Hybrid Control Using Fuzzy Sliding Mode Control of Doubly Fed Induction Machine

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***Abstract*— In this article, we present a new sliding mode control strategy applied to the doubly fed induction machine. The proposed control combines sliding mode and fuzzy logic to achieve robust control. This technique finds its strongest justification for the problem of using a nonlinear control law robust to the uncertainties of the model. The objective of this control is improved the outputs generated by the doubly fed induction machine supply decoupled by orientation of the stator flux. Finally, the performance of the system was tested and compared by simulation in terms of follow-up of instructions, and the robustness with respect to the parametric variations of this machine. The simulation results obtained clearly show the effectiveness of this control.**

***Keywords*— doubly fed induction machine, sliding mode control, fuzzy logic, hybrid control, Stator flux orientation.**

I. INTRODUCTION

For several years, sliding mode control (SMC) has remained one of the most studied areas of control in research. Indeed, the robustness and the simplicity which characterize it, are the essential reasons which often lead us to seek more on this technique.

The sliding mode control algorithm is classified in VSS (Variable Structure System) control systems. This technique is based on the principle that it is easier to control a 1st order system than it is to control an nth order system, whether linear or not. The principle of this type of system with variable structure consists in bringing, whatever the initial conditions, the point representative of the evolution of the system on a hyper surface of the phase space (representing a set of relations, static, between state variables). The surface considered is then designated as being the sliding or switching surface [1]. The resulting dynamic behavior, called the ideal sliding regime, is completely determined by the parameters and equations defining the surface. The advantage of obtaining such a behavior is twofold: on the one hand, there is a reduction in the order of the system, and on the other hand, the sliding regime insensitive to disturbances occurring in the same directions as the inputs.

The sliding mode control has largely proven its effectiveness through reported theoretical studies, its main fields of application are robotics and electric motors [2-7]. The advantage that such a control provides and which makes it so important is its robustness with respect to the perturbations and uncertainties of the model. However, these performances are obtained at the cost of certain disadvantages [8-10]:

- A chattering or chattering phenomenon caused by the discontinuous part of this control and which can have a harmful effect on the actuators;
- The system is subjected at all times to a high control in order to ensure its convergence to the desired state and this is not desirable.

Among the solutions proposed to these problems, mention may be made of limit-band sliding mode control which consists in replacing the switching function in the control by a saturation function.

In fact, this solution is only a special case of the fuzzy sliding mode control, hence the interest in using a control which combines fuzzy logic and sliding mode in order to obtain a robust and smooth control. The control proposed in this article is called the fuzzy sliding mode control. In order to test its efficiency and robustness, the latter is applied to the control of the doubly fed induction machine, taking into account its kinematic constraint and its dynamic model.

The article is structured as follows: First, a dynamic model of the doubly fed induction machine (DFIM) was proposed under Matlab/Simulink. Then, a sliding mode control strategy of the doubly fed induction machine which allows independent control of the output state variables. In the fourth section, we synthesize a sliding-fuzzy control law of DFIM. Finally, robustness tests of the machine control will be carried out, simulations will be presented.

II. MATHEMATICAL MODELLING OF DFIM

The dynamic model of DFIM in (d, q) reference, which includes both the electrical and mechanical dynamics, can be described by the matrix form as follows [11, 12]:

$$\dot{X} = AX + BU \tag{1}$$

Where:

$$X = [\varphi_{sd} \quad \varphi_{sq} \quad I_{rd} \quad I_{rq}]^T, U = [V_{sd} \quad V_{sq} \quad V_{rd} \quad V_{rq}]^T$$

$$[A] = \begin{bmatrix} -\frac{1}{T_s} & \omega_s & \frac{M}{T_s} & 0 \\ -\omega_s & -\frac{1}{T_s} & 0 & \frac{M}{T_s} \\ \alpha & -\beta\omega & -\delta & (\omega_s - \omega) \\ \beta\omega & \alpha & -(\omega_s - \omega) & -\delta \end{bmatrix} ;$$

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} \end{bmatrix}$$

With: $\sigma = 1 - \frac{M^2}{L_r L_s}$; $T_r = \frac{L_r}{R_r}$; $T_s = \frac{L_s}{R_s}$; $\alpha = \frac{M}{\sigma L_r L_s T_s}$; $\beta = \frac{M}{\sigma L_r L_s}$; $\delta = \frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{M^2}{L_s T_s L_r}\right)$

The mechanical equation is of the following form:

$$J\frac{d\Omega}{dt} = C_{em} - C_r - f\Omega \quad (2)$$

With:

C_{em} and C_r : the electromagnetic torque and the resisting torque (the mechanical load) ;

f and J : coefficient of friction and moment of inertia of the rotor shaft.

The electromagnetic torque is expressed as a function of currents and flows by:

$$C_{em} = P\frac{M}{L_s}\left(\varphi_{sq}I_{rd} - \varphi_{sd}I_{rq}\right) \quad (3)$$

With respectively:

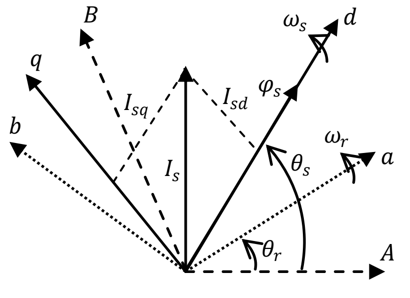
I_{sd}, I_{sq}, I_{rd} and I_{rq} : Direct and quadratic stator and rotor currents of the two-phase system;

$\varphi_{sd}, \varphi_{sq}, \varphi_{rd}$ and φ_{rq}: Direct and quadrature stator and rotor flux of the two-phase system;

P: The number of pole pairs of the DFIM.

The examination of the expression of the torque of the machine shows that it results from a difference of two components in quadrature of the stator current and of the rotor flux which presents a complex coupling between the quantities of the machine. The control is that linked to the rotating field so that the axis (d) coincides with the desired direction of the flow, which can be rotor, stator, or air gap. Thus it is possible to orient the different flows of the machine [13, 14].

The principle of the orientation of the stator flux in the direct transformation of park is illustrated in figure 1.



(A) : Stator phase
(a) : Rotor phase
(dq) : Park landmark

Fig. 1. Stator flux orientation on the d axis [11].

By choosing a (d, q) frame of reference linked to the rotating stator field and by aligning the stator flux vector with the d axis, this results in: $\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$.

If one supposes that the electrical network is stable, that leads to φ_s constant. In addition, the stator resistance can be neglected. Based on these considerations, we obtain: $V_{sd} = 0$, $V_{sq} = V_s$ and $V_{sq} = V_s/\omega_s$.

Adapting the above equations to the simplifying assumptions gives:

$$\begin{cases} I_{sd} = \frac{\varphi_s}{L_s} - \frac{M}{L_s}I_{rd} \\ I_{sq} = -\frac{M}{L_s}I_{rq} \end{cases} \quad (4)$$

$$\begin{cases} \varphi_{rd} = \left(L_r - \frac{M^2}{L_s}\right)I_{rd} + \frac{V_s M}{\omega_s L_s} \\ \varphi_{rq} = \left(L_r - \frac{M^2}{L_s}\right)I_{rd} \end{cases} \quad (5)$$

$$\begin{cases} V_{rd} = R_r I_{rd} + \sigma L_r \frac{dI_{rd}}{dt} + \frac{M}{L_s}V_{sd} \\ \qquad -(\omega_s - \omega)\sigma L_r I_{rq} \\ V_{rq} = \left(R_r + \frac{M^2}{L_s T_s}\right)I_{rq} + \sigma L_r \frac{dI_{rq}}{dt} + \frac{M}{L_s}V_{sq} \\ \qquad -\frac{M}{L_s}\omega\varphi_{sd} + (\omega_s - \omega)\sigma L_r I_{rd} \end{cases} \quad (6)$$

The Backstepping approach, which we will apply to the control of the DFIM, is based on the principle of the orientation of the stator flux.

The model of the machine, equation 1, in the reference (d, q) is given by:

$$\begin{cases} \dot{\varphi}_{sd} = \frac{M}{T_s}I_{rd} - \frac{1}{T_s}\varphi_{sd} + V_{sd} \\ \dot{\varphi}_{sq} = \frac{M}{T_s}I_{rq} - \omega_s\varphi_{sd} + V_{sq} \\ \dot{I}_{rd} = -\delta I_{rd} + (\omega_s - \omega)I_{rq} + \alpha\varphi_{sd} - \frac{MV_{sd}}{\sigma L_s L_r} + \frac{V_{rd}}{\sigma L_r} \\ \dot{I}_{rd} = -(\omega_s - \omega)I_{rd} - \delta I_{rq} + \beta\omega\varphi_{sd} - \frac{MV_{sq}}{\sigma L_s L_r} + \frac{V_{rq}}{\sigma L_r} \\ \dot{\Omega} = -\frac{1}{J}\left(P\frac{M}{L_s}\varphi_{sd}I_{rq} + f\Omega + C_r\right) \end{cases} \quad (7)$$

III. Sliding Mode Control

The primary concept of SMC is first to attract the states of the machine right into a certainly decided on region, after which to layout a control regulation with a view to usually hold the machine in that region [14]. In summary, a SMC is split into 3 parts:

A. Choice of switching surface

For a non-linear system presented in the following form:

$$\begin{aligned} \dot{X} &= f(X,t) + g(X,t).u(X,t) \\ X &\in R^n, u \in R \end{aligned} \quad (8)$$

Where:

$f(X,t)$, $g(X,t)$ are continuous and unsure nonlinear functions, meant limited.

We take the shape of trendy equation given with the aid of using J.J.E Slotine to decide the sliding surface given with the aid of using [15]:

$$\begin{aligned} S(X) &= \left(\frac{d}{dt} + \lambda\right)^{n-1} e \\ e &= X^d - X \end{aligned} \quad (9)$$

Where λ : positive coefficient; e : error on the signal to be adjusted; n : system order.

B. Convergence condition

The convergence situation is described with the aid of using the equation Lyapunov [16], it makes the region appealing and invariant.

$$S(X)\dot{S}(X) < 0 \quad (10)$$

C. Control calculation

The control set of rules is described with the aid of using the relation:

$$u = u^{eq} + u^{n} \quad (11)$$

Where:

u^{eq} : is the equal control vector, may be acquired with the aid of using thinking about the situation for the sliding regime;

u^{n} : is the switching part of the control (the correction factor).

In order to relieve the unwanted chattering phenomenon, J.J.E Slotine and W. Li proposed a method to lessen it, with the aid of using the "sign" function of the switching surface [15]. The switching a part of the control u^{n} is described with the aid of using:

$$u^{n} = k\ \mathrm{sign}\big(S(X)\big) \quad (12)$$

With k is the controller gain.

To obtain the sliding mode control of a doubly-fed induction machine, the surfaces are chosen according to the error between the reference input signal and the measured signals as follows [14]:

A. Speed regulation surface

For $n = 1$, the speed control manifold can be obtained from equation (22) as follow:

$$S(\Omega) = \Omega_{ref} - \Omega \quad (13)$$

The derivative of the surface is:

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} - \dot{\Omega} \quad (14)$$

Substituting the expression (equation (7)) of $\dot{\Omega}$ in equation (14), we obtain:

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} + \frac{1}{J}\left(\frac{p.M}{L_s}\varphi_{sd} I_{rq} + f\Omega + C_r\right) \quad (15)$$

We take:

$$I_{rq} = I_{rq}^{eq} + I_{rq}^{n} \quad (16)$$

The control appears clearly in the following equation:

$$\dot{S}(\Omega) = \dot{\Omega}_{ref} + \frac{1}{J}\left(\frac{p.M}{L_s}\varphi_{sd}\left(I_{rq}^{eq} + I_{rq}^{n}\right) + f\Omega + C_r\right) (17)$$

During the sliding mode and in steady state, we have: $S(\Omega) = 0$, $\dot{S}(\Omega) = 0$ and $I_{rq}^{n} = 0$. The equation of the equivalent control becomes:

$$I_{rq}^{eq} = -\frac{J L_s}{pM\varphi_{sd}}\left(\dot{\Omega}_{ref} + \frac{f}{J}\Omega + \frac{C_r}{J}\right) \quad (18)$$

During the convergence mode, the condition $S(\Omega)\dot{S}(\Omega) < 0$ must be verified. By replacing the expression of the equivalent control in the expression of the derivative of the surface, we obtain:

$$\dot{S}(\Omega) = \frac{pM\varphi_{sd}}{J L_s} I_{rq}^{n} \quad (19)$$

We ask:

$$I_{rq}^{n} = k_{I_{rq}}.sat\big(S(\Omega)\big) \quad (20)$$

To check the condition of stability of the system, the constant $k_{I_{rq}}$ must be negative.

B. Stator flux regulation surface

The stator flux regulation surfaces, given by the following equations:

$$S(\varphi_{sd}) = \varphi_{sd}^{ref} - \varphi_{sd} \quad (21)$$

$$\dot{S}(\varphi_{sd}) = \dot{\varphi}_{sd}^{ref} - \dot{\varphi}_{sd} \quad (22)$$

We replace the expression of $\dot{\varphi}_{sd}$ from equation (7) in equation (22):

$$\dot{S}(\varphi_{sd}) = \dot{\varphi}_{sd}^{ref} - \left(V_{sd} + \frac{M}{T_s} I_{rd} - \frac{1}{T_s}\varphi_{sd}\right) \quad (23)$$

The control current I_{rd}^{ref} defined by:

$$I_{rd}^{ref} = I_{rd}^{eq} + I_{rd}^{n} \quad (24)$$

During the sliding mode and in the steady state, we have: $S(\varphi_{sd}) = 0$, $\dot{S}(\varphi_{sd}) = 0$ and $I_{rd}^{n} = 0$. Then the equivalent command is given by:

$$I_{rd}^{eq} = \frac{T_s}{M}\left(\dot{\varphi}_{sd}^{ref} - V_{sd} + \frac{1}{T_s}\varphi_{sd}\right) \quad (25)$$

By replacing the expression of the equivalent command in the expression of the derivative of the surface, we obtain:

$$\dot{S}(\varphi_{sd}) = -\frac{M}{T_s} I_{rd}^{n} \quad (26)$$

So, for the condition $S(\varphi_{sd}) \cdot \dot{S}(\varphi_{sd}) < 0$ to be verified, we take:

$$I_{rd}^{n} = k_{I_{rd}}.sat\big(S(\varphi_{sd})\big) \quad (27)$$

With: $k_{I_{rd}}$ positive constant.

C. Direct rotor current regulation surface with limitation

In order to limit all possible overshoots of the current I_{rd}, we add a current limiter defined by:

$$I_{rd}^{lim} = I_{rd}^{max}.sat(I_{rd}) \quad (28)$$

The forward stator current error is defined by:

$$e = I_{rd}^{lim} - I_{rd} \quad (29)$$

The expression of the direct stator current control surface is given by:

$$S(I_{rd}) = e = I_{rd}^{lim} - I_{rd} \quad (30)$$

The derivative of the surface is:

$$\dot{S}(I_{rd}) = \dot{I}_{rd}^{lim} - \dot{I}_{rd} \quad (31)$$

We replace the expression of $\dot{I}_{rd}$ from equation (7) in equation (31), we find:

$$\dot{S}(I_{rd}) = \dot{I}_{rd}^{lim} - \left(-\delta I_{rd} + (\omega_s - \omega)I_{rq} + \alpha\varphi_{sd} - \frac{M}{\sigma L_s L_r}V_{sd} + \frac{1}{\sigma L_r}V_{rd}\right) \quad (32)$$

The control reference voltage V_{rd}^{ref} is defined by:

$$V_{rd}^{ref} = V_{rd}^{eq} + V_{rd}^{n} \quad (33)$$

During the sliding mode and in the steady state, we have: $S(I_{rd}) = 0$, $\dot{S}(I_{rd}) = 0$ and $V_{rd}^{n} = 0$.

So, the equivalent command is given by:

$$V_{rd}^{eq} = \left(\dot{I}_{rd}^{lim} + \delta I_{rd} - (\omega_s - \omega)I_{rq} - \alpha\varphi_{sd} + \frac{M}{\sigma L_s L_r}V_{sd}\right)\sigma L_r \quad (34)$$

We replace the expression of the flow φ_{sd} (equation 4 with $I_{sd} = 0$), the expression (34) becomes:

$$V_{rd}^{eq} = \left(\dot{I}_{rd}^{lim} + \frac{1}{\sigma T_r}I_{rd} + \frac{M}{\sigma L_s L_r}V_{sd} - (\omega_s - \omega)I_{rq}\right)\sigma L_r \quad (35)$$

By replacing the expression of the equivalent control (equation 35) in the expression of the derivative of the surface, we obtain:

$$\dot{S}(I_{rd}) = -\frac{1}{\sigma L_r}V_{rd}^{n} \quad (36)$$

For the condition $S(I_{rd})\dot{S}(I_{rd}) < 0$ must be verified, we take:

$$V_{rd}^{n} = k_{V_{rd}}.sat(S(I_{rd})) \quad (37)$$

With: $k_{V_{rd}}$ positive constant.

D. *Quadrature rotor current regulation surface with limitation*

In order to limit all possible overshoots of the current I_{rq}, we add a current limiter defined by:

$$I_{rq}^{lim} = I_{rq}^{max}.sat(I_{rq}) \quad (38)$$

The equation for the quadrature stator current control can be obtained by:

$$S(I_{rq}) = I_{rq}^{lim} - I_{rq} \quad (39)$$

The derivative of the surface is:

$$\dot{S}(I_{rq}) = \dot{I}_{rq}^{lim} - \dot{I}_{rq} \quad (40)$$

We replace the expression of the current I_{rq} from equation (7) in equation (40):

$$\dot{S}(I_{rq}) = \dot{I}_{rq}^{lim} - \left(-(\omega_s - \omega)I_{rd} - \delta I_{rq} + \beta\omega\varphi_{sd} - \frac{M}{\sigma L_s L_r}V_{sq} + \frac{1}{\sigma L_r}V_{rq}\right) \quad (41)$$

The control reference voltage V_{rq}^{ref} is defined by:

$$V_{rq}^{ref} = V_{rq}^{eq} + V_{rq}^{n} \quad (42)$$

During the sliding mode and in steady state, we have: $S(I_{rq}) = 0, \dot{S}(I_{rq}) = 0$ and $V_{rq}^{n} = 0$.

So, the equivalent command is given by:

$$V_{rq}^{eq} = \left(\dot{I}_{rq}^{lim} + (\omega_s - \omega)I_{rd} + \delta I_{rq} - \beta\omega\varphi_{sd} + \frac{M}{\sigma L_s L_r}V_{sq}\right)\sigma L_r \quad (43)$$

By replacing the expression of the equivalent control in the expression of the derivative of the surface, we obtain:

$$\dot{S}(I_{rq}) = -\frac{1}{\sigma L_r}V_{rq}^{n} \quad (44)$$

For the condition $S(I_{rq})\dot{S}(I_{rq}) < 0$ must be verified, we take:

$$V_{rq}^{n} = k_{V_{rq}}.sat\left(S(I_{rq})\right) \quad (45)$$

With:

$k_{V_{rq}}$ positive constant.

IV. FUZZY SLIDING MODE CONTROL

The predominant downside of sliding mode control is the excessive switching frequency (chattering). This phenomenon is unwanted due to the fact it could excite unmodeled excessive frequency modes withinside the controlled system.

To remedy this phenomenon, a control that will provide performance prediction even if the system model is not well known is needed. This control must also adapt to variations in parameters or external disturbances. These types of control are generally called "intelligent control", working primarily on the principles of fuzzy logic and genetic algorithms.

A. *Principle of fuzzy logic*

In conventional set theory, an element does or does not belong to a set, so the degree to which an element belongs to a set can only be zero or equal to unity. On the other hand in the theory of fuzzy sets, an element can more or less belong to a set, the degree of membership of an element to a fuzzy set can take any value included in the interval [0, 1].

B. *Structure of a fuzzy controller*

Unlike conventional tuning techniques, fuzzy logic tuning does not use specific or precise formulas or mathematical relationships. But, it manipulates inferences with several fuzzy rules based on AND, OR, THEN, … etc. Fuzzy operators, applied to linguistic variables [14, 17-19].

A fuzzy logic regulator consists of the following four parts: the basis of the rules, the fuzzification, the inference engine and the defuzzification.

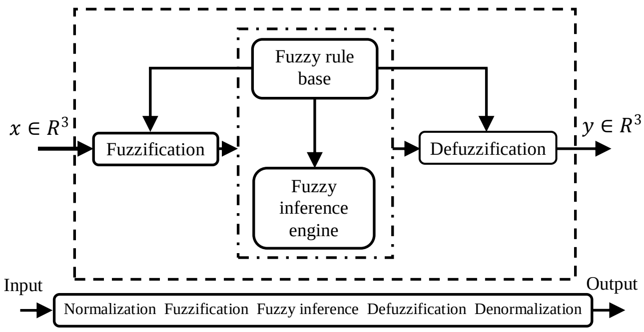


Fig. 2. General block diagram of a fuzzy controller [18].

C. *Development of a fuzzy regulator for the DFIM*

In what follows, the active and reactive power regulators are replaced by a sliding-fuzzy mode regulator to obtain robust high-performance regulation. An equivalent control part (SMC) and a fuzzy logic control (FLC) part are contained in this fuzzy sliding mode control (FSMC), figure (3), proposed by the following equation:

$$u_{FSMC} = u_{eq} + u_f \quad (46)$$

Where:

u_{eq} is the equivalent control which indicates the notion of the state trajectory along the sliding surface.

u_f is the fuzzy control (attractive), is a constant, which is set to satisfy the robustness requirement the mathematical development of this control is given in the previous section.

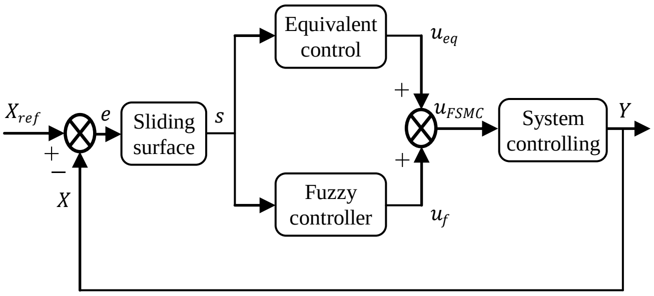


Fig. 3. Schematic of hybrid control slidnig-fuzzy.

The fuzzy controller developed in this work is by the following figure:

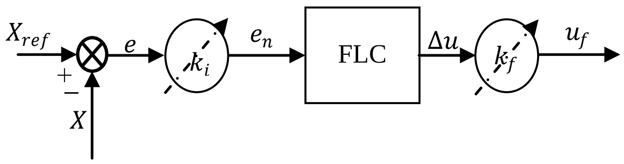


Fig. 4. Block diagram of a fuzzy controller.

In the figure above, the proposed fuzzy controller is composed by: A normalization factor k_i associated with the error (e) and k_f associated with the variation of the control Δu, fuzzification block of the error, fuzzy control rules, decide the control gains k_i according to the current operating state of the controlled system and a defuzzification block used to convert the fuzzy control variation to a digital value.

In the proposed controller (fuzzy logic system of the Mamdani type), we note that i1 is important to choose the values of k_i and k_f. A good choice and with a good distribution can guarantee a successful conception. On the other hand, a bad choice leads to long corrections in the following steps; it is often even necessary to redefine the ranges of values in order to avoid failure in the design. A good choice requires experience and knowledge of the system to be controlled.

Fuzzy rules can be written as shown in table I.

TABLE I. THE BASIS RULES OF THE FSMC.

Input	Negative Big	Negative Medium	Zero	Positive Medium	Positive Big
Output	Positive Big	Positive Medium	Zero	Negative Medium	Negative Big

The membership functions for input and output are shown in Figure (5) and Figure (6), respectively.

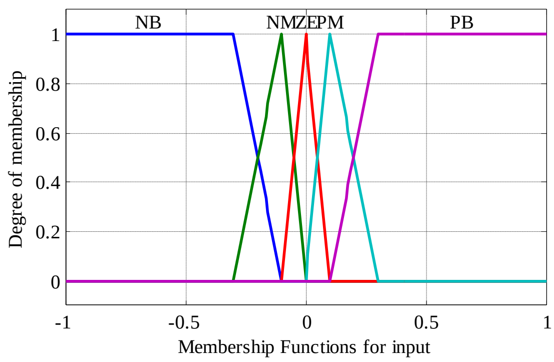


Fig. 5. Membership functions of input (e).

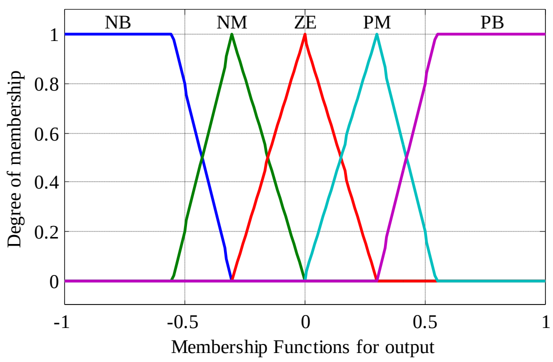


Fig. 6. Membership functions of output (u_f).

The block diagram of FSMC of a DFIM is illustrated by the figure below:

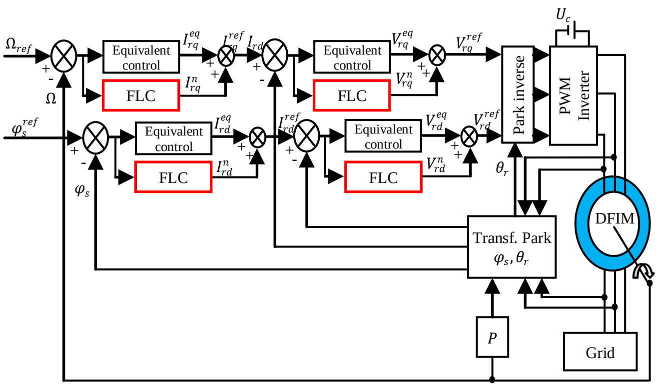


Fig. 7. Block diagram of the hybride sliding-fuzzy control of a DFIG.

V. RESULTS OBTAINED

The objective of this step is to control the doubly fed induction machine by fuzzy-sliding mode control. Different tests will be applied to show the performance of this control.

A. Machine operation when varying the speed

The simulation results during the variation of the speed are grouped together in figure 8. We notice the good continuation of the speed towards its new reference, the flow undergone a slight variation at the time of the speed change.

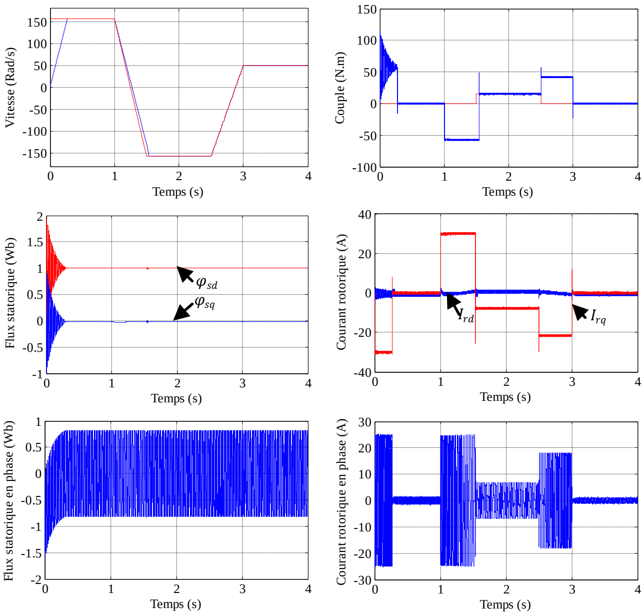


Fig. 8. Simulation results when varying the speed

B. Operation of the machine during variation of the rotor resistance

Figure (9) illustrates the dynamic responses of the machine, speed, torque, stator flux and rotor currents, during the variation of R_r by +100% of its nominal value between times t=1.5s and t=2.5s. We notice that no change in speed, torque and flow. Decoupling is still maintained.

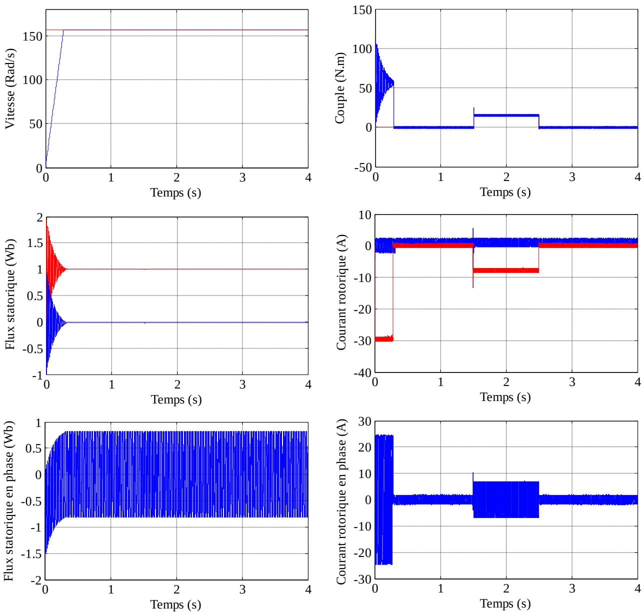


Fig. 9. Simulation results when varying the rotor resistance

C. Machine operation during stator resistance variation

The simulation results represented by figure (10) obtained for an increase in R_s of 100% of its nominal value. We can notice that no change in the speed variation and a small variation in the flow.

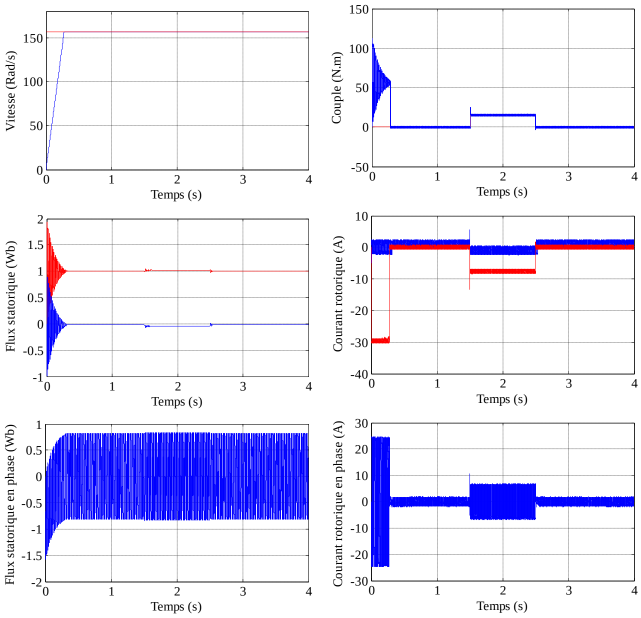


Fig. 10. Simulation results when changing stator resistance.

D. Results interpretation

The simulation results of the change in the speed setpoint show that the latter follows their reference well and we can see the improvement in response time. So, we can say that the hybrid fuzzy sliding control is effective (minimum chattering).

According to the results obtained during the variation of the rotor and stator resistances does not cause any undesirable effect at the level of all the dynamic responses, and this shows the robustness of the control used in the face of the parametric variation of the machine as well as the decoupling is always maintained between flux and torque.

VI. CONCLUSION

In this article, after having introduced the theory of sliding mode control, we presented a control law of the doubly fed induction machine using the technique of stator flux orientation.

In order to improve the responses generated by our engine, another control law also uses the sliding mode technique is proposed. This is the hybrid fuzzy sliding control.

Simulation results are better compared to vector control and sliding mode control. So we can say that the sliding-fuzzy command is robust to external disturbances and to parametric variations unlike the control by sliding mode.

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