

Adaptive control of a wind turbine based on a DFIG using a grid-independent rotor supply

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Abstract—The main objective of this article is to adapt an independent power supply system to optimize the energy production of a wind turbine and thus eliminate power outages on the electrical grid when supplying power to the rotor of a doubly-fed induction generator (DFIG). This system uses a permanent magnet synchronous generator (PMSG) to supply power to the DFIG rotor and offers robust control, comparing PI and sliding mode control methods as a function of varying reference parameters. We begin by presenting the dynamic model of the wind turbine connected to the various generators, followed by the electrical model of the PMSG and DFIG with the control strategy. Next, we explain the theory and mathematical equation of the AC/DC rectifier and the DC/AC inverter. Then, we present the PI controller and the sliding mode control method. Finally, simulation results comparing the PI and sliding mode control methods illustrate and demonstrate the performance and feasibility of this system.

Keywords—DFIG, wind, PMSG, PI controller, Sliding mode, rectifier AC/DC, inverter DC/AC, control strategy.

I. INTRODUCTION

Wind energy is presented as an optimal solution for lowering fossil fuel consumption and mitigating environmental pollution. As a clean and freely available energy resource, it has progressed steadily over the years thanks to technological innovation and advances in energy control [1].

In wind turbine systems, the production of electrical energy is undergoing significant development thanks to the emergence of new technologies that allow the operation of new systems called multi-source or multi-generator systems. The choice of the system has become more important as it depends on new criteria related to the different technical and environment problems [2].

The doubly-fed induction generator (DFIG) is currently preferred in wind energy systems for its stability against wind speed fluctuations, accurate reference tracking, enhanced power generation, and affordable cost [3][4][5]. Nevertheless, this system still suffers from drawbacks

related to parameter variations and production losses when the electrical grid feeding the DFIG rotor is interrupted.

To overcome these limitations and guarantee robust electrical power production, a new configuration called the dual-generator wind turbine system has been proposed to ensure continuous power generation. This system integrates a permanent magnet synchronous generator (PMSG) alongside a doubly-fed induction generator. The maximum wind power captured is converted to mechanical power, which subsequently drives both generators (PMSG and DFIG) to produce electrical energy. Part of the PMSG's output power is used to energize the DFIG rotor via two static converters: an AC/DC rectifier and a DC/AC inverter.

The power regulation of the DFIG stator is achieved using a PI and a SMC controller. A comparison between the PI and SMC methods is presented to select the controller that best meets the robustness and stability requirements.

The rest of the article is structured as follows: the wind turbine model is presented in section II.. Sections III and IV

deal with the AC/DC and DC/AC converter models, respectively. Sections V and VI describe the PI and SMC controllers used, respectively. Section VII presents the simulation results. Finally, the conclusions are summarized.

II. WIND TURBINE SYSTEM MODEL

The wind turbine is described in figure 1.

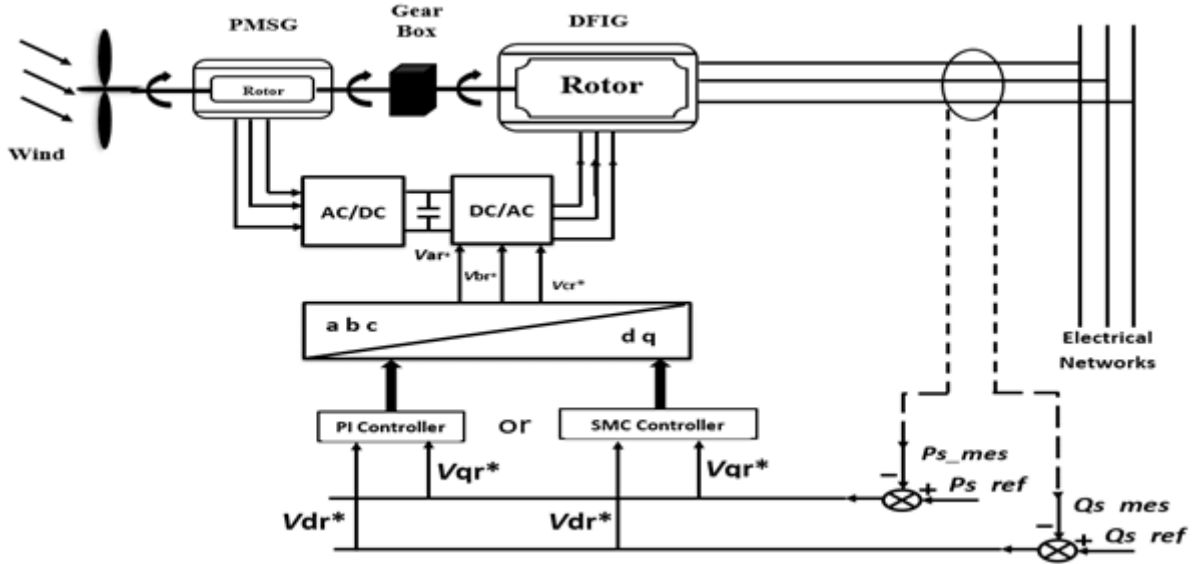


Fig. 1. Wind Turbine system.

A. The wind turbine model:

The power extracted by a wind turbine is expressed by the following equation [6] :

$$P = \frac{1}{2} \rho S v^3 \quad (1)$$

The available part of this energy that can be captured is:

$$P = \frac{1}{2} \rho C_P S v^3 \quad (2)$$

The equation of the turbine is:

$$\Gamma_m = \Gamma_{em} + f\Omega + J \frac{d\Omega}{dt} \quad (3)$$

B. The PMSG model:

The model of permanent magnet synchronous generator is:

$$\begin{cases} v_{as} = R_s i_{as} + \frac{d\varphi_{as}}{dt} \\ v_{bs} = R_s i_{bs} + \frac{d\varphi_{bs}}{dt} \\ v_{cs} = R_s i_{cs} + \frac{d\varphi_{cs}}{dt} \end{cases} \quad (4)$$

Using the Park model, the permanent magnet synchronous generator equation is given by[8-9] :

$$\begin{cases} v_d = R_s i_d + L_d \frac{di_d}{dt} - L_q i_q \omega \\ v_q = R_s i_q + L_q \frac{di_q}{dt} + L_d i_d \omega + \phi_f \omega \end{cases} \quad (5)$$

The following relationship gives the electromagnetic torque [9][10]:

$$\Gamma_{em} = \frac{3}{2} p \left((L_d - L_q) i_{ds} i_{qs} + \phi_f i_{qs} \right) \quad (6)$$

C. The DFIG model:

Using the Park transformation, the DFIG equations can be expressed as follows [11]

$$\left\{ \begin{aligned} v_{ds} &= R_s i_{ds} + \frac{d}{dt} \phi_{ds} - \omega_s \phi_{qs} \\ v_{qs} &= R_s i_{qs} + \frac{d}{dt} \phi_{qs} + \omega_s \phi_{ds} \\ v_{dr} &= R_r i_{dr} + \frac{d}{dt} \phi_{dr} - (\omega_s - \omega_r) \phi_{qr} \\ v_{qr} &= R_r i_{qr} + \frac{d}{dt} \phi_{qr} + (\omega_s - \omega_r) \phi_{dr} \end{aligned} \right. \quad (7)$$

$$\begin{cases} \phi_{ds} = L s i_{ds} + M_{sr} i_{dr} \\ \phi_{qs} = L s i_{qs} + M_{sr} i_{qr} \\ \phi_{dr} = L r i_{dr} + M_{sr} i_{ds} \\ \phi_{qr} = L r i_{qr} + M_{sr} i_{qs} \end{cases} \quad (8)$$

$$\Gamma_{em} = p \frac{M_{sr}}{L_s} (\phi_{qs} i_{dr} - \phi_{ds} i_{qr}) \quad (9)$$

D. The DFIG control strategy:

From Park transformation, the active and reactive powers are written as follows [10] [11]:

$$\begin{cases} P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s = V_{qs} i_{ds} - V_{ds} i_{qs} \end{cases} \quad (10)$$

And, after using the flux orientation method, we can write:

$$\begin{cases} \phi_{qs} = 0 ; \phi_{ds} = \phi_s \\ V_{qs} = V_s ; V_{ds} = 0 \end{cases} \quad (11)$$

Substituting equation (11) in (10) we have:

$$\begin{cases} P_s = V_{qs} i_{qs} \\ Q_s = V_{qs} i_{ds} \end{cases} \quad (12)$$

By combining (7), (8), and (12), equation (12) becomes:

$$\begin{cases} P_s = -V_s \frac{M}{L_s} i_{qr} \\ Q_s = -V_s \frac{M}{L_s} i_{dr} + \frac{V_s^2}{L_s \omega_s} \end{cases} \quad (13)$$

The equation voltage of the rotor can be expressed by:

$$\begin{cases} v_{qr} = R_r i_{qr} + \delta \frac{di_{qr}}{dt} + \omega_g \delta i_{dr} + \frac{g M V_s}{L_s} \\ v_{dr} = R_r i_{dr} + \delta \frac{di_{dr}}{dt} - \omega_g \delta i_{qr} \end{cases} \quad (14)$$

Where: $\delta = L_r - \frac{M^2}{L_s}$ is the leakage factor, and

$g = (\omega_s - \omega_r) / \omega_r$ is generator slip.

III. RECTIFIER MODELLISATION AC/DC

The AC/DC converter consists of six diodes arranged according to the structure illustrated in the figure 2. The converter is powered by a three-phase voltage system.

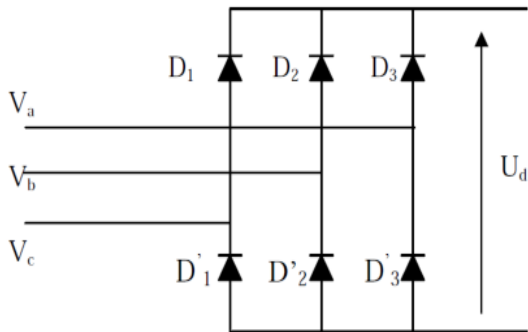


Fig. 2. AC/DC rectifier.

In this rectifier system, we have:

$$\begin{aligned} D_i \text{ in conduction position, Si: } & \begin{cases} V_i = \text{Max}(V_j) \\ i = 1, 2, 3 \text{ and } j = 1, 2, 3 \end{cases} \\ D'_i \text{ in conduction position, Si: } & \begin{cases} V'_i = \text{Min}(V_j) \\ i = 1, 2, 3 \text{ and } j = 1, 2, 3 \end{cases} \end{aligned}$$

So, the output voltage of this rectifier is given by:

$$U_d = \text{Max}(V_j) - \text{Min}(V_j); j = 1, 2, 3 \quad (15)$$

IV. INVERTER MODELLISATION DC/AC

The DC/AC converter is presented by its power circuit in figure 3:

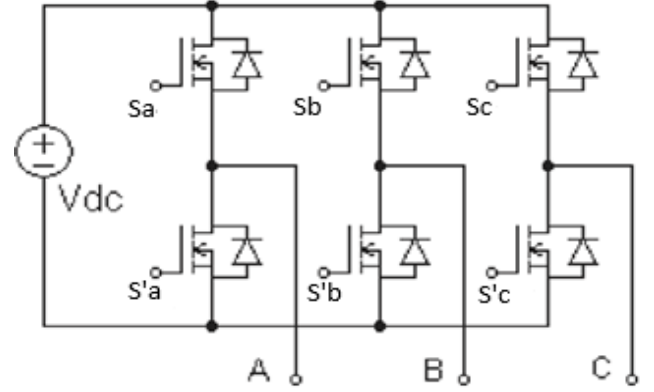


Fig. 3. DC/AC inverter.

We can obtain the inverter output branch voltages as follows:

$$\begin{cases} V_{AN} = S_a \times V_{dc} \\ V_{BN} = S_b \times V_{dc} \\ V_{CN} = S_c \times V_{dc} \end{cases} \quad (16)$$

Where S_a , S_b and S_c design the switches states.

Equation of compound voltages:

$$\begin{cases} V_{AB} = V_{AN} + V_{NB} = V_{AN} - V_{BN} = (S_a - S_b) V_{dc} \\ V_{BC} = V_{BN} + V_{NC} = V_{BN} - V_{CN} = (S_b - S_c) V_{dc} \\ V_{CA} = V_{CN} + V_{NA} = V_{CN} - V_{AN} = (S_c - S_a) V_{dc} \end{cases} \quad (17)$$

Equation of simple voltages:

$$\begin{cases} V_{AN} = \frac{1}{3} (2V_{AN} - V_{BN} - V_{CN}) \\ V_{BN} = \frac{1}{3} (2V_{BN} - V_{AN} - V_{CN}) \\ V_{CN} = \frac{1}{3} (2V_{CN} - V_{AN} - V_{BN}) \end{cases} \quad (18)$$

After the replace of equation 16 in the equation 18, we find:

$$\begin{cases} V_{AN} = \frac{1}{3}V_{dc}(2S_a - S_b - S_c) \\ V_{BN} = \frac{1}{3}V_{dc}(2S_b - S_a - S_c) \\ V_{CN} = \frac{1}{3}V_{dc}(2S_c - S_a - S_b) \end{cases} \quad (19)$$

Finally, the inverter equation are expressed by:

$$\begin{cases} V_{as} = \frac{1}{3}V_{dc}(2S_a - S_b - S_c) \\ V_{bs} = \frac{1}{3}V_{dc}(2S_b - S_a - S_c) \\ V_{cs} = \frac{1}{3}V_{dc}(2S_c - S_a - S_b) \end{cases} \quad (20)$$

V. PI CONTROLLER

In this system, we are interested to control the powers (P_s , Q_s) and the currents (I_{dr} , I_{qr}) by PI controller.

A. Rotor currents control:

Figure 4 shows the rotor currents control by the proportional-integral controller. The simplified transfer function obtained from equation (14) corresponds to a first-order system.

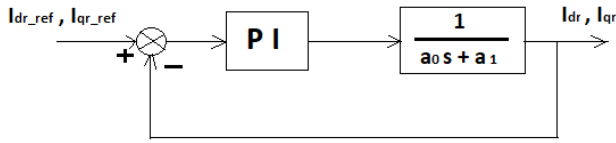


Fig. 4. Transfer function of a PI controller

The PI transfer function controller:

$$C_s = K_p + \frac{K_i}{s} \quad (21)$$

Accordingly, the open-loop transfer function takes the following form:

$$T(s) = \frac{K_p s + K_i}{a_0 s^2 + a_1 s} \quad (22)$$

Where $a_0 = \delta$ and $a_1 = R_r$

The resulting closed-loop transfer function can be expressed as:

$$F(s) = \frac{T(s)}{1+T(s)} = \frac{1 + \tau s}{\frac{a_0}{K_i} s^2 + \left(\tau + \frac{a_1}{K_i}\right) s + 1} \quad (23)$$

$$\text{Where: } \tau = \frac{K_p}{K_i}$$

B. Active and reactive power control:

The Figure 5 illustrated the control loop of powers (P_s , Q_s) using PI regulator.

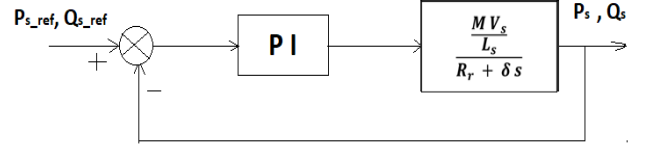


Fig. 5. Transfer function of active and reactive power PI controller

The PI transfer function controller is:

$$C(s) = \frac{1+s T_n}{s T_i} \quad (24)$$

Where T_i and T_n are respectively the constant time of the integration correlation and the integration time constant.

The open-loop transfer function:

$$F_0(s) = \frac{1+s T_n}{s T_i} \frac{M V_s}{R_r + \delta s} \quad (25)$$

In a closed loop, we obtain the following transfer function:

$$\begin{aligned} F_F(s) &= \frac{F_0(s)}{1 + F_0(s)} = \frac{\frac{1+s T_n}{s T_i} \frac{M V_s}{R_r + \delta s}}{1 + \frac{1+s T_n}{s T_i} \frac{M V_s}{R_r + \delta s}} \\ F_F(s) &= \frac{M V_s}{T_i \delta L_s} \frac{1 + T_n s}{s^2 + \left(\frac{R_r}{\delta} + \frac{T_n M V_s}{T_i \delta L_s}\right) s + \frac{M V_s}{T_i \delta L_s}} \\ F_F(s) &= K_r \frac{1 + T_n s}{s^2 + \left(\frac{R_r}{\delta} + \frac{T_n M V_s}{T_i \delta L_s}\right) s + \frac{M V_s}{T_i \delta L_s}} \quad (26) \end{aligned}$$

$$\text{Where: } K_r = \frac{M V_s}{T_i \delta L_s}$$

VI. SLIDING MODE CONTROL

As a robust nonlinear control method, Sliding Mode Control (SMC) stabilizes system dynamics under uncertain conditions. It is simple to implement and exhibits strong robustness against disturbances. SMC is structured around three main stages [12]

- The first step consists in choosing sliding surface:

$$\begin{cases} S(X) = \left(\frac{d}{dt} + \lambda_c \right)^{n-1} e \\ e = X^d - X \end{cases} \quad (27)$$

With:

$$\begin{cases} X = [x, \dot{x}, \dots, x^{n-1}]^T \\ X^d = [x^d, \dot{x}^d, \ddot{x}^d, \dots]^T \end{cases} \quad (28)$$

- The second step is to guarantee the conditions for the convergence and the stability of the system:

$$(S(X))(\dot{S}(X)) \leq 0 \quad (29)$$

- The third step the law control design:

$$u = u^{eq} + u^n \quad (30)$$

Where u^n is the switching term, u^{eq} is the equivalent control.

We apply sliding mode control theory to control the powers (P_s , Q_s). [12]

A. Active power control

Taking $n=1$ for the purpose of power control, the active power control surface takes the following form::

$$S(P) = (P_s^{ref} - P_s) \quad (31)$$

We define:

$$\dot{S}(P) = (\dot{P}_s^{ref} - \dot{P}_s) \quad (32)$$

We substitute equation 13 in 32:

$$\dot{S}(P) = \left(\dot{P}_s^{ref} + V_s \frac{M}{L_s} \dot{i}_{qr} \right) \quad (33)$$

We use equations 14 and 33, We obtain:

$$\dot{S}(P) = \left(\dot{P}_s^{ref} + V_s \frac{M}{L_s L_r \sigma} (v_{qr} - R_r i_{qr}) \right) \quad (34)$$

With: $\sigma = 1 - \frac{M^2}{L_r L_s}$

Replacing the expression of v_{qr} with $v_{qr}^{eq} + v_{qr}^n$ the equation 34 become:

$$\dot{S}(P) = \left(\dot{P}_s^{ref} + V_s \frac{M}{L_s L_r \sigma} ((v_{qr}^{eq} + v_{qr}^n) - R_r i_{qr}) \right) \quad (35)$$

In steady state and in the slip mode, we have:

$$S(P) = 0, \quad \dot{S}(P) = 0, \quad v_{qr}^n = 0 \quad (36)$$

According to the equation 35 and 36, the equivalent term command is written:

$$v_{qr}^{eq} = -\dot{P}_s^{ref} \frac{\sigma L_s L_r}{V_s M} + R_r i_{qr} \quad (37)$$

For the convergence mode, based on the condition $S(P)\dot{S}(P) \leq 0$ we set:

$$\dot{S}(P) = -V_s \frac{M}{\sigma L_s L_r} v_{qr}^n \quad (38)$$

The switching term is defined by:

$$v_{qr}^n = K v_{qr} \text{sign}(S(P)) \quad (39)$$

Where $K v_{qr}$ is a positive parameter.

B. Control of reactive power

Taking $n=1$ for the purpose of power control, the reactive power control surface is given by:

$$S(Q) = (Q_s^{ref} - Q_s) \quad (40)$$

We define:

$$\dot{S}(Q) = (\dot{Q}_s^{ref} - \dot{Q}_s) \quad (41)$$

We substitute equation 13 in 41:

$$\dot{S}(Q) = \left(\dot{Q}_s^{ref} - \left(-V_s \frac{M}{L_s} \dot{i}_{dr} \right) \right) \quad (42)$$

We use equations 14 and 43, We obtain:

$$\dot{S}(Q) = \left(\dot{Q}_s^{ref} + V_s \frac{M}{L_s L_r \sigma} (v_{dr} - R_r i_{dr}) \right) \quad (43)$$

Replacing the expression of v_{dr} with: $v_{dr}^{eq} + v_{dr}^n$ the equation 43 become:

$$\dot{S}(Q) = \left(\dot{Q}_s^{ref} + V_s \frac{M}{L_s L_r \sigma} ((v_{dr}^{eq} + v_{dr}^n) - R_r i_{dr}) \right) \quad (44)$$

In steady state and in the slip mode, we have:

$$S(Q) = 0, \quad \dot{S}(Q) = 0, \quad v_{dr}^n = 0 \quad (45)$$

From the equation 35 and 36, the equivalent term command is written:

$$v_{dr}^{eq} = -\dot{Q}_s^{ref} \frac{\sigma L_s L_r}{V_s M} + R_r i_{dr} \quad (46)$$

For the convergence mode, based on the condition $S(Q)\dot{S}(Q) \leq 0$ we set:

$$\dot{S}(Q) = -V_s \frac{M}{\sigma L_s L_r} v_{dr}^n \quad (47)$$

Therefore, the switching term is given by:

$$v_{dr}^n = K v_{dr} \text{sign}(S(Q)) \quad (48)$$

Where $K v_{dr}$ is a positive parameter.

VII. IMPLEMENTATION AND RESULTS

A PI controller together with a sliding mode controller is used to achieve active and reactive power control. The Blocks diagram of PMSG-DFIG/PI and PMSG-DFIG/SMC system are presented respectively in Figure 6 and Figure 7.

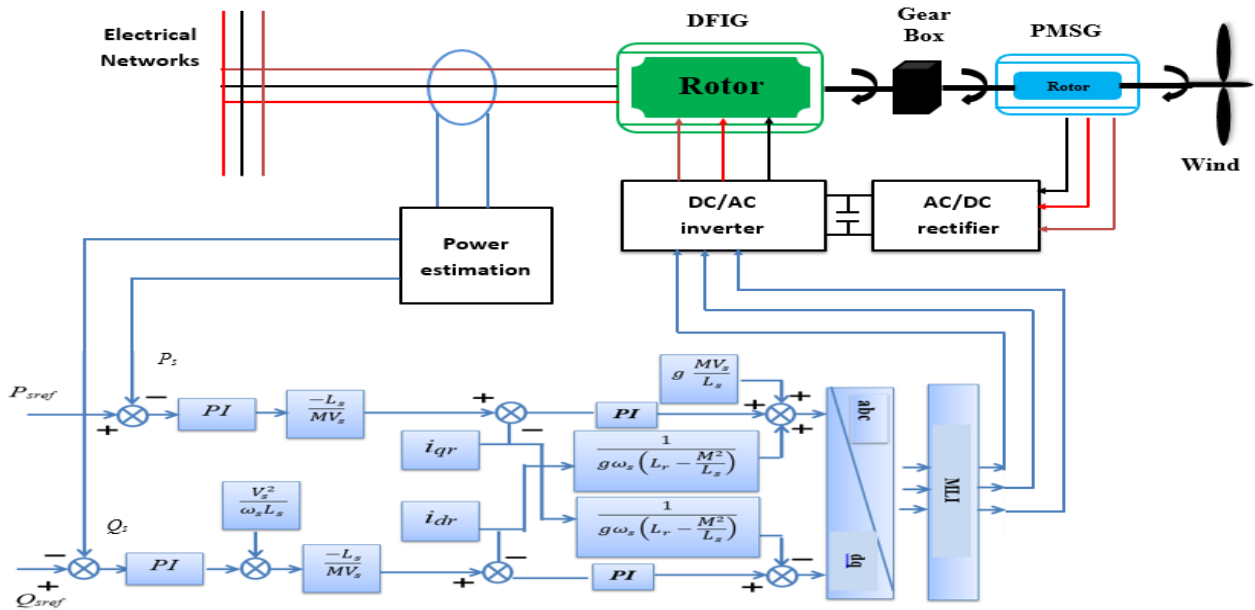


Fig. 6. PMSG-DFIG/PI control system.

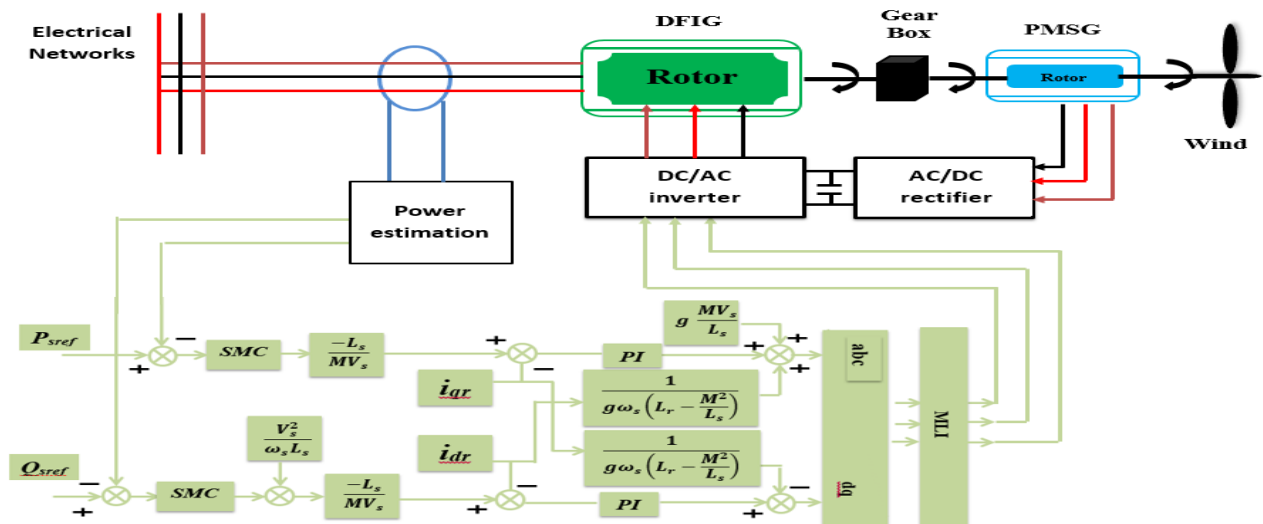


Fig. 7. PMSG-DFIG/SMC control system.

The simulation of the systems illustrated in Figures 6 and 7 is carried out in the MATLAB-Simulink environment. The primary objective of controlling the dual-generator wind system (PMSG-DFIG) is to improve both performance and stability when reference values fluctuate.

The variation in mechanical speed is illustrated in Figure 8 with different values (50, 90, 40, and 125 rad/s).

As illustrated in Figures 9 and 10, the PMSG produces active power (P_s) and reactive power (Q_s) based on the wind speed, and these powers are utilized to supply the DFIG rotor.

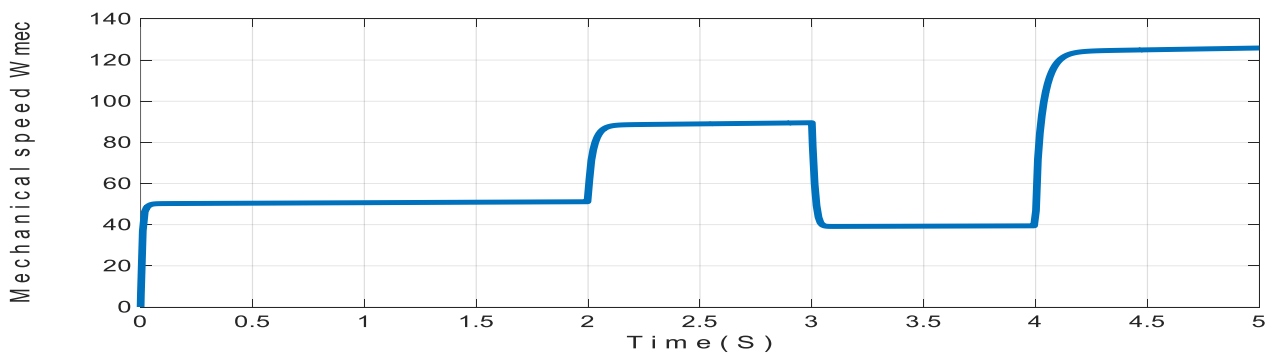


Fig. 8. Mechanical speed variation.

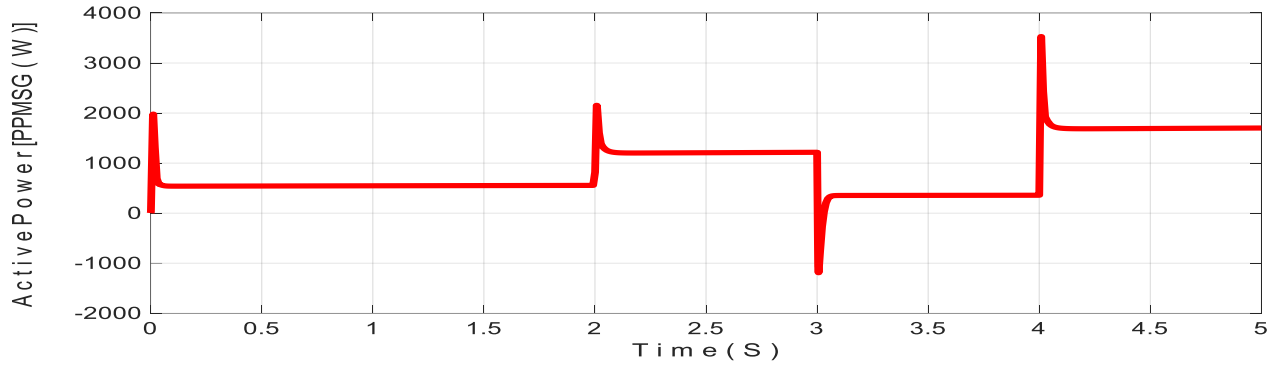


Fig. 9. Active power supplying the DFIG rotor and generated by the PMSG.

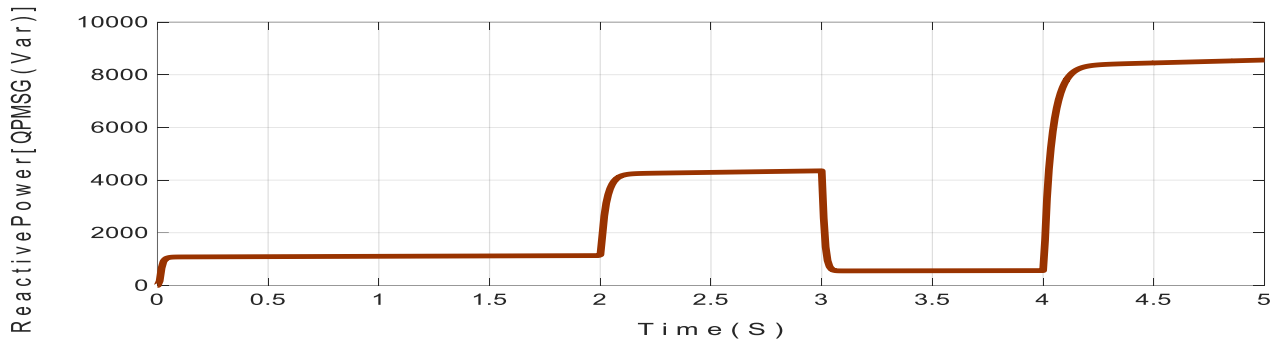


Fig. 10. Active power supplying the DFIG rotor and generated by the PMSG.

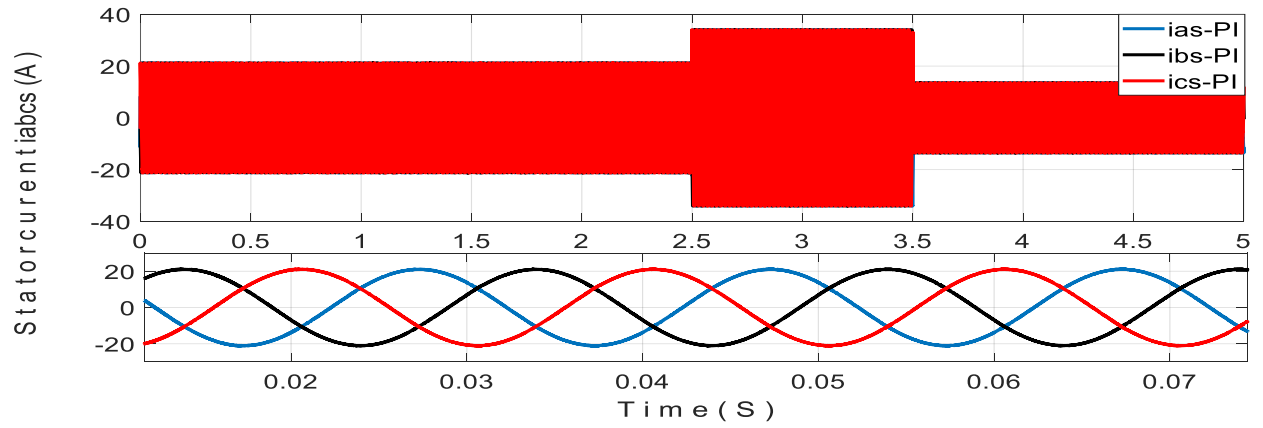


Fig. 11. Stator current of DFIG generator controlled by PI controller.

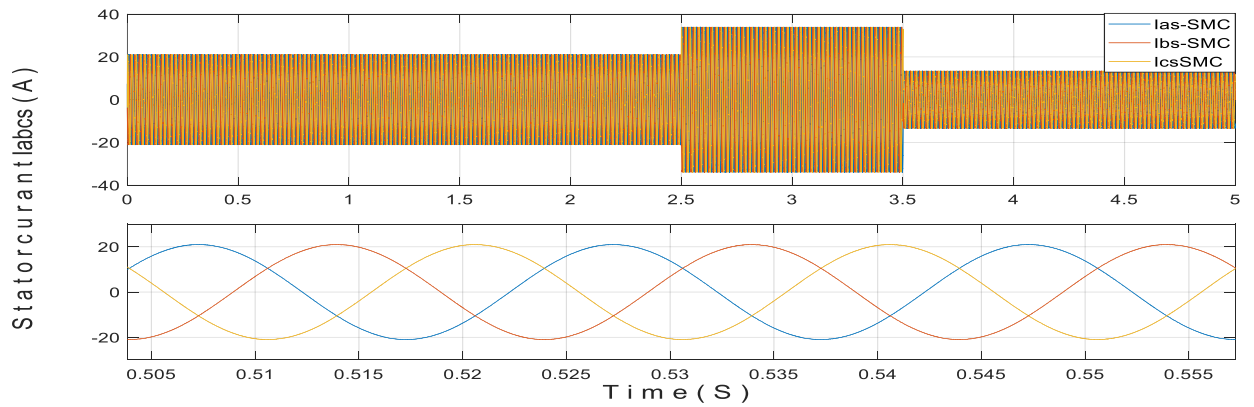


Fig. 12. Stator current of DFIG generator controlled by SMC controller.

The variation of the stator current over time, as produced on the grid by the system under changing active and reactive power references, is depicted in Figures 11 and 12.

For system robustness, we carried out a comparison between the regulation of the current at the output of the DFIG by two modes of regulation (PI regulation and sliding mode) as shown in figure 13.

We therefore observe good robustness of the SMC regulation of the generated stator current compared to the PI regulation..

The time-based regulation of DFIG's active (P_s) and reactive (Q_s) powers under varying active and reactive power references is shown in Figures 14 and 15. For controlling the P_s and Q_s produced by the DFIG, the SMC controller yields a notably better system response than the PI controller

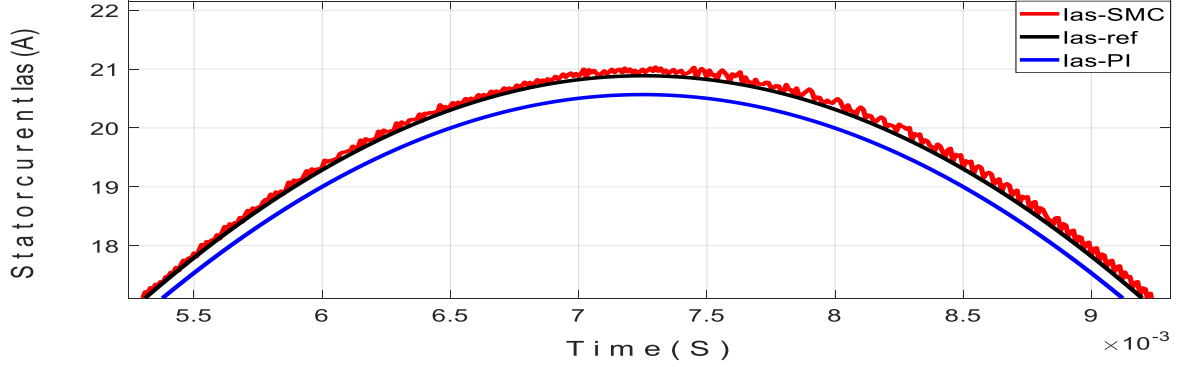


Fig. 13. Comparison between PI and SMC control in zooming mode.

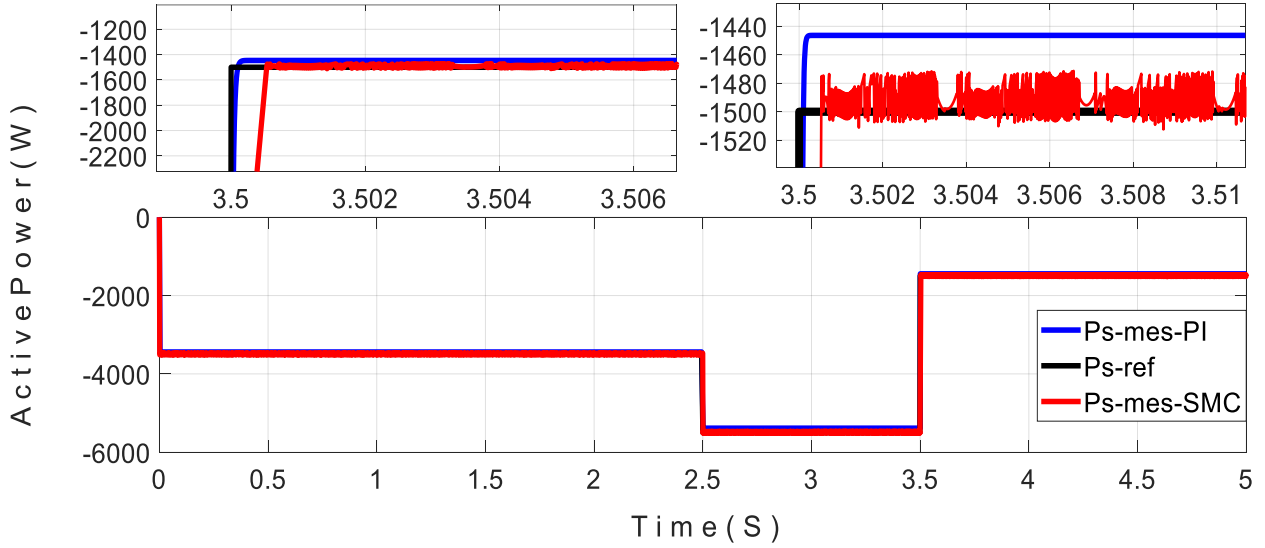


Fig. 14. Comparison between PI and SMC in the active powers adaptation

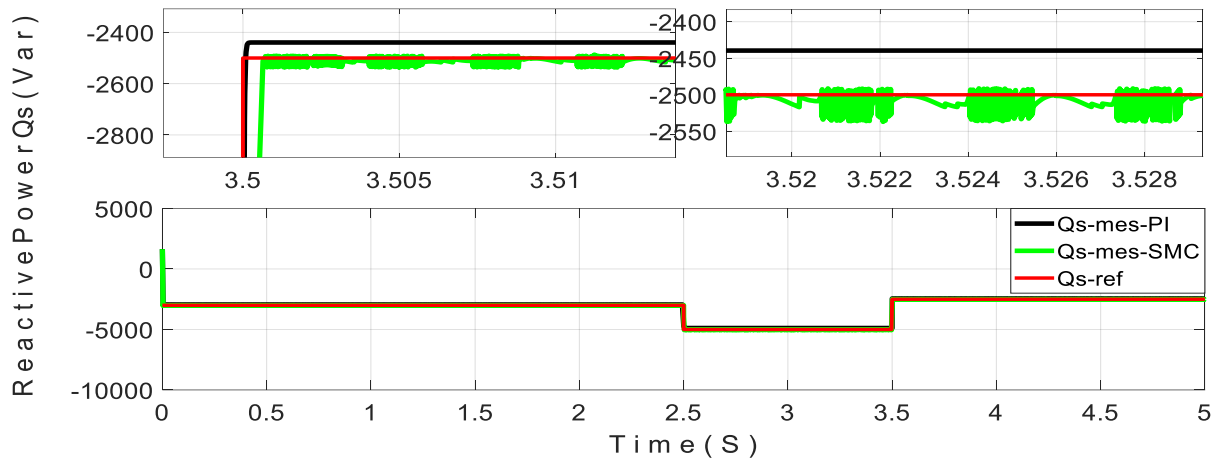


Fig. 15. Comparison between PI and SMC in the reactive powers adaptation

VIII. CONCLUSION

The principle objective of this article, is to establish an independent power supply system, to eliminate the problem of power outages in electrical networks when supplying the rotor of a DFIG using a PMSG, and elaborate a robust control, responding to stability criteria and desired performances, for wind system in variation of system reference parameters.

So firstly, the double generator wind turbine system(PMSG-DFIG) is presented using PMSG to feed a DFIG rotor.

An AC/DC rectifier and a DC/AC inverter are used to interface the PMSG stator with the DFIG rotor. The P_s and Q_s powers delivered by the PMSG are employed to energize the DFIG rotor.

Subsequently, the regulation of P_s and Q_s is achieved through both PI and sliding mode control (SMC) methods. The simulation outcomes confirm the stability of the two-generator system. Moreover, the SMC control method demonstrates enhanced dynamic performance and greater robustness relative to the PI controller in the context of this adaptive power generation system

Finally, this paper concludes that this system (double generator wind turbine system(PMSG-DFIG)) has a good stability and high robustness in the presence of variations in the reference parameter system and interruptions in electrical network.

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