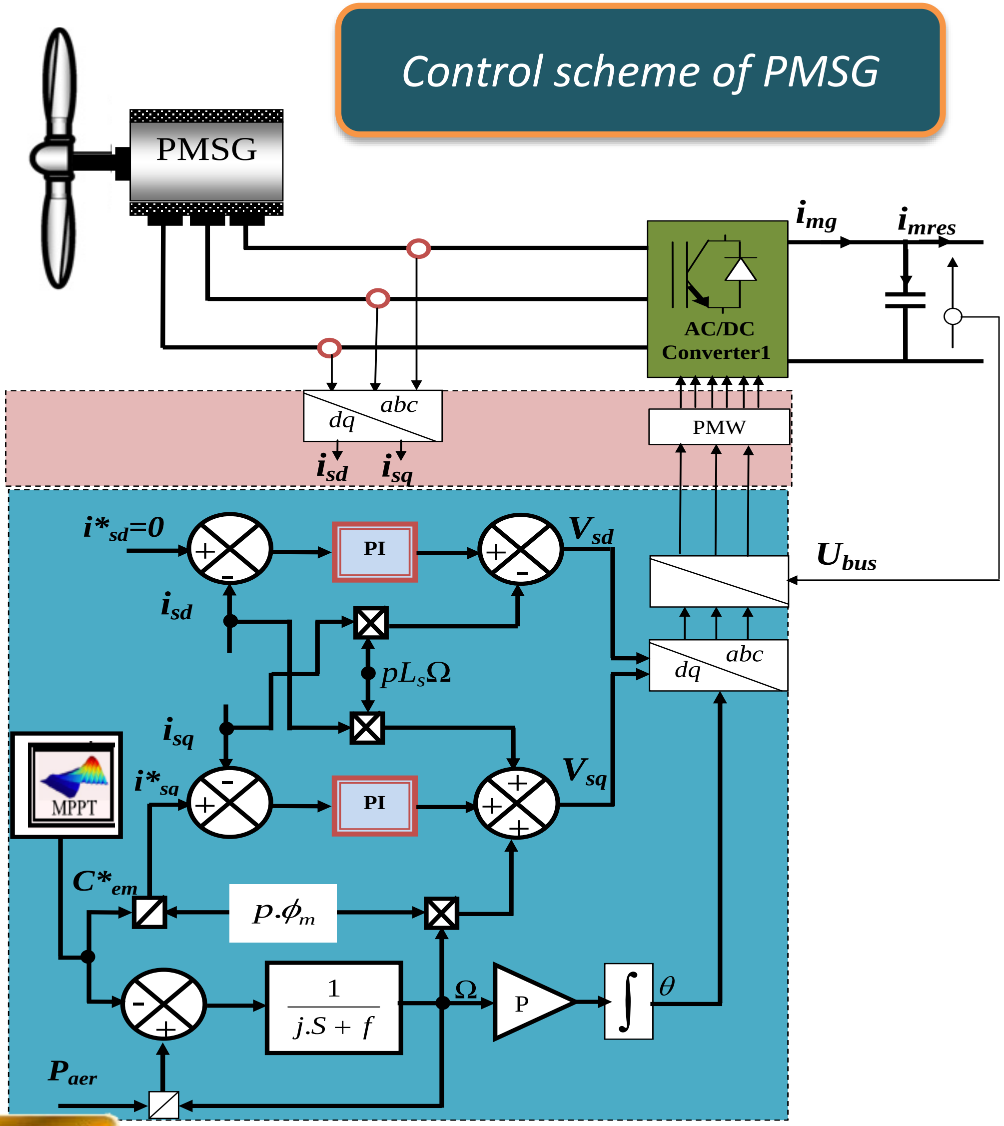
This figure shows the control strategy of the wind generator. This strategy is based on the vector control applied to PMSG to extract maximum wind power (MPPT). The principle of this control is to impose a reference direct current $i_{sd\text{-}ref}$ equal to zero and a quadratic current reference $i_{sq\text{-}ref}$ proportional to the reference electromagnetic torque given by the MPPT algorithm as follows:

$$i_{sd}^{*}=0\,,\qquad i_{sq}^{*}=\frac{C_{em}^{*}}{p\phi}$$

The wind turbine operates in MPPT to extract the maximum power. Therefore, the reference electromagnetic torque *Cem** is determined as follows:

$$C_{em}^{*}=C_{em-MPPT}=\frac{1}{2}\frac{\rho\pi R^{5}C_{p-\max}}{\lambda_{opt}^{3}}\Omega_{m}^{2}$$

Control scheme of PMSG



DEVELOPMENT OF CONVENTIONAL VECTOR CONTROL

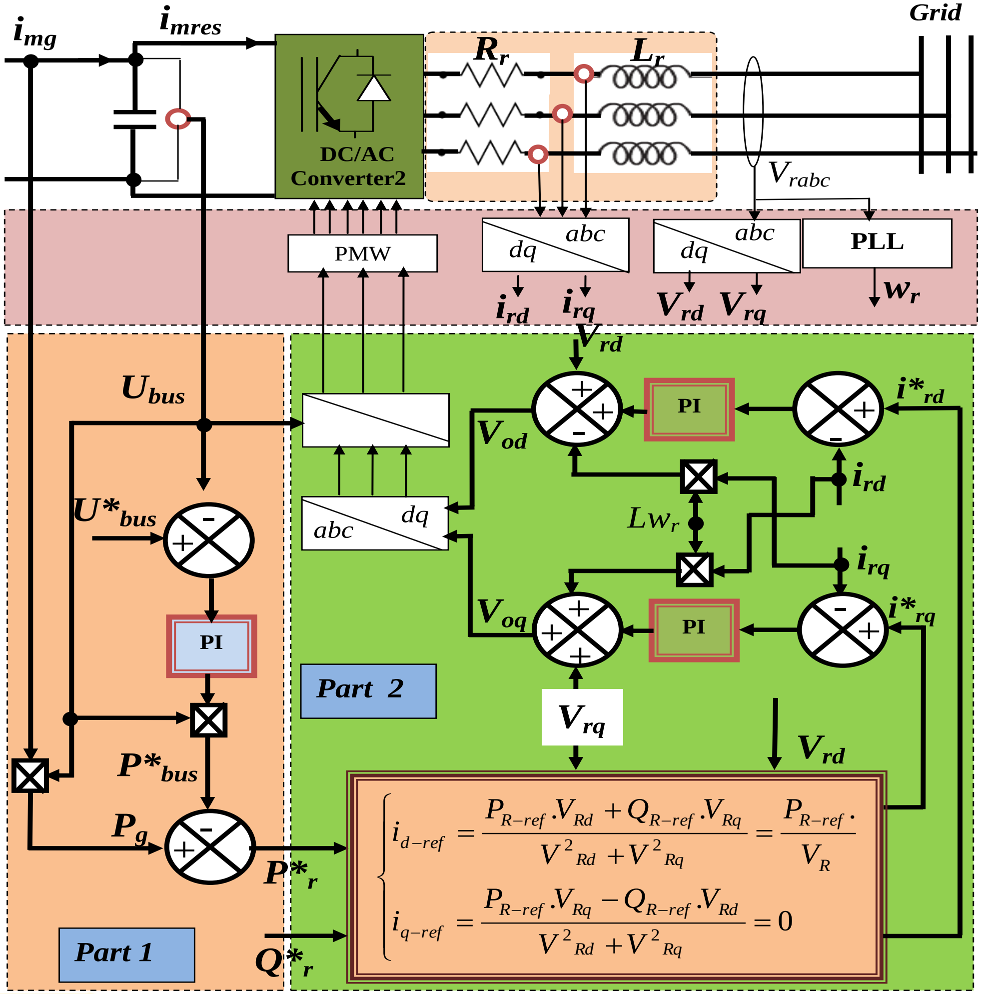
A controller at the DC bus is mastered in Part 1 of this figure to maintain its voltage to a constant value regardless of the wind speed variations.

The using of a decentralized renewable generator to participate in the system services requires a control strategy to ensure a smooth and fast connection between the WECS and the grid (Part 2). Consequently, a control vector is applied to the converter 2 based on the management of active and reactive power exchanged between the main grid and our production system.

The two references powers $P_{r\text{-}ref}$ and $Q_{r\text{-}ref}$ provide the two currents $I_{rd\text{-}ref}$ and $I_{rq\text{-}ref}$ as follows:

$$\begin{cases} i_{d-ref} = \dfrac{P_{r-ref} V_{rd} + Q_{r-ref} V_{rq}}{V^2{}_{rd} + V^2{}_{rq}} \\ i_{q-ref} = \dfrac{P_{r-ref} V_{rq} - Q_{r-ref} V_{rd}}{V^2{}_{rd} + V^2{}_{rq}} \end{cases}$$

Control scheme grid side converter



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DEVELOPMENT OF SECOND ORDER SLIDING MODE CONTROL

Due to the limited performance of the conventional vector control, in particular its sensitivity to strong wind speed variations and high nonlinearity of the various components of the studied system.

A sliding mode control approach is proposed. It offers many advantages such as insensitivity to strong wind speed fluctuations and to system nonlinearity. The major drawback of the first order sliding mode being the chattering phenomenon which is characterized by fluctuations, this phenomenon is undesirable and harmful for actuators.

To remedy this problem, a control strategy by second order sliding mode control (SOSM) has been proposed allowing reduce the chattering effect. This technique is the objective of the next part of our study.

DEVELOPMENT OF SECOND ORDER SLIDING MODE CONTROL

Control scheme of PMSG

- To regulate the currents components *isq* and *isd* to their references, it is required to define the sliding surfaces, as follows:

$$\begin{cases} S_1 = i_{sd} - i_{sd-ref} \\ S_2 = i_{sq} - i_{sq-ref} \end{cases}$$

It follows that:

$$\begin{cases} \dot{S}_1 = \dot{i}_{sd} - \dot{i}_{sd-ref} \\ \ddot{S}_1 = \varphi_1(t,x) + \gamma_1(t,x)\dot{V}_{sd} \end{cases} \quad and \quad \begin{cases} \dot{S}_2 = \dot{i}_{sq} - \dot{i}_{sq-ref} \\ \ddot{S}_2 = \varphi_2(t,x) + \gamma_2(t,x)\dot{V}_{sq} \end{cases}$$

- Where $\varphi_1(t,x)$, $\varphi_2(t,x)$, $\gamma_1(t,x)$, and $\gamma_2(t,x)$ are uncertain bounded functions that satisfy:

$$\varphi_i > 0, |\varphi_i| > \phi_i, 0 < \Gamma_{mi} < \gamma_i < \Gamma_{Mi}, \quad i = 1,2$$

- The proposed second-order sliding mode control has been designed using the super twisting algorithm. So, the controller contains two parts:

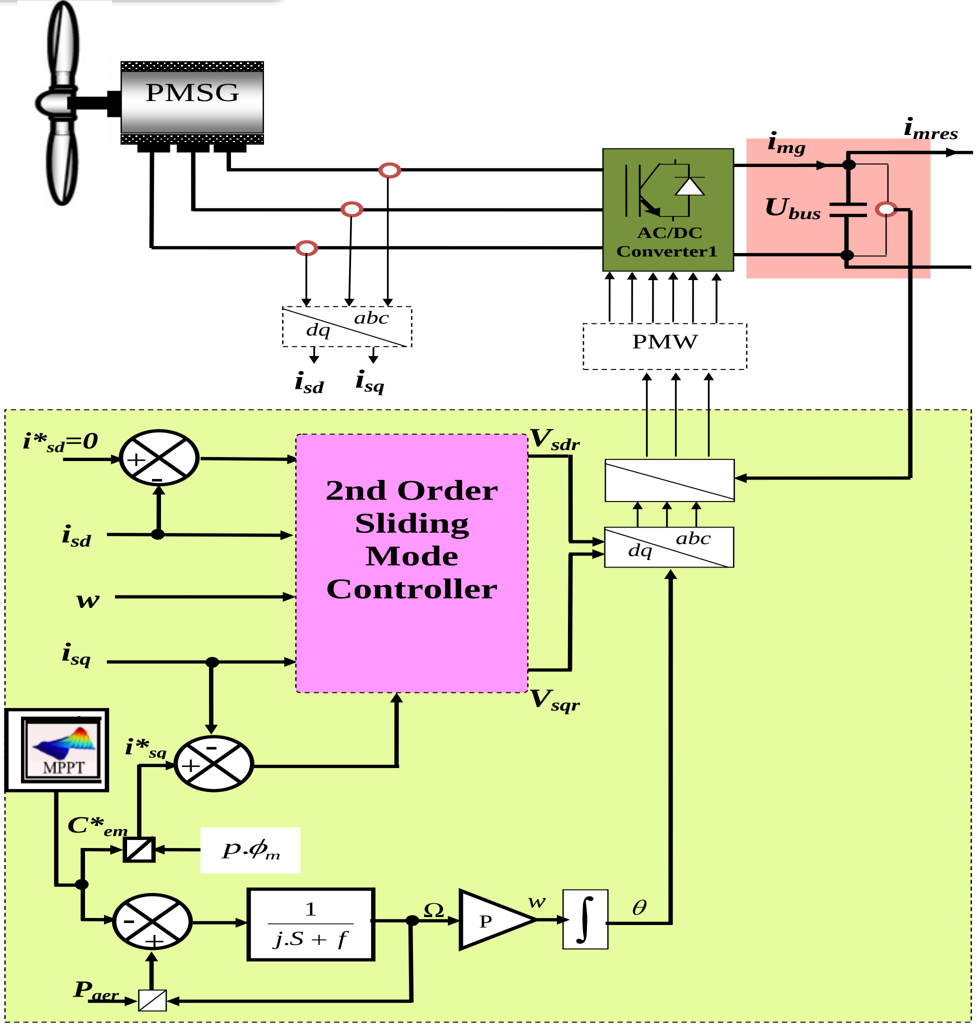
$$\begin{cases} V_{sd-ref} = V_{sd-eq} + V_1 + V_2; \begin{cases} \dot{V}_1 = -\alpha_1.sign(S_1) \\ V_2 = -\beta_1 |S_1|^{\rho} sign(S_1) \end{cases} \\ V_{sq-ref} = U_{sq-eq} + U_1 + U_2; \begin{cases} \dot{U}_1 = -\alpha_2.sign(S_2) \\ U_2 = -\beta_2 |S_2|^{\rho} sign(S_2) \end{cases} \end{cases}$$

DEVELOPMENT OF SECOND ORDER SLIDING MODE CONTROL

Control scheme of PMSG

- To ensure the sliding manifolds convergence to zero in finite time, the gains β_i and α_i defined in the preceding equation can be chosen as follows :

$$\begin{cases} \alpha_i > \dfrac{\phi_i}{\Gamma_{mi}} \\ \beta^2_i \geq \dfrac{4\phi_i \Gamma_{Mi}(\alpha_i + \phi_i)}{\Gamma^3_{mi}(\alpha_i - \phi_i)} ; i = 1,2 \\ 0 < \rho \leq 0.5 \end{cases}$$



DEVELOPMENT OF SECOND ORDER SLIDING MODE CONTROL

Control scheme grid side converter

- The sliding surfaces are chosen as:

$$\begin{cases} S_3 = i_{d-ref} - i_d \\ S_4 = i_{q-ref} - i_q \end{cases}$$

It follows that:

$$\begin{cases} \dot{S}_3 = \dot{i}_d - \dot{i}_{d-ref} \\ \ddot{S}_3 = \varphi_3(t,x) + \gamma_3(t,x)\dot{V}_{od} \end{cases} \quad and \quad \begin{cases} \dot{S}_4 = \dot{i}_q - \dot{i}_{q-ref} \\ \ddot{S}_4 = \varphi_4(t,x) + \gamma_4(t,x)\dot{V}_{oq} \end{cases}$$

- Where $\varphi_1(t,x)$, $\varphi_2(t,x)$, $\gamma_1(t,x)$, and $\gamma_2(t,x)$ are uncertain bounded functions that satisfy:

$$\varphi_j > 0, \left|\varphi_j\right| > \phi_j, 0 < \Gamma_{mj} < \gamma_j < \Gamma_{Mj}, \quad j = 3,4$$

- The proposed SOSM is based on the super twisting algorithm. So, the controller contains two parts:

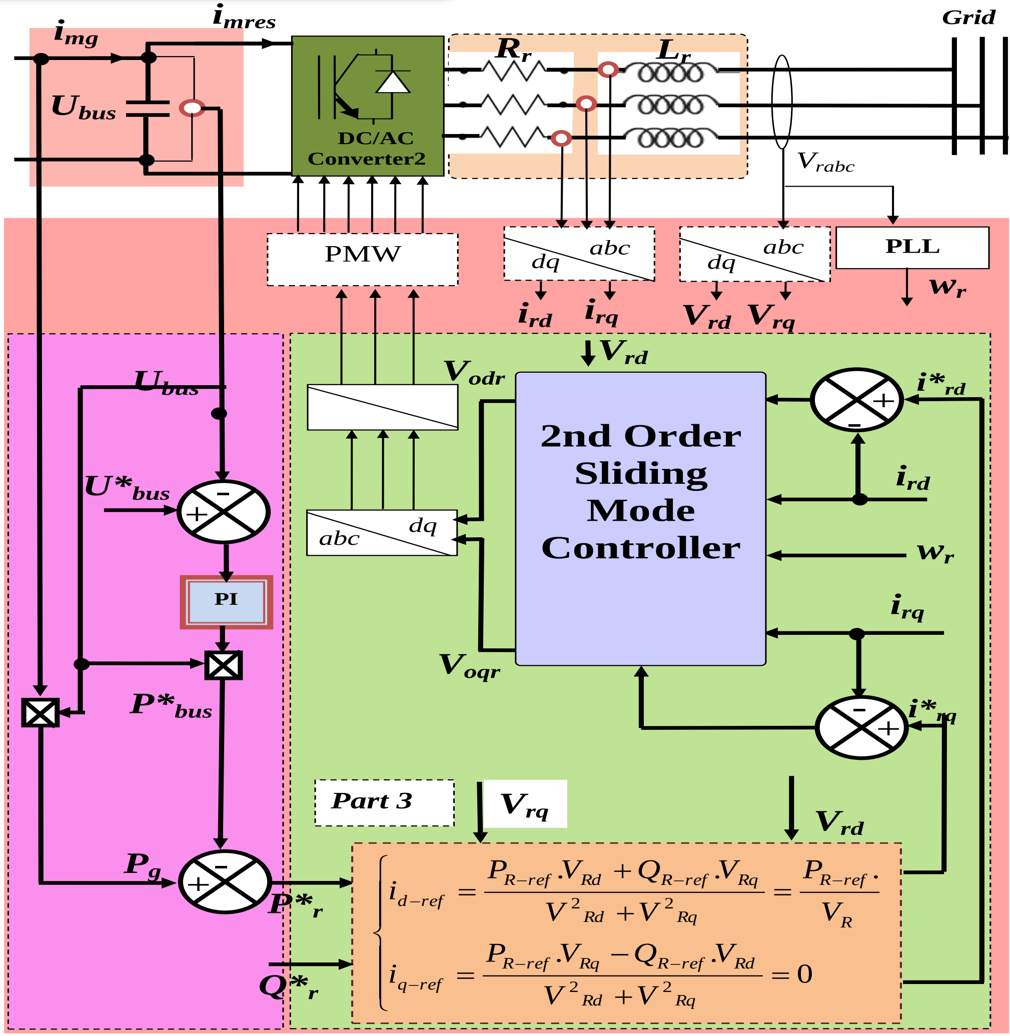
$$\begin{cases} V_{od-ref} = V_{od-eq} + V_3 + V_4; \begin{cases} \dot{V}_3 = -\alpha_3 . sign(S_3) \\ V_4 = -\beta_3 \left|S_3\right|^{\rho} sign(S_3) \end{cases} \\ V_{oq-ref} = U_{oq-eq} + U_3 + U_4; \begin{cases} \dot{U}_3 = -\alpha_4 . sign(S_4) \\ U_4 = -\beta_4 \left|S_4\right|^{\rho} sign(S_4) \end{cases} \end{cases}$$

DEVELOPMENT OF SECOND ORDER SLIDING MODE CONTROL

Control scheme grid side converter

- To ensure the sliding manifolds convergence to zero in finite time, the gains β_j and α_j defined in the preceding equation can be chosen as follows :

$$\begin{cases} \alpha_j > \dfrac{\phi_j}{\Gamma_{mj}} \\ \beta^2_j \ge \dfrac{4\phi_j \Gamma_{Mj}(\alpha_j + \phi_j)}{\Gamma^3_{mj}(\alpha_j - \phi_j)} ; j = 3,4 \\ 0 < \rho \le 0.5 \end{cases}$$



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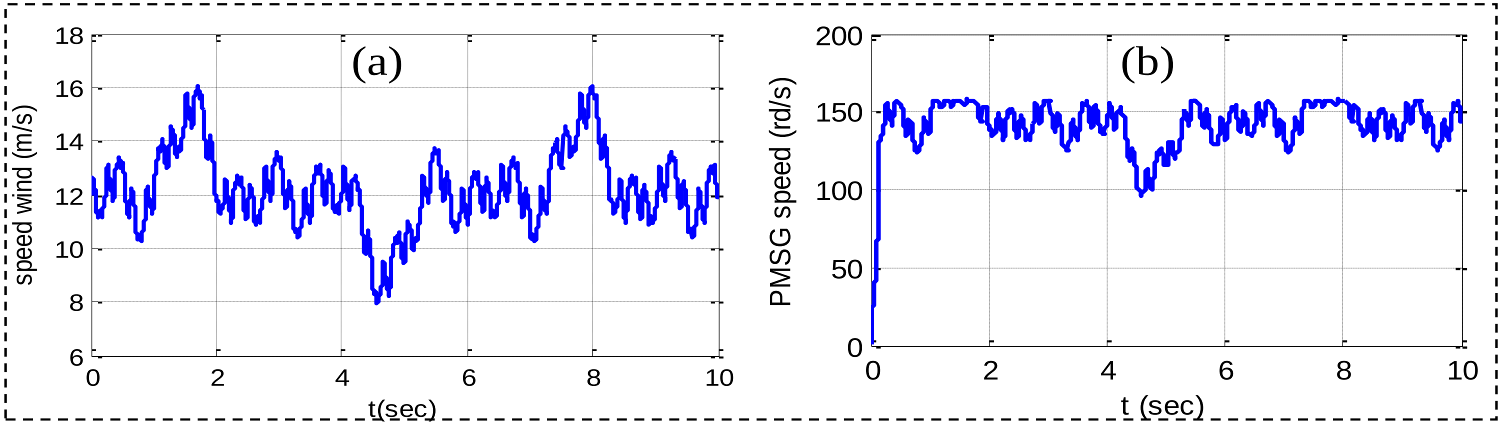
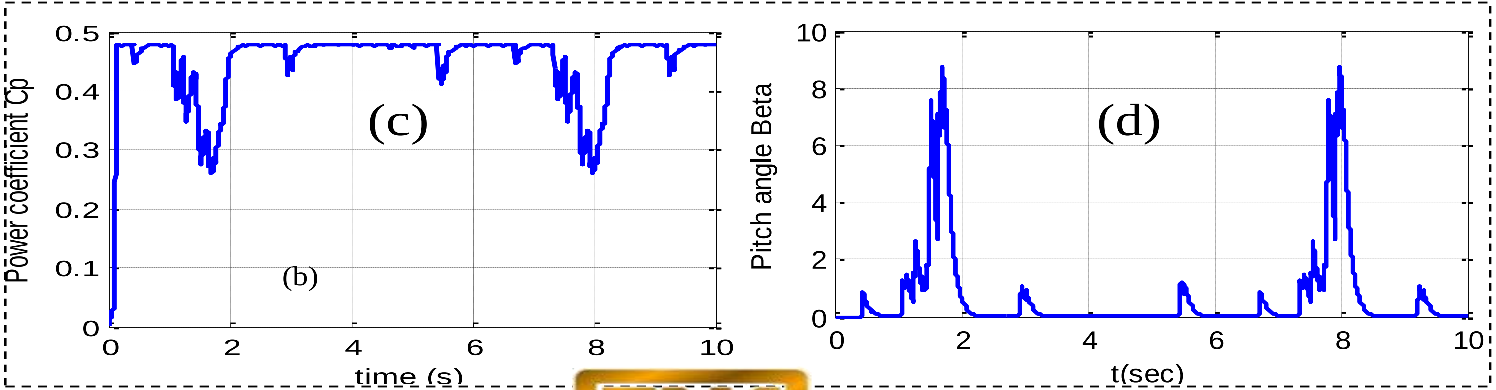
CASE STUDY AND SIMULATION RESULTS

A wind turbine is designed to rotate at a nominal speed and produce a nominal power. For this, a control system called 'pitch angle' was inserted in order to control the power output of the wind turbine and thus to limit it when the wind speed is high. The mechanical speed of the machine is given by Figure b and Figure d gives the variation of the pitch angle β. The operation of this control system is summarized as follows: when the wind speed exceeds its nominal value this angle β increases, subsequently a power coefficient C_p decrease (Figure c).



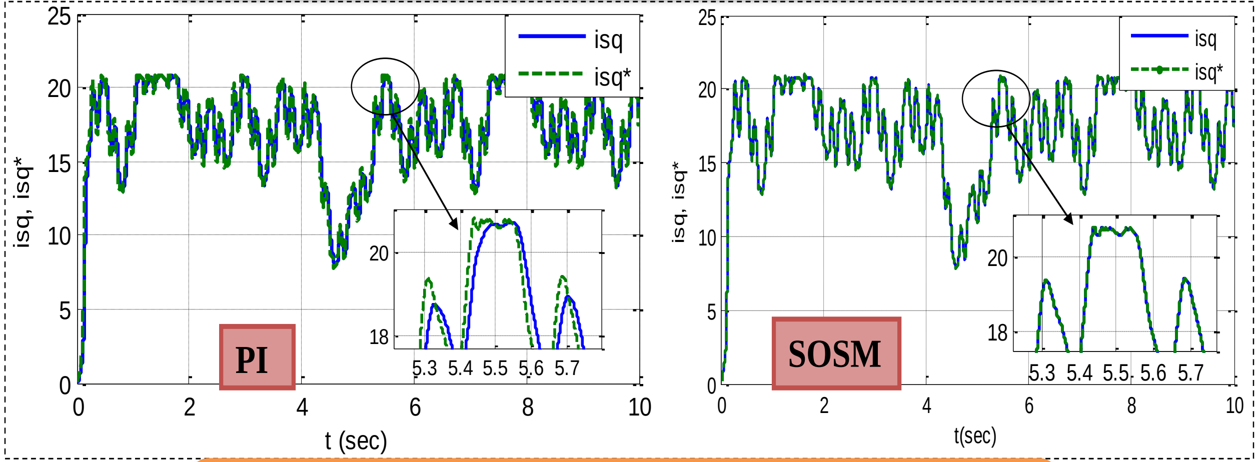


CASE STUDY AND SIMULATION RESULTS

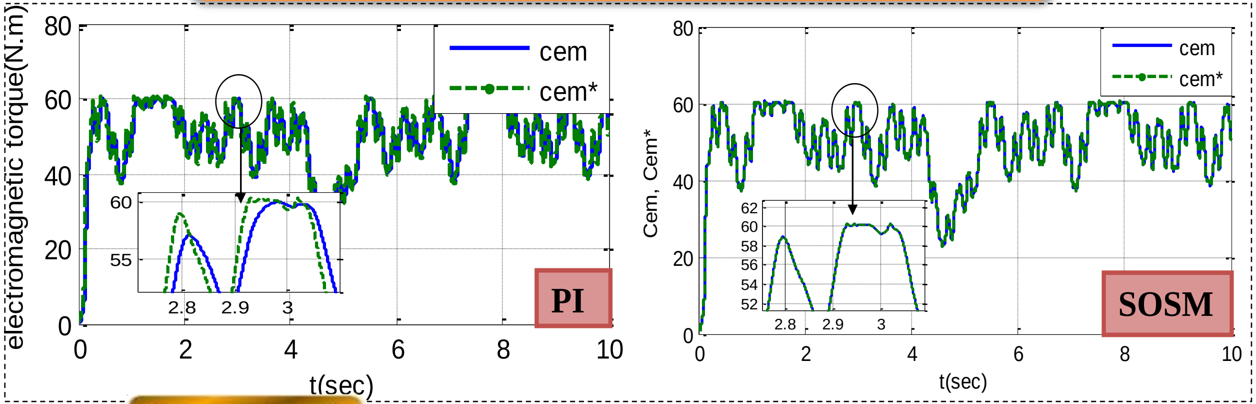
-- A comparative study between the PI controller and the second order sliding mode controller

This test is done to show the robustness of the control applied to our system according to wind speed variations. The responses obtained with the two types of control clearly show that the system operated with the SOSM is more robust compared to the PI structure. For the PI control, it is observed that the error on the quadratic component of stator current and electromagnetic torque caused by the change in speed is very important, so the couple and the current do not respond instantly. For this, a control by SOSM which gives good performance was implanted.

Quadratic component of stator current isq



Electromagnetic torque Cem

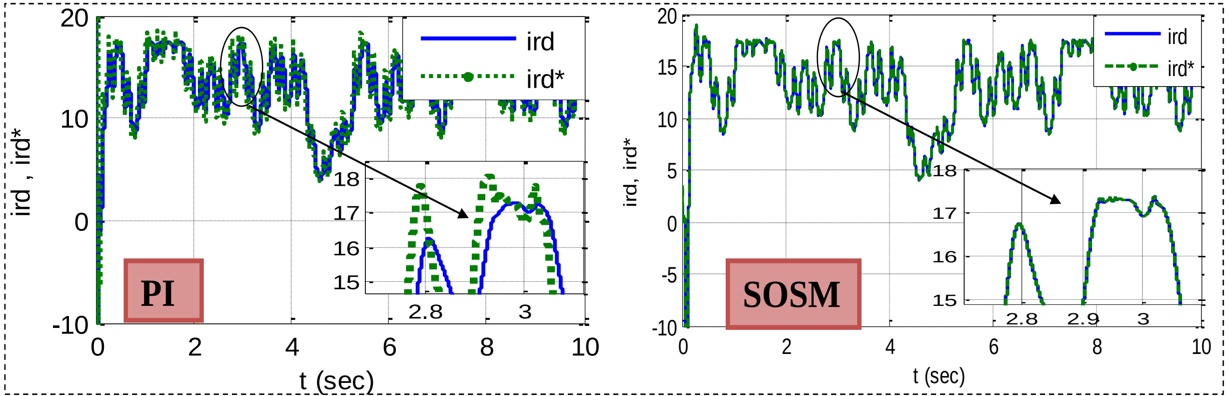


CASE STUDY AND SIMULATION RESULTS

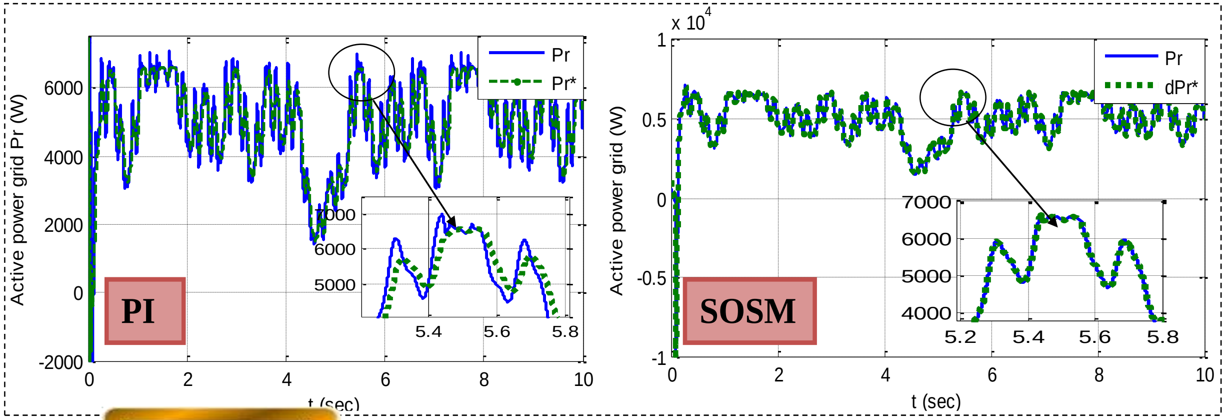
-- A comparative study between the PI controller and the second order sliding mode controller

These figures show respectively the evolution of direct current component and active power injected into the grid, the response of these two curves shows that the SOSM is better than the PI structure from the standpoint of response time and disturbances rejection. The strong wind speed change affects classical vector control compared to SOSM control

Direct current component injected into the grid



Active power injected into the grid



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CONCLUSION

- This paper deals with a control strategy of the variable speed wind energy conversion system based on the PMSG and connected to the distribution network.

- The second order sliding mode control approach (SOMC) is used to implement the Maximum Power Point Tracking, DC link voltage regulation and unity power factor control. The employed control strategy can regulate both the total reactive and active power independently.

- System responses with the proposed SOMC method are validated via simulations and compared with those of conventional PI controllers. So, this proposed regulator has several advantages, over conventional Proportional Integral (PI) one, such as fast dynamic response, perfect decoupling, the insensitivity to external disturbances and large fluctuations in wind speed.

END OF PRESENTATION

THANK YOU FOR YOUR ATTENTION