Super Twisting Algorithm Direct Power Control of DFIG using Space Vector Modulation

Farida. Mazouz*, Sebti. Belkacem,

*LEB, Department of   Electrical Engineering, University Mostefa Ben Boulaid   Batna-2 Algeria

*f.mazouz@univ-Batna2.dz, s.belkasem@univ-batna2.dz

Abstract: This paper presents the super-twisting algorithm (STA) direct power control (DPC) scheme for the control of active and reactive powers of grid-connected DFIG. Simulations of 5 KW DFIG has been presented to validate the effectiveness and robustness of the proposed approach in the presence of uncertainties with respect to vector control (VC). The proposed controller schemes with fixed gains are effective in reducing the ripple of active and reactive powers, effectively suppress sliding-mode chattering and the effects of parametric uncertainties not affecting system performance.

  Keywords: DFIG , SVM, VC, 2-SMC, STA, Wind Turbine (WT), parameters uncertainly.

1. Introduction

In recent years and with its economic and environmental benefits, wind energy has become more and more a source of energy for many countries, İn addition, and because of its advantages, the dual feed induction generator (DFIG) is currently the generator of choice for driven wind turbines [1-8]. The vector control (VC) using conventional   proportional-integral (PI) controllers allows decoupled control of the active and reactive powers typically applied for their simplicity [9-10]. However, the VC structure strongly count on the parameters of the machine and require exact knowleduses of the system model, therefore can not ensure the robustness of the system in the face of parameter variations and model uncertainties. Different strategies have been presented in the literature to remedy the aforementioned difficulties. Direct torque control (DTC) or direct power control (DPC) has been introduced in [11-12]. The application of DPC on the DFIG had many advantages over the classical VC method: no coordinate transformations, no current loops, less dependence on parameters. From its basic version the classical direct power control causes fluctuations in the currents, the reactive, active powers and the variable switching frequency because of the use of hysteresis regulators. Several approaches are suggested on the development of DPC techniques operating at a constant switching frequency. using space vector modulation [13-16]. its precaution is elimination of the hysteresis regulators and the switching table. The reduction of the power pulsation and the quality of the power has been achieved. These controllers are not robust to uncertain parameters.

The authors suggested the application of   DPC in a DFIG-based wind turbine system under unbalanced grid voltage conditions [17-18]. The control strategy consists of a purely sinusoidal and balanced stator and GSC current injector, without the need to extract the negative sequence harmonics. The dual frequency pulses of the reactive power of the stator and the torque are completely eliminated when the torque / power is changed in transient and transient conditions when the voltage is unstable.

Several model predictive direct power control (MP-DPC) techniques were proposed in [19-20]. Its advantages over conventional control techniques such as multivariate control do not require phase locked loops (PLLs) or the removal of cascading control loops, good reference tracking to grid parameter variations. The drawback of the MPC command takes a long time for execution, so the method finds its application much more in slow systems with large sampling period where the application of numerical methods does not pose a problem. For fast sampled high frequency systems such as motors, robots ..., the online digital solution of the optimization problem may be impractical. Also, it is useful to look for quick and effective solutions.

Sliding mode control (SMC) is an effective control strategy that has been well developed in the literature because of its simplicity, robustness to parameter variations and external disturbances. This algorithm has already been suggested in different applications [21-23]. The combination of this algorithm and DPC improves power responses. The disadvantage of this combination is that the use of the discontinuous function introduces a static error, high frequency oscillations due to chattering phenomena, this phenomenon is the major disadvantage of hits practical implementation. In literature a lot of work to suppresses chattering, for example, replacing the discontinuous saturation control function. This technique was one of the classical techniques used to reduce ripples. Although this method reduces chattering but the controller becomes continuous and the SMC characteristics, such as convergence and robustness, can not be achieved and steady-state errors can also occur. Another technique is to use a second-order or higher sliding-mode command, such as super-twisting , which combines a MPPT using a fuzzy logic algorithm [24]. In [25-28], the authors propose controllers in second order sliding control.

The purpose of this paper is to use a second order continuous sliding mode control for a DFIG drive, this control strategy presents attractive features such as robustness to parametric uncertainties and attenuate chattering. The proposed strategy is compared with vector control.

2. WIND TURBINE MODELING

The relationship between the wind power and wind speed by the rotor blade of a wind turbine can be expressed as:

$$P_v = \frac{1}{2}.\rho.S.v^3 \tag{1}$$

The mechanical power expression as [30]:

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

The tip speed ratio is described by:

$$\lambda = \frac{R.\Omega_{turbine}}{v} \tag{3}$$

The aerodynamic torque is expressed by:

$$T_{aer} = \frac{P_{aer}}{\Omega_{turbine}} = C_p(\beta,\lambda).\frac{1}{2}.\rho.S.v^3.\frac{1}{\Omega_{turbine}} \qquad (4)$$

$$J = \frac{J_{turbine}}{G^2} + J_g \qquad (5)$$

The dynamic equation can be written as follows [31]:

$$T_g - T_{em} = J.\frac{d\Omega_{turbine}}{dt} + f.\Omega_{mec} \qquad (6)$$

3. MODELING OF THE DFIG

In the synchronous repository (d-q) we can highlight the DFIG dynamic equations as follows [4]:

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\[2mm] V_{qs} = R_s I_{qs} + \dfrac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \\[2mm] V_{dr} = R_r I_{dr} + \dfrac{d\varphi_{dr}}{dt} - \omega_r \varphi_{qr} \\[2mm] V_{qr} = R_r I_{qr} + \dfrac{d\varphi_{qr}}{dt} + \omega_r \varphi_{dr} \end{cases} \qquad (7)$$

The flux equations are given by:

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + M I_{dr} \\ \varphi_{qs} = L_s I_{qs} + M I_{qr} \\ \varphi_{dr} = L_r I_{dr} + M I_{ds} \\ \varphi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \qquad (8)$$

We present the torque equation as follows:

$$T_{em} = p\frac{M}{L_s}(I_{qr}\varphi_{ds} - I_{dr}\varphi_{qs}) \qquad (9)$$

We define the supplied active and reactive powers as:

$$\begin{aligned} P_s &= (V_{ds}I_{ds} + V_{qs}I_{qs}) \\ Q_s &= (V_{qs}I_{ds} - V_{ds}I_{qs}) \end{aligned} \qquad (10)$$

The Figure 1. represented the equivalent circuit of a DFIG expressed in the synchronous rotating reference frame.
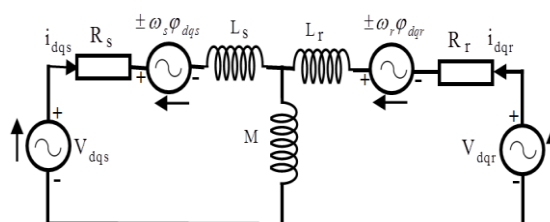

Figure 1. Equivalent circuit of a DFIG in synchronous rotating reference frame.

. MODEL OF SVM TECHNICS FOR INVERTER

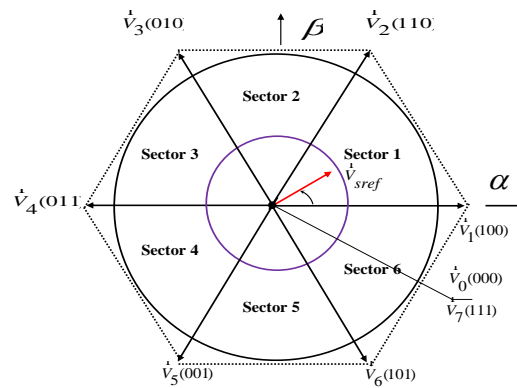Three phase voltage-fed PWM inverters are shown in Figure 2.

Figure 2. Model of SVM techniques for inverter.

Each voltage vector in every sector, is composed by basic space voltage vector of the two side of sector and one zero vector. For example, in the first sector, we have a compound spatial vector expressed by [13]:

$$\overline{V}_{s\,ref}\,T_s = \overline{V}_0 T_0 + \overline{V}_1 T_1 + \overline{V}_2 T_2 \qquad (11)$$

With: $T_s = T_0 + T_1 + T_2$

Where, T_0, T_1 and T_2 is the working time of basic space voltage vectors.

PRINCIPAL OF VECTOR CONTROL APPLIED TO THE DFIG

The vector control based on the stator flux orientation makes it possible to independently control the active and reactive powers by the rotor side converter (RSC). The currents are controlled by two PI correctors which determine the references of the voltages to be applied (Vrd, Vrq).

The objective of VC is consists in maintain $\varphi_{qs} = 0$, and $\varphi_{ds} = \varphi_s$. where φ_s represent the reference flux. By remplasing the principle of vector control, the electromagnetique torque is presented as:

$$T_{em} = p \frac{M}{L_s}(I_{qr}\varphi_s) \qquad (12)$$

The rotor voltages expression according to the rotor currents are obtained by the organization of the equations (7) and (8) by:

$$V_{dr} = R_r \cdot I_{dr} + (L_r - \frac{M^2}{L_s}) \cdot \frac{dI_{dr}}{dt} - g \cdot w_s \cdot (L_r - \frac{M^2}{L_s}) \cdot I_{qr}$$

$$V_{qr} = R_r \cdot I_{qr} + (L_r - \frac{M^2}{L_s}) \cdot \frac{dI_{qr}}{dt} - g \cdot w_s \cdot (L_r - \frac{M^2}{L_s}) \cdot I_{dr} + g \cdot \frac{M \cdot V_s}{L_s} \qquad (13)$$

Negligible stator resistance Rs and the stator flux is constant oriented along the axis, we can deduct from equation (7):

$$V_{ds} = \frac{d\varphi_s}{dt} = 0$$

$$V_{qs} = V_s = \omega_s \varphi_{qs} \qquad (14)$$

We can be expressed the active and reactive powers with the rotor currents as follows:

$$P_s = -(V_s \frac{M}{L_s} I_{qr})　\qquad\qquad (15)$$

$$Q_s = (\frac{V_s^2}{L_s w_s} - V_s \frac{M}{L_s} I_{dr})　\qquad\qquad (16)$$

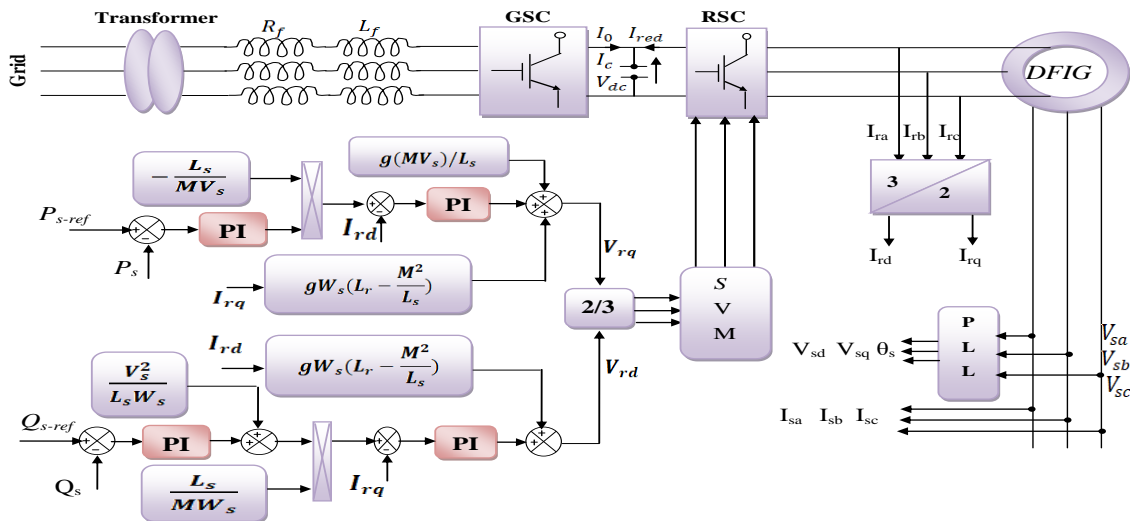The simplified diagram of the vector control is illustrated in Figure 3

Figure 3. Vector control of DFIG.

DESIGN OF SECOND ORDRE SLIDING MODE CONTROL OF DFIG

The purpose of the SMC is to converge the system state trajectories to a predefined sliding variety. The controller causes unwanted high frequency ripples. The second order sliding mode control is useful for reducing "chattering" as it applies to the second derivative of the system. This section introduces the Super Twisting algorithm. In order to reduce the chattering phenomenon, and maintaining the properties of robustness and convergence of the system in finite time. In this control, the sliding surfaces are chosen so as to be compatible with the errors in the powers of the stator.

6. 1. Super Twisting Algorithm

The (STA) among the most popular second-order sliding mode algorithms. This algorithm only applies to systems of relative degree 1. Its interest lies in the reduction of chattering, due to the continuity of the control signal. This command breaks down into an algebraic and integral term. We can therefore consider this algorithm as a nonlinear generalization of a PI [25]. The Super-Twisting algorithm, like other algorithms of the same categorical, requires only the information on S and causes the cancellation of that one in a finite time; it also makes it possible to construct a differentiator called generally an exact differentiator [26]. The command law of fuper-twisting is formed of two parts; the first u1 is defined by its derivative with respect to time; while the second u2 is continuous and depending on the slip variable. The control law is suggested by [27]:

$$u = -\alpha |s|^{\frac{1}{2}} \text{sign(s)} - \beta \int \text{sign(s).dt} \qquad (17)$$

where α and β are positive bounded constants.

The controller gains α and β should be over-estimated respecting to the system bounds with uncertainty in order to get a robust controller, as given in [28].

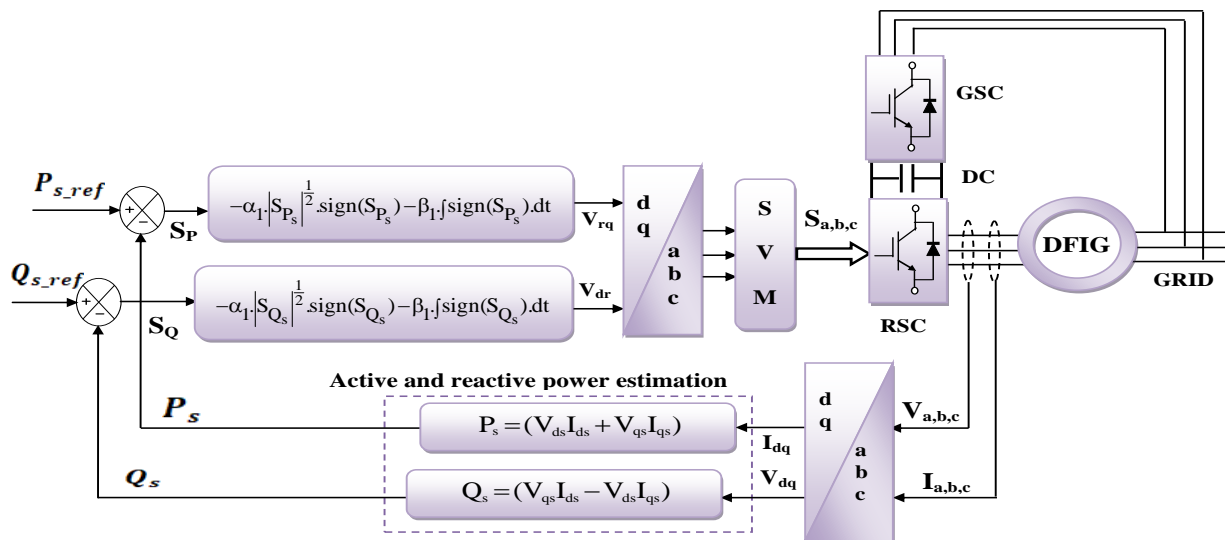Figure 4 illustrates the proposed 2-SMC-SVM scheme for controlling active and reactive powers.

Figure 4. Block diagram of the control structure by 2- SMC.

7. SIMULATION RESULTS

In order to validate the results obtained through the different approaches, it is necessary to make a comparison of the static and dynamic characteristics of the two control techniques under the same operating conditions and in the same simulation configuration. Simulation studies of the DFIG-based training system were performed using MATLAB / Simulink. The parameters of a wind turbine and a DFIG are presented in Table.2.

7. 1. Simulation Results Without Parametric Variation

A. Simulation Results With Constant Speed

Simulations involving vector control and second order sliding mode control schemes. DFIG is used in a constant speed mode. Figures 5 and 6 compare the responses of the system during different active and reactive power steps for the two schemes, respectively. As these figures show, the robustness of the proposed controller scheme is also confirmed in terms of tracking aptitude compared to VC.

The stator phases current are shown in figures 7. It can be seen that the current waviness also has a noticeable reduction in the proposed algorithm compared to the classical algorithm.
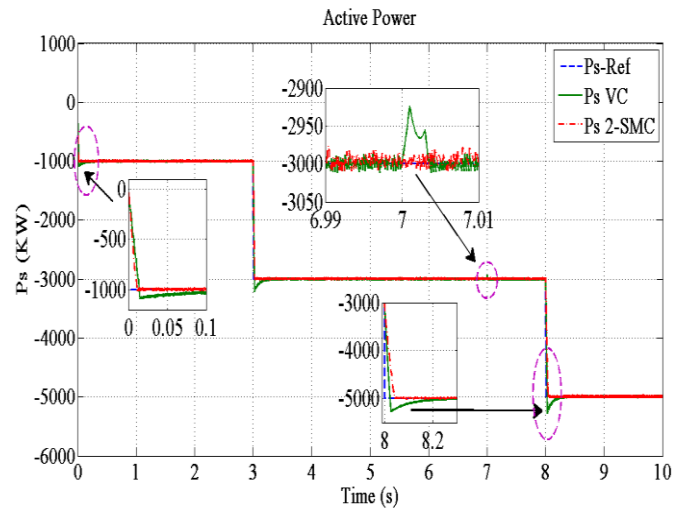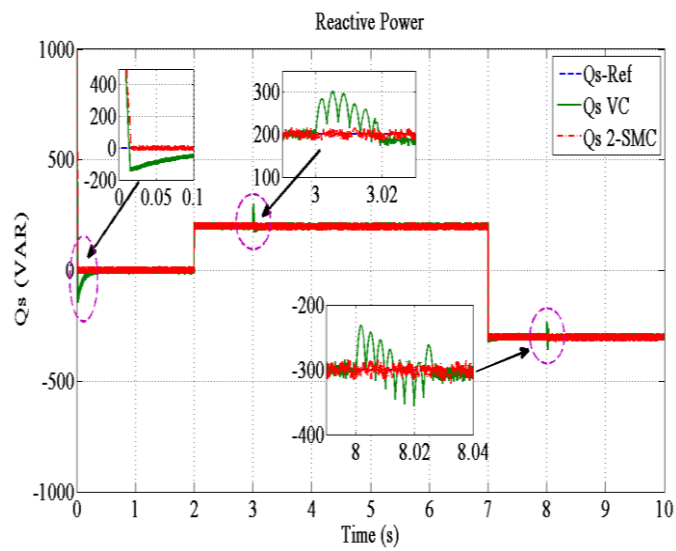
Figure 5. Active power response.

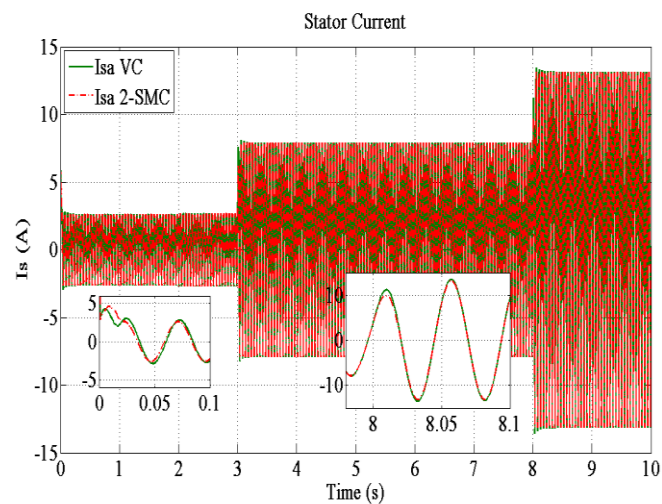**Figure 6.** Reactive power response.

Figure 7. Waveform of stator current

B. Simulation Results with Variable Speed Wind Turbine

In order to test the influence of the variation of wind speed for both strategies. The reactive and active powers as well the stator current are illustrated in Figures (8 to 10), these results show that the suggested approach provides near-perfect performance in terms of system tracking performance relative to classical vector control. However, noticeable improvements have been recorded thanks to the new approach.
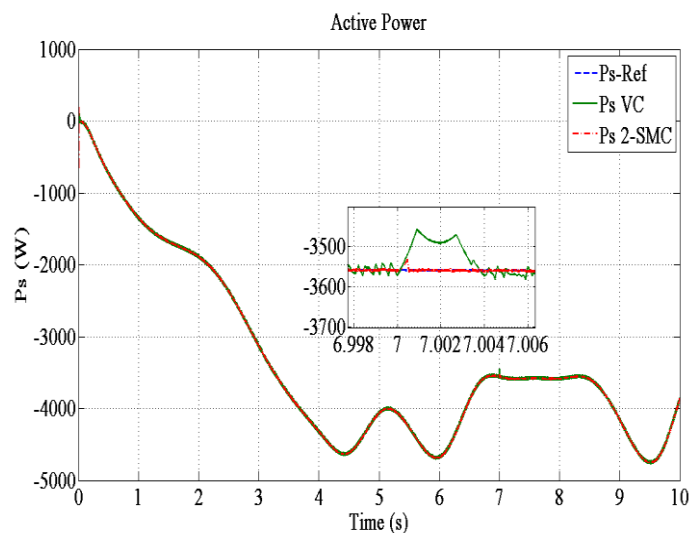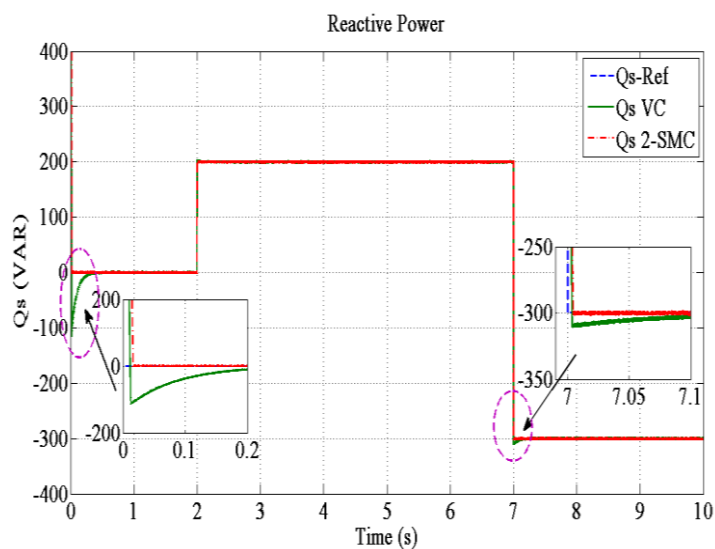

Figure 8. Response of stator active power

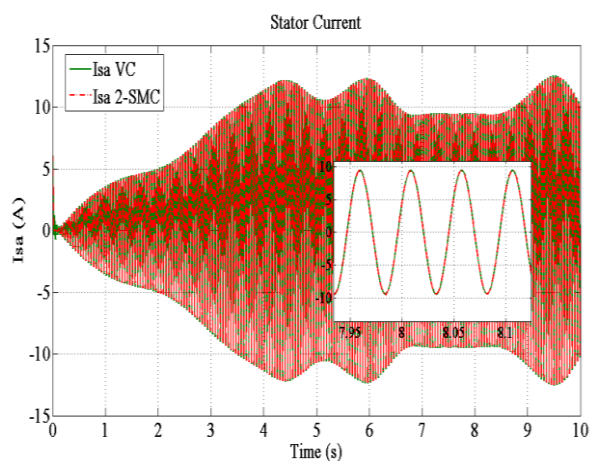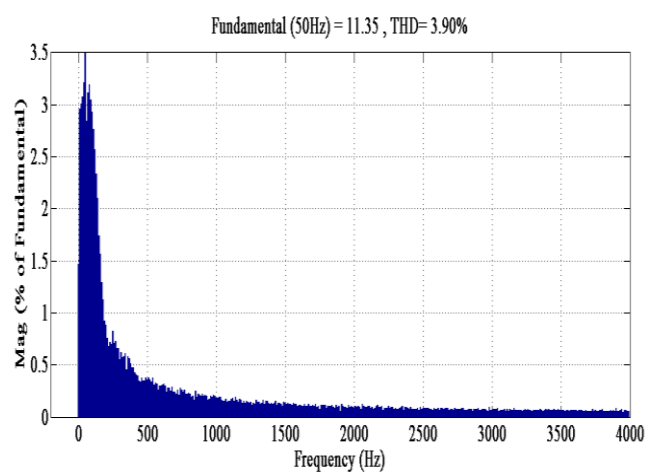**Figure 9.** Reactive power response.

Figure 10. Waveform of stator current

(a)
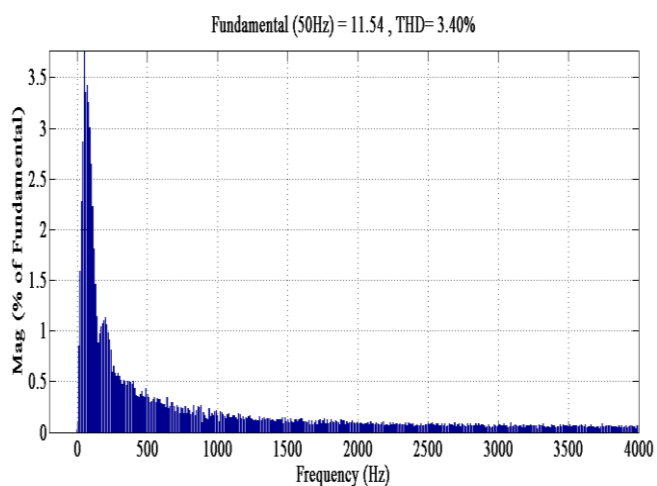
(b)

Figure 11. Stator current   harmonic spectra, Ps = -5 kW, Qs = 0 kVar ,(a) VC, (b) 2-SMC.

Further to investigate the performance of the proposed scheme, the stator current harmonic spectra with Ps = -5 kW and Qs = 0 kVar for different control strategies are obtained as shown in Fig. 11. It can be seen that traditional VC-SVM results in higher stator current harmonic distortion than those

obtained by 2-SMC-SVM schemes.

7. 2. Simulation Results With Parametric Uncertainty

To study the influence of the electrical parameter variation on the behavior of the DFIG, we also simulated the system for a +150% of the nominal rotor resistance and inductance at time t = 5.5s. The figure12 and 13 illustrates the evolution of the powers, we note from this result, the scheme (VC) has a slight variation due to the variations of Lr and Rr. The proposed method is robust against parameter variations and allows a fast and suitable dynamic response.
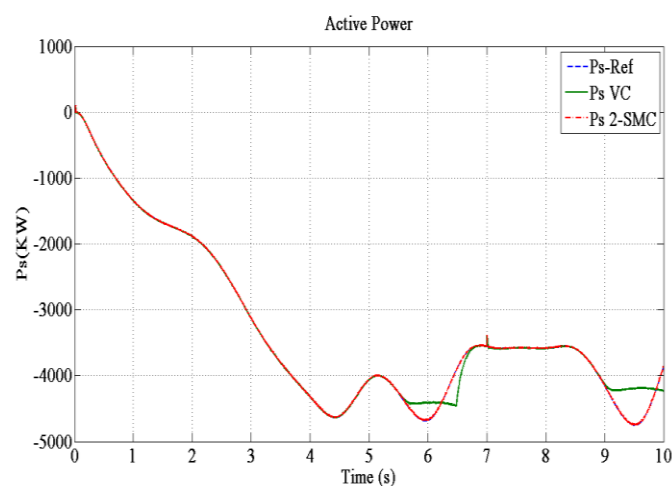
Figure 12. Simulated results of stator active power.
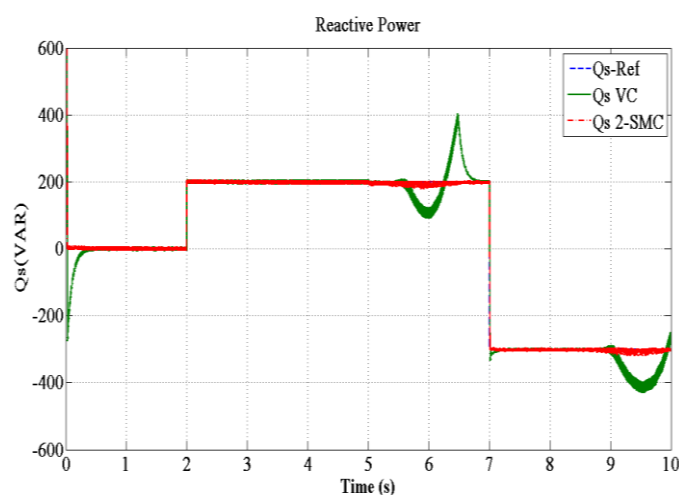

Figure 13. Simulated results of stator reactive power.

Table 1 presents the quantitative analysis of the two approaches. The comparison among the presented techniques for power control implicates that the proposed scheme gives much less chattering with a seamless transient response.

TABLE 1. Performances comparison of the two controllers.

Approach	VC	2-SMC

Sensitivity to parameters variation	Medium	Low
Stator current spectrum (THD)	Medium	Low
Chattering	Medium chattering	Small chattering
Ps transient performance	Medium settling time	Fast with low settling time
Rising time of Ps	0.12 s	0.01 s
Qs transient performance	Medium settling time	Low settling time
Rising time of Qs	0.18 s	0.016 s
Implementation Complexity	High	Medium

8. CONCLUSION

In this paper, second order sliding mode control for DFIG has been presented. The suggested control has been compared to the vector control. Simulation results demonstrate that the power ripples and total harmonics distortion (THD) are lower in second order sliding mode control compared with classical control. The effectiveness of the proposed controller was verified using simulation tests with a 5 KW DFIG. Moreover, the proposed controller was examined for DFIG parameter variations it has been demonstrated that the suggested algorithm gives better performance.

The advantages of the suggested algorithm are highlighted by the following points:

1. Good robustness against the machine's parameter

2. Improvements of the stator current spectrum.

APPENDIX

TABLE 2. Machine parameter and the WT values

Machine data		WT data	
Pn	5 KW	R	3.1915m
Vs	220/380 V	N	2
In	16 A	G	1
f	50 Hz	J	7.68 Kg.m^2
Ls	0.094 H	f	0 N.m.s^{-1}
Lr	0.088 H		
M	0.0135 H		
Rs	0.95 Ω		
Rr	1.08 Ω		

P   3

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