Fuzzy Sliding Mode Control Second Order of Wind Turbine Based on DFIG

Lakhdar Saihi
Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS) Centre de Développement des Energies Renouvelables (CDER), Adrar, Algeria
sadysaihi@live.fr

Youcef Bakou
Unité de Recherche en Energies Renouvelables en Milieu Saharien (URERMS) Centre de Développement des Energies Renouvelables (CDER), Adrar, Algeria
youcefbakou@gmail.com

Abdelkader Harrouz
Department of Hydrocarbon and Renewable energy, Ahmed Draïa University, LDDI laboratory
Adrar, Algeria
abd.harrouz@univ-adrar.edu.dz

Mohammed Boura
Department of Sciences Technology University of Tahri Mohammed Béchar, Algeria
b.mido@yahoo.fr

Ilhami COLAK
Department of Electrical Electronics Eng., Faculty of Engineering Architecture, Nisantasi University, Istanbul, Turkey
ilhcol@gmail.com

Korhan Kayisli
Department of Electrical Electronics Eng., Faculty of Engineering , Gazi University, Ankara, Turkey
korhankayisli@gmail.com

***Abstract*— *Abstract*- This paper study a robust fuzzy sliding mode second order control for a horizontal axis wind turbine based on doubly fed induction generator (DFIG) supplied directly in the stator by the grid and fed by converter side rotor (CSR) in rotor. In the first section, we present the model of the wind turbine system (mechanical and electrical part). In second part, in order to control the stator powers (active and reactive) of the DFIG, the robust control is proposed uses the combination between sliding mode second order strategy based on super twisting algorithm with fuzzy logic control is applied in order to reduce the chattering phenomenon and ameliorate the quality of energy on a classical sliding mode second order control. This technique (FSMSO) provides better performance and robustness for the DFIG control (reduce the chattering effect, ameliorate the quality of energy). Simulations results are presented and discussed for the whole system.**

Keywords— DFIG; fuzzy logic; sliding mode second order control; super twisting; chattering phenomenon.

I. INTRODUCTION

The wind energy considered among renewable energies and deserved solution to classical energy sources that pollute the climate, the wind is free availability in all world [1], [2]. The majority of wind turbines systems are fixed speed, when we use speed variable in turbines chain is augmenting due to many advantages. Doubly fed induction generators (DFIG) widely applied in variable speed wind of wind turbine chain. There are many advantages to using of DFIG in a wind energy chain [1], [2].

In the control part, various techniques of the control DFIG appeared; through them the Sliding Mode control second order. This strategy is a modern control method for nonlinear systems [2], [3]. It allows sequentially and systematically, selecting the Lyapunov function, to determine the control law of the system. Its principle is to establish in a constructive manner the control law of the nonlinear system by considering some state variables as virtual drives and develop intermediate control laws [4], [5], However, the SMCSO has a major disadvantage which is the chattering phenomenon created by the discontinuous part of this control. In order to remove this effect, one way to improve sliding mode second order controller performance is hybrid with fuzzy logic control, which can be applied to reduce the chattering effect and ameliorate the quality of energy of the SMCSO controller. The main objective of this paper is illustrating the feature and advantages of the fuzzy sliding mode second order for control the stator powers active and reactive of DFIG equipped on horizontal axis wind turbine [6].

This paper is organized as follow: in the second section, mechanical part (wind turbine) and electrical part (DFIG) model are presented. The third part is devoted to the fuzzy sliding mode second order control method of the DFIG. In next part is illustrated results of simulation and finally conclusions are summarized in the last section.

II. WIND TURBINE BASED ON DFIG MODEL

The wind turbine system converts the kinetic energy of the wind into mechanical energy. It is made up of the same blades (three blades) installed in a shaft connected to a speed multiplier having a conversion ratio G. This multiplier in turn drives the shaft of the electric generator (Fig. 1.) [1], [3], [4], [5].

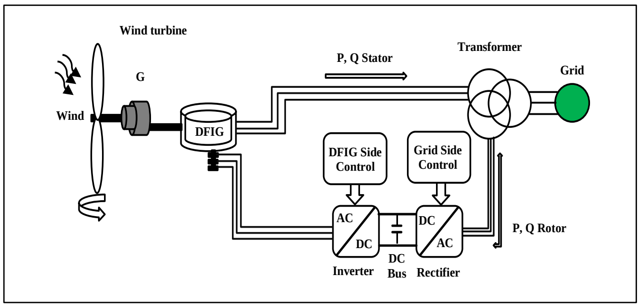

Fig. 1. Topology of DFIG system.

The wind power is obtain by [1], [2]:

$$P_t = \frac{1}{2}\,\rho\, S\, v^3\, C_p\,(\lambda,\beta) \qquad (1)$$

with; $C_p\,(\lambda,\beta) = \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\,\beta - 5\right) e^{-\left(\frac{21}{\lambda_i}\right)}$; $\lambda = \frac{r\,\Omega_t}{v}$.

where; ρ (kg.m^{-3}): air density, $S = \pi r^2$: sweep area of the turbine blade (m^2), v (m.s^{-1}): wind speed, $C_p\,(\lambda,\beta)$: power coefficient, λ : speed ratio, β : pitch angle.

A. Dfig Model

The DFIG model in the d–q reference frame is described as [3], [4]:

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s\, \varphi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_s\, \varphi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r)\, \varphi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_s - \omega_r)\, \varphi_{dr} \end{cases} \quad (2)$$

with; $\varphi_{dr} = l_s i_{ds} + l_m i_{dr}$; $\varphi_{qs} = l_s i_{qs} + l_m i_{qr}$; $\varphi_{dr} = l_r i_{dr} + l_m i_{ds}$; $\varphi_{qr} = l_r i_{qr} + l_m i_{qs}$: the stator and rotor flux.

The mechanical expression [4], [5]:

$$T_g - T_{em} = J\frac{d\Omega_t}{dt} + f\,\Omega_t \quad (3)$$

with; $T_{em} = p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds})$ in d-q reference frame.

The stator powers (active and reactive) in d-q reference frame, are written as [3], [4]:

$$\begin{cases} P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \\ Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \end{cases} \quad (4)$$

We applied the technique Field-oriented control of stator, in order to eliminate the coupling between the powers. The principle of this method consists in aligning of the stator vector flux φ_{ds} with the axis d allows getting constant electrical voltages and currents in permanent mode $\varphi_{ds} = \varphi_s$, $\varphi_{qs} = \frac{d\varphi_{qs}}{dt} = 0$ [3] , [4] , [5]:

According to FOC, the expression of the electromagnetic torque and stator powers active and reactive are simplified as [3], [4], [5]:

$$\begin{cases} T_{em} = -p(\varphi_s \frac{l_m}{l_s} i_{qr}) \\ P_s = -v_s \frac{l_m}{l_s} i_{qr} \\ Q_s = -v_s \frac{l_m}{l_s} i_{dr} + \frac{{v_s}^2}{l_s \cdot \omega_s} \end{cases} \quad (5)$$

The DFIG control stator powers (active and reactive) are achieved by the control of rotor currents of the DFIG. For that, a relationship between the rotor currents and the rotor voltages is illustrated [2], [3], [5]:

$$\begin{cases} v_{dr} = R_r i_{dr} + l_r \sigma \frac{di_{dr}}{dt} - (g\omega_s l_r \sigma i_{qr}) \\ v_{qr} = R_r i_{qr} + l_r \sigma \frac{di_{qr}}{dt} + g\omega_s l_r \sigma i_{dr} + g\, \frac{l_m v_s}{l_s} \end{cases} \quad (6)$$

with; $\sigma = (1 - \frac{{l_m}^2}{l_s \cdot l_r})$

III. Fuzzy Siding Mode Second Order Control Strategy of DFIG

Sliding mode second order control (SMSO-C) is one of the most interesting nonlinear control strategies. This technique generalizes the basic sliding mode concept through acting on the second-order time derivatives of the sliding surface, rather than affecting the first derivative as in the order of the first SMC. In order to reduce the effects of chattering phenomenon and unwanted mechanical effort which, is affected the energy quality. SMSO appears to be a very attractive solution [6], [7], [8].

There are different techniques used to synthesize the HOSM such as the twisting, super-twisting an, among others [9], [10], [11]. In this paper, the fuzzy super-twisting algorithm is proposed.

A. Control laws

The principle of control by sliding mode is to force the trajectories of the system to reach a given surface, sliding surface, and then stay there [9], [10], [11]. And to design it, one must follow three steps which are:

- The choice of the sliding surface:

$$s(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) \quad (7)$$

where; $\lambda > 0$, n is the order of the system; $e(t)$: error of the variable to be controlled; $s(t)$: sliding surface [10], [11].

In this case n=1 then $s(t) = e(t)$, we choose the error between the stator powers of the reference ($P_{s\text{-ref}}$, $Q_{s\text{-ref}}$) and measured stator powers (P_s, Q_s) as surfaces in second order sliding mode control, so that we can write the following expression:

$$\begin{cases} e_{P_s} = P_s^{ref} - P_s \\ e_{Qs} = Q_s^{ref} - Q_s \end{cases} \quad (8)$$

The derivative of these errors is given [12], [13]:

$$\begin{cases} \dot{e}_{P_s} = \dot{P}_s^{ref} + v_s \frac{l_m}{l_s} i_{qr} \\ \dot{e}_{Q_s} = \dot{Q}_s^{ref} + v_s \frac{l_m}{l_s} i_{dr} \end{cases} \quad (9)$$

we have; $i_{dr} = \frac{1}{l_r\sigma}(v_{dr} - R_r i_{dr} - g\omega_s l_r \sigma i_{qr})$; $i_{qr} = \frac{1}{l_r\sigma}\left(v_{qr} - R_r i_{qr} - g\omega_s l_r \sigma i_{dr} - g\,\frac{l_m v_s}{l_s}\right)$.

By replacing the expression of i_{dr} and i_{qr} we obtain:

$$\begin{cases} \dot{e}_{P_s} = \dot{P}_s^{ref} + v_s \frac{l_m}{l_s}\frac{1}{l_r\sigma}\left(v_{qr} - R_r i_{qr} - g\omega_s l_r \sigma i_{dr} - g\,\frac{l_m v_s}{l_s}\right) \\ \dot{e}_{Q_s} = \dot{Q}_s^{ref} + v_s \frac{l_m}{l_s}\frac{1}{l_r\sigma}(v_{dr} - R_r i_{dr} - g\omega_s l_r \sigma i_{qr}) \end{cases} \quad (10)$$

Second derivative of errors can get [11], [12]:

$$\begin{cases} \ddot{e}_{P_s} = \ddot{P}_s^{ref} + \frac{l_m v_s}{l_s l_r \sigma}(-R_r i_{qr} - g\omega_s l_r \sigma i_{dr}) + \left(\frac{l_m v_s}{l_s l_r \sigma}\right)\dot{v}_{qr} \\ \ddot{e}_{Q_s} = \ddot{Q}_s^{ref} + \frac{l_m v_s}{l_s l_r \sigma}(-R_r i_{dr} - g\omega_s l_r \sigma i_{qr}) + \left(\frac{l_m v_s}{l_s l_r \sigma}\right)\dot{v}_{dr} \end{cases} \quad (11)$$

- The establishment of conditions of existence

The convergence condition is defined by the LYAPUNOV function V(x), which makes the surface attractive and invariant [11]. The control objective is to drive the system trajectory to reach the sliding manifold $S = \dot{S} = 0$ in finite time [11], [12], [14]. The sliding mode will exist only if the following condition is verified:

$$\mathrm{V(x)} = S\,\dot{S} < 0 \quad (12)$$

- The determination of the control law

There are several techniques of algorithms generating the convergence of S and $\dot{S}$ to zero. The most used in literature are twisting and super-twisting [10]. In the case of a SMSO control, the control appears explicitly in $\ddot{S}$ can be written in the following form [12], [13], [15]:

$$\ddot{S} = \rho(x,t) + \varphi(x,t)v \tag{13}$$

where; $\rho(x,t) = \frac{\delta}{\delta u}\dot{S}(x,t,u)$; $\varphi(x,t) = \frac{\delta}{\delta t}\dot{S}(x,t,u) + \frac{\delta}{\delta x}\dot{S}(x,t,u)[A(x)x + B(x)u]$.

We can written $\ddot{e}_{P_s}, \ddot{e}_{Q_s}$ the same form of eq (19) to appear the control vector u, then we can applied the super twisting algorithm [16], [17]:

$$\begin{cases} \ddot{e}_{P_s} = \dot{G}_{P_s} + \left(\frac{l_m v_s}{l_s l_r \sigma}\right)\dot{v}_{qr} \\ \ddot{e}_{Q_s} = \dot{G}_{Q_s} + \left(\frac{l_m v_s}{l_s l_r \sigma}\right)\dot{v}_{dr} \end{cases} \tag{14}$$

with; $\dot{G}_{P_s} = \ddot{P}_s^{ref} + \frac{l_m v_s}{l_s l_r \sigma}\left(-R_r i_{qr} - g\omega_s l_r \sigma i_{dr}\right)$; $\dot{G}_{Q_s} = \ddot{Q}_s^{ref} + \frac{l_m v_s}{l_s l_r \sigma}\left(-R_r i_{dr} - g\omega_s l_r \sigma i_{qr}\right)$.

We can determine V_{qr} and V_{dr}:

$$\begin{cases} V_{qr} = u_{P_s} + \alpha_{P_s}|S(P_s)|^{\rho} sign\left(S(P_s)\right) \\ V_{dr} = u_{Q_s} + \alpha_{Q_s}|S(Q_s)|^{\rho} sign\left(S(Q_s)\right) \end{cases} \tag{15}$$

with; $u_{P_s} = w_{P_s} sign\left(S(P_s)\right)$, $u_{Q_s} = w_{Q_s} sign\left(S(Q_s)\right)$, $w_{P_s} > \frac{C_{P_s}}{K_{P_s m}}$; $\alpha_{P_s}^2 \geq \frac{4C_{P_s}K_{P_s M}(w_{P_s}+C_{P_s})}{K_{P_s m}^2 K_{P_s m}(w_{P_s}+C_{P_s})}$; $0 < \rho \leq 1$; $w_{Q_s} > \frac{C_{Q_s}}{K_{Q_s m}}$; $\alpha_{Q_s}^2 \geq \frac{4C_{Q_s}K_{Q_s M}(w_{Q_s}+C_{Q_s})}{K_{Q_s m}^2 K_{Q_s m}(w_{Q_s}+C_{Q_s})}$; $0 < \rho \leq 1$

B. *Fuzzy second order sliding mode control*

In order to improve the performance of DFIG in the context of wind power production, we are interested in the new control technique proposed in this article which improves performance and reduces the chattering phenomenon of sliding mode control, this technique is a hybrid method which combines Fuzzy and SMSOC. The structure of the fuzzy sliding mode second order controller is shown in (Fig .2.) [9], [10], [18], [19]:

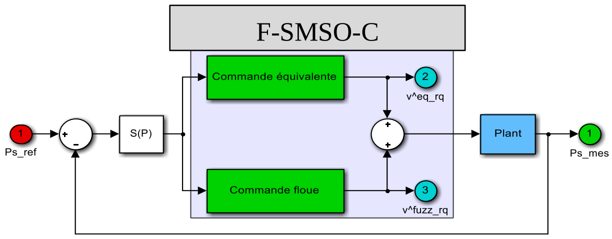

Fig. 2. Block diagram of the fuzzy sliding mode second order controller.

Fuzzy sliding mode second order controller (FSMOS) is a modification of the super twisting algorithm, where the switching controller term $\boldsymbol{sing(S(x))}$, has been replaced by a fuzzy controller as given below [20], [21], [22]:

$$u = u_{fuzzy\_1} + u_{fuzzy\_2} \tag{16}$$

with; $\dot{u}_1 = -w.S_{fuzzy}(P_s, Q_s)$; $u_{fuzzy\_2} = -\alpha\left|S_{fuzzy}(P_s, Q_s)\right|^{\rho}.S_{fuzzy}(P_s, Q_s)$.

$$\begin{cases} V_{qr} = u_{fuzzy P_s} + \alpha_{P_s}\left|S_{fuzzy}(P_s)\right|^{\rho} S_{fuzzy}\left(S(P_s)\right) \\ V_{dr} = u_{fuzzy\_Q_s} + \alpha_{Q_s}\left|S_{fuzzy}(Q_s)\right|^{\rho} S_{fuzzy}\left(S(Q_s)\right) \end{cases} \tag{17}$$

with; $u_{fuzzy\_Q_s} = w_{P_s} S_{fuzzy}\left(S(P_s)\right)$; $u_{fuzzy\_Q_s} = w_{P_s} S_{fuzzy}\left(S(Q_s)\right)$.

Recently, fuzzy logic (FL) controller one of the most interesting nonlinear control approaches and more robust than classical nonlinear controllers, is the important branches of strategies artificial intelligence that is able to reproduce human reasoning and occupies a large place in modern research fields [13]. This technique becomes very dominant in several industrial fields. The fuzzy logic setting does not request mathematical model, but uses inferences with multiple rules, these rules are described in table 2; based on linguistic information of the dynamic behaviour system, can applied with imprecise inputs [13].

The basic structure of a fuzzy logic controller consists three main parts: Fuzzification, Inference engine, Defuzzification, it has two inputs and an output, the block diagram of the FL controller, is shown in (Fig .3.).

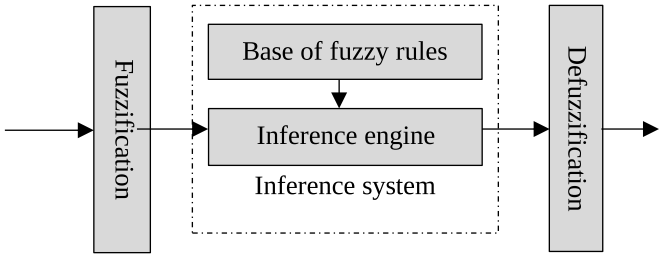

Fig. 3. System FL.

To generate the fuzzy system, we defined three fuzzy sets Negative, Zero and Positive, shown in Table 1, the Membership functions in triangular shape has been defined as follows [13], [23], [24]:

TABLE I. MEMBERSHIP FUNCTIONS.

BN	big negative	**MN**	medium negative	**Z**	Zero	**MN**	medium positive	**MP**	medium positive

The rule base of Fuzzy was defined in the Table 2 to develop the inference system:

TABLE II. RULE BASES OF CURRENT FUZZY CONTROLLER.

DE/E	**N**	**Z**	**P**
N	BN	MN	Z
Z	MN	Z	MP
P	Z	MP	BP

To achieve the objective, a Mamdani-type fuzzy logic system is utilized, and the membership function of the resulting aggregation is created by maximum method. The defuzzification of the control output is attained by adopting the centroid operator. Table 3 shows the parameters of FL controller:

TABLE III. PARAMETERS OF FL CONTROLLER.

FIS type	Mamdani
And method	Min
Or method	Max
Implication	Min
Aggregation	Max
Defuzzification	Centroid

IV. SIMULATION RESULTS

The fuzzy sliding mode second order and the conventional sliding mode second order strategies used for the control of DFIG stator powers (active/ reactive) are implemented in MATLAB-Simulink.

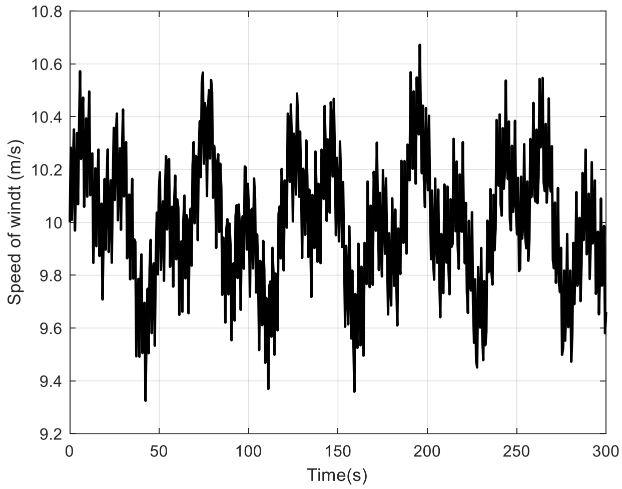

Fig. 4. Wind speed and rotor speed of DFIG.

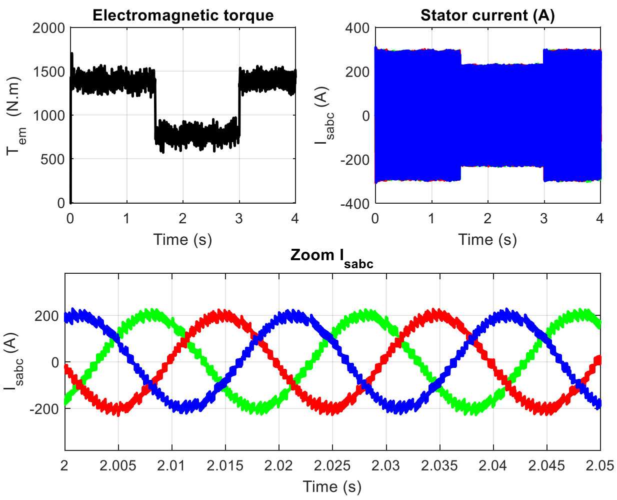

Fig. 5. Current stator and electromagnetic torque of DFIG.

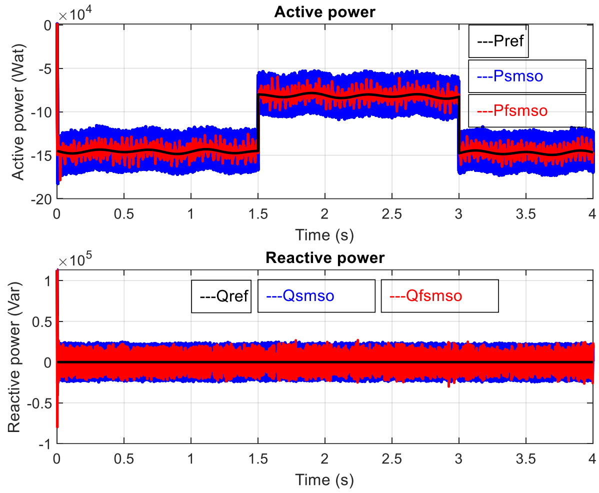

Fig. 6. Trajectory tracking of active reactive power.

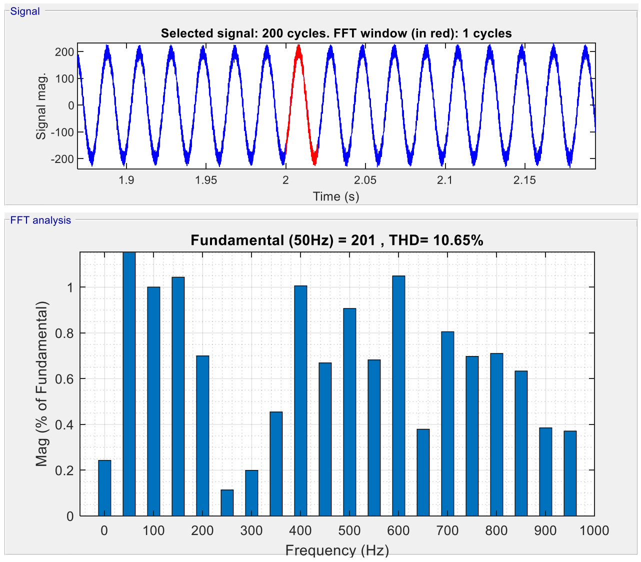

Fig. 7. Stator currents THD with SMSO.

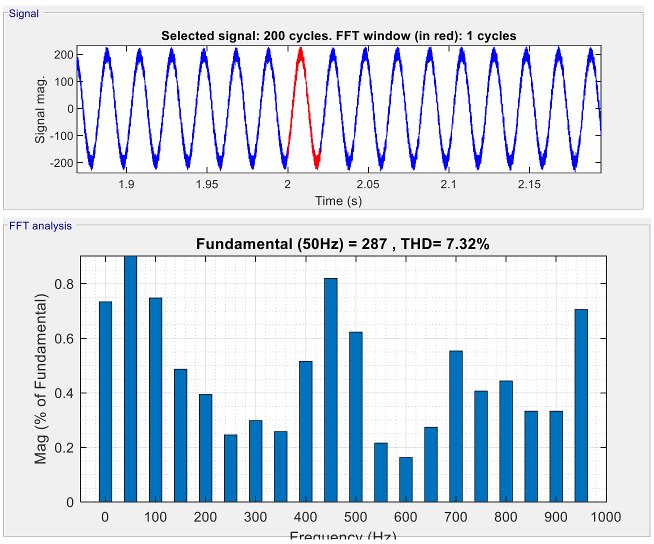

Fig. 8. Stator currents THD with FSMSO.

Fig. 4 is presented wind speed on (m/s) [± 10 m/s] and Fig. 5 present the behavior of the stator current and electromagnetic torque of DFIG for the FSMSO strategies. All these variables depend on the wind speed variation. Fig. 6 presents the stator powers (active and reactive) of DFIG controlled by the proposed FSMSO (red line) and SMSO (blue line), and their references (black line).

The results obtained illustrate that the proposed FSMSO controller presents better performance robustness in terms of reference tracking (time response, overshoot), sensitivity to perturbation and chattering phenomena compared to the conventional SMSO algorithm even in the presence of reference variations. Also, Fig. 8 illustrates the THD value is greatly improved with FSMSO (7.32%) compared to SMSO (10.65%), which allows improving the quality of the energy generated by wind turbine based on DFIG.

V. Conclusions

The fuzzy sliding mode second order control (FSMSO-C) of a horizontal axis wind turbine system associated with DFIG (doubly fed induction generator) connected directly to the grid by the stator and fed by CSR (converter side rotor) has been presented in this study. The results of simulation obtained with the proposed control (FSMSO) compared to the conventional second order sliding mode strategy, it can be concluded that this technique (FSMSO) is more efficient in tracking a time-varying trajectory, in addition to reduce chattering and improve the quality of energy of the generated power when the speed is varying.

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