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Fuzzy Sliding Mode Controller for Induction Machine Feed by Three Level Inverter

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ABSTRACT

In this paper, using synthesis of a hybrid control is applied to the speed of an induction motor feed by three-level inverter. Based on the combination of the fuzzy logic and the sliding mode approach, this method has the advantage of combining the performances of the two types of controllers. The fuzzy logic confers a very appreciable flexibility to the reasoning which usesand makes it possible to take into account Imprecisions and uncertainties, The sliding mode is a controller for nonlinear systems with non-constant parameters; it leads to precision and robustness, and allows solving problems obtained by conventional control laws. To lift the stresses of external disturbance and makes the system more performing and more robust, the two controllers of fuzzy logic and sliding mode are combined.

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1. INTRODUCTION

Conventional control laws of the PID type are very efficient in the case of linear systems with constant parameters. For nonlinear systems or non-constant parameters, these control lawsmay be insufficient because they are not robuste especially when the requirements on precision and other dynamic characteristics of the system are strict. One has to make call to laws of order insensible to the variations of the parameters, to the disruptions and to the nos linéarités.

Variable structure control laws are a solution to these problems, One solution is to use a robust algorithm such as model reference adaptive control, fuzzy logic control (FLC), or sliding-mode control (SMC) [1], [2], [3]. Fuzzy control (FLC) possesses several advantages such as robustness,being model free, universal approximation theorem, and rule-based algorithm [4],[5],[6]. The easyway of defining a fuzzycontroller by rules with an obvious physical meaning has helped to expand this control technique [7].

The control by sliding mode has largely provedits effectiveness through the theoretical studies reported; these main fields of application are robotics and electricmotors. It is a robust control because the high-gain feedback control input cancels nonlinearities, uncertainty parameters, and external disturbances [7]. However, these performances are obtainedat the cost of certain disadvantages, a chattering phenomenon or chatter caused by the discontinuous part of this control and which can have a detrimental effect on the actuators, the system is subjected at each moment to a high command, Ensureits convergence to wards the desired state and this is not desirable.

Among the solutions proposed to these problems, the control by fuzzy sliding mode, hence the advantage to use a control that combines the fuzzy logic and the sliding mode in order to obtain a robust and smooth control. the mathematical model of the induction machine is developed and presented in section 2, section 3 shows the modeling of a NPC multilevel inverter, the indirect field oriented control of induction machine is shows in secion 4.

Section 5 shows the develempent of PI controller and the application to induction machine, sliding mode controllers design for induction machine is given in section 6. The proposed fuzzy sliding mode control is show in section 7; section 8 shows the simulation results using matlab Simulink, finally the conclusion drawn in section 11.

2. MATHEMATICAL MODEL OF THE INDUCTION MACHINE

The modeling step of the induction machine is essential for the development of control laws.

In order to lighten the mathematical notations, wewill use the indices s,r to designate the stator and rotor spectively, and d, q for the direct and quadrature axes

2.1 Electrical Equations

$$\begin{cases} v_{ds} = R_s.i_{ds} - \dot{\theta}_s.\varphi_{qs} + \frac{d\varphi_{ds}}{dt} \\ v_{qs} = R_s.i_{qs} + \dot{\theta}_s.\varphi_{ds} + \frac{d\varphi_{qs}}{dt} \\ v_{dr} = 0 = R_r.i_{dr} - \dot{\theta}_r.\varphi_{qr} + \dfrac{d\varphi_{dr}}{dt} \\ v_{qr} = 0 = R_r.i_{qr} + \dot{\theta}_r.\varphi_{dr} + \dfrac{d\varphi_{qr}}{dt} \end{cases} \quad (1)$$

$$\begin{cases} \varphi_{ds} = L_s\ .i_{ds} + M.i_{dr} \\ \varphi_{qs} = L_s\ .i_{qs} + M.i_{qr} \\ \varphi_{dr} = M.i_{ds} + L_r\ .i_{dr} \\ \varphi_{qr} = M.i_{qs} + L_r\ .i_{qr} \end{cases} \quad (2)$$

2.2 Mechanical Equation

$$c_e = \frac{3}{2}.p.\frac{M}{L_r}.\left(\varphi_{dr}.i_{qs} - \varphi_{qr}.i_{ds}\right) \quad (3)$$

3. MODELING OF A NPC THREE-LEVEL INVERTER

The structure of a multilevel inverter makes it possible to synthesize a sinusoidal signal, starting from several levels of tension, more the number of levels is large plus the output voltage Approaches the sinusoid with a minimum of distortion of harmonic[11], [12].

The connection function Fki defines the state of each switch, where k is the arm number and i is the switch number. In the controllable mode, the connection functions of the inverter are linked by:

$$\begin{cases} F_{k1} = 1 - F_{k4} \\ F_{k2} = 1 - F_{k3} \end{cases} \quad (4)$$

The half-arm connection function is defined as follows:

$$\begin{aligned} {F^b}_{k1} &= F_{k1}F_{k2} \\ {F^b}_{k0} &= F_{k3}F_{k4} \end{aligned} \quad (5)$$

The potentials of the nodes A, B, C with respect to the mid-points M of the three-phase - inverter are expressed by:

$$\begin{cases} V_{AM} = {F^b}_{11}U_{c1} - {F^b}_{10}U_{c2} \\ V_{BM} = {F^b}_{21}U_{c1} - {F^b}_{20}U_{c2} \\ V_{CM} = {F^b}_{31}U_{c1} - {F^b}_{30}U_{c2} \end{cases} \quad (6)$$

The simple output voltages of the inverter are deduced as a function of the potentials of the nodes with respect to the midpoint by the following relation:

$$\begin{cases} V_A = (2V_{AM} - V_{BM} - V_{CM})/3 \\ V_B = (2V_{BM} - V_{CM} - V_{AM})/3 \\ V_C = (2V_{CM} - V_{AM} - V_{BM})/3 \end{cases} \tag{7}$$

This makes it possible to express the simple voltages by using the functions of connections of the half arms by:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \left\{ \begin{bmatrix} F^b{}_{11} \\ F^b{}_{21} \\ F^b{}_{31} \end{bmatrix} U_{c1} - \begin{bmatrix} F^b{}_{10} \\ F^b{}_{20} \\ F^b{}_{30} \end{bmatrix} U_{c2} \right\} \tag{8}$$

4. INDIRECT FIELD-ORIENTED CONTROL INDUCTION MACHINE

The principle of speed control by the indirect field oriented control is presented in Figure 1

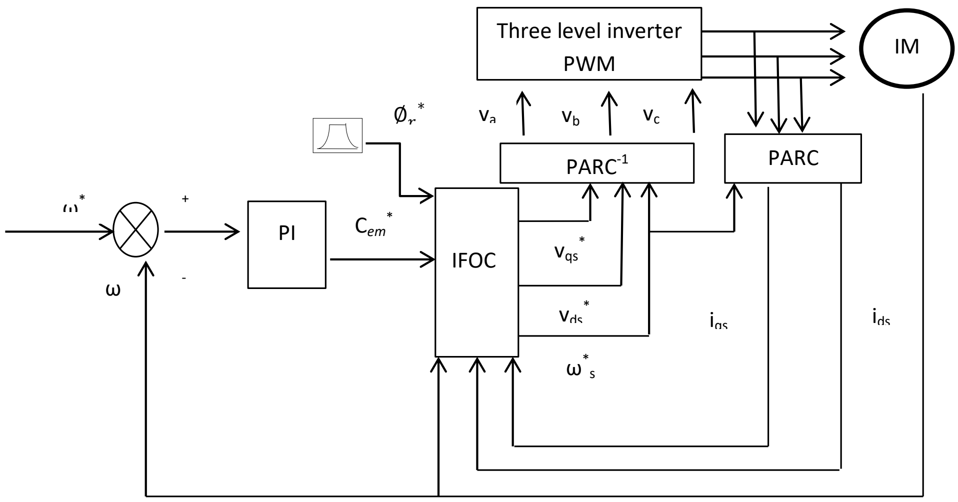

Figure 1. The indirect field oriented control of an induction machine

In this method, the rotor flux is not regulated, so there is no need for a sensor, no estimation or a flow observer. If the amplitude of the actual rotor flux is not used, its position must be known to effect the coordinate changes.This requires the presence of a rotor position sensor.

The IFOC control block (generates the three control variablesv_{ds}^*, v_{qs}^* and ω_s^* as a function of the two reference inputs(ω^* and $\emptyset_r^*$) which ensure her decoupling. In this command, the angle$\theta_s$used in the transforms of Park is calculated by:

$$\theta_s = \int \left(\omega + \frac{i_{qs}^*}{T_r . i_{ds}^*} \right) dt \tag{9}$$

With:

$$i_{ds}^* = \frac{\emptyset_r^*}{L_m} \tag{10}$$

5. PI CONTROLLER DESIGN FOR SPEED OF AN INDUCTION MACHINE

The speed controller determines the reference torque in order to maintain the corresponding speed. For the cascade to be justified, it is necessary that the loop intern is very fast compared to that speed.
The mechanical equation gives:

$$\frac{\omega}{C_{em}} = \frac{P}{f_c + J.s} \tag{11}$$

The block diagram of the speed control is therefore carried out as indicated in Figure 2.

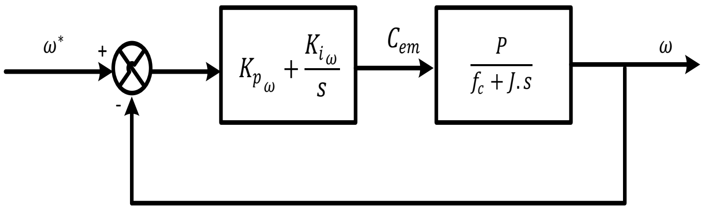

Figure 2.Block diagram of the speed control.

The closed loop transfer function is given by:

$$\frac{\omega}{\omega^*} = \frac{(k_{p\omega}.s + k_{i\omega})\frac{P}{J}}{\rho(s)} \tag{12}$$

The characteristic equation $\rho(s)$ is:

$$\rho(s) = s^2 + \frac{f_c + k_{p\omega}.P}{J}.s + \frac{k_{i\omega}.P}{J} = 0 \tag{13}$$

By imposing two complex conjugated poles$s_{1,2} = -\rho \pm j.\rho$ in closed loop and by identification, the parameters of the regulator PI are obtained:

$$\begin{aligned} k_{i\omega} &= \frac{2.J.\rho^2}{P} \\ k_{p\omega} &= \frac{2.\rho.J - f_c}{P} \end{aligned} \tag{14}$$

6. SLIDING MODE CONTROLLER

Sliding mode control (SMC) is a nonlinear control technique featuring remarkable properties of accuracy, robustness, and easy tuning and implementation [13].

The sliding mode technique consists of bringing the state path of a system towards the sliding surface and swiching by means of appropriate switching logic around it to the equilibrium point, it is the sliding phenomenon.

- The design of sliding mode controllers mainly requires
- Three steps, [14], [15], [16] namely
- The choice of the sliding surface;
- The condition of convergence;
- The calculation of control law.

6.1 Choice of sliding surface

The switching function is a scalar function, such as the variable to be adjusted Slides on this surface to reach the origin of the phase plane. In reference [17], a general equation has been proposed to determine the sliding surface which ensures the convergence of a variable to its desired value defined as follows [16], [17]:

$$S(x) = \mathrm{e(x)} + \lambda_1.\frac{d}{dt}.e(x) + \cdots + \lambda_m.\frac{d^m}{dt^m}.e(x) \tag{15}$$

With:

$$\mathrm{e(x)} = \omega^*_s - \omega_s \tag{16}$$

$\lambda_i\ (i = 1,2, \ldots, m)$ Is a positive constant, interpreting the control bandwidth desired and m is a relative degree, equal to the number of times to derive the output for Display the command.

6.2 Condition of convergence

This is the mode in which the variable to be adjusted moves from any Point in the phase plane and tends towards the switching surface $S(x) = 0$.

This mode is characterized by the control law and the convergence criterion, in this paper the direct switching function proposed by Emilianov and Utkin [15], [16], [17], and which can be formulated by the following sufficient condition [18]:

$$S(x).\dot{S}(x) < 0 \tag{17}$$

6.3 Calculation of control law

Once the selected slip surface and the convergence criterion are satisfied, the necessary condition are determined to bring the variable to be controlled to the surface and then to its equilibrium point. In the VSC theory, there are different ways of choosing the parameters to define switching logic, in the literature there are three types of widespread structures, linear feedback control with switched gain, Relay, and equivalent control. In the latter, two approaches are preferred in the control of electrical machines because they are more appropriate [19].

In this case, the method chosen is that of the equivalent command, so we have:

$$u = u_{eq} + u_n \tag{18}$$

u_{eq} is determined from the convergence condition.

u_n is calculated to ensure the attractiveness of the state variable to be controlled to the switching surface.

Definition of the speed control surface

The structure includes a speed control loop which imposes the control Cemref with slip surface is deduced on the basis of the concepts of the reference [17] and is given by:

$$e(\omega) = \omega_{ref} - \omega_r \tag{19}$$

$$s(\omega) = \lambda.\, e(\omega) + \dot{e}(\omega) \tag{20}$$

$$s(\omega) = \lambda(\omega_{ref} - \omega_r) + (\dot{\omega}_{ref} - \dot{\omega}_r) \tag{21}$$

Considering the condition of the sliding regime $s(\omega)$ is zero, one obtains the equivalent control law:

$$c_{emeq} = f.\, \omega_r + c_r \tag{22}$$

During the convergence mode and in order to satisfy the condition $S(x).\dot{S}(x) < 0$, the following equation is adopted:

$$c_{emeq} = k.\, sat(s(\ \omega)) \tag{23}$$

This gives us the reference control at the output of the c_{emref} controller for speed control.

$$c_{emref} = f.\, \omega_r + c_r + k.\, sat(s(\ \omega)) \tag{24}$$

7. FUZZY SLIDING MODE CONTROLLER

To improve the performance and robustness of our control, and to avoid the chattering phenomenon of our system, are combined the sliding mode control with the control of the fuzzy logic.

The fuzzy logic control algorithm is a series of IF……THEN rules. Every fuzzy control rule in the rule base is a relationship between the input variables, membership functions and an output action or command [20]. Table 1 shows the Fuzzy Controller Rule Base for the input and output variable. The proposed controller uses following linguistic labels BN(big negative), MN(medium negative), SN(small

negative), EZ(zero), SP(small positive), MP(medium positive), BP(big positive). Each of the inputs and output contain membership function with all these seven linguistics.
Figure 3shows the input and output membership functions.

Table 1. Units for Magnetic Properties

$s(\omega)$ / ω_s	BN	MN	SN	EZ	SP	MP	BP
BN	BN	BN	BN	BN	MN	SN	EZ
MN	BN	BN	BN	MN	SN	EZ	SP
SN	BN	BN	MN	SN	EZ	SP	SP
EZ	BN	MN	SN	EZ	SP	MP	MP
SP	MN	SN	EZ	SP	MP	BP	MP
MP	SN	EZ	SP	MP	BP	BP	MP
BP	EZ	SP	MP	BP	BP	BP	MP

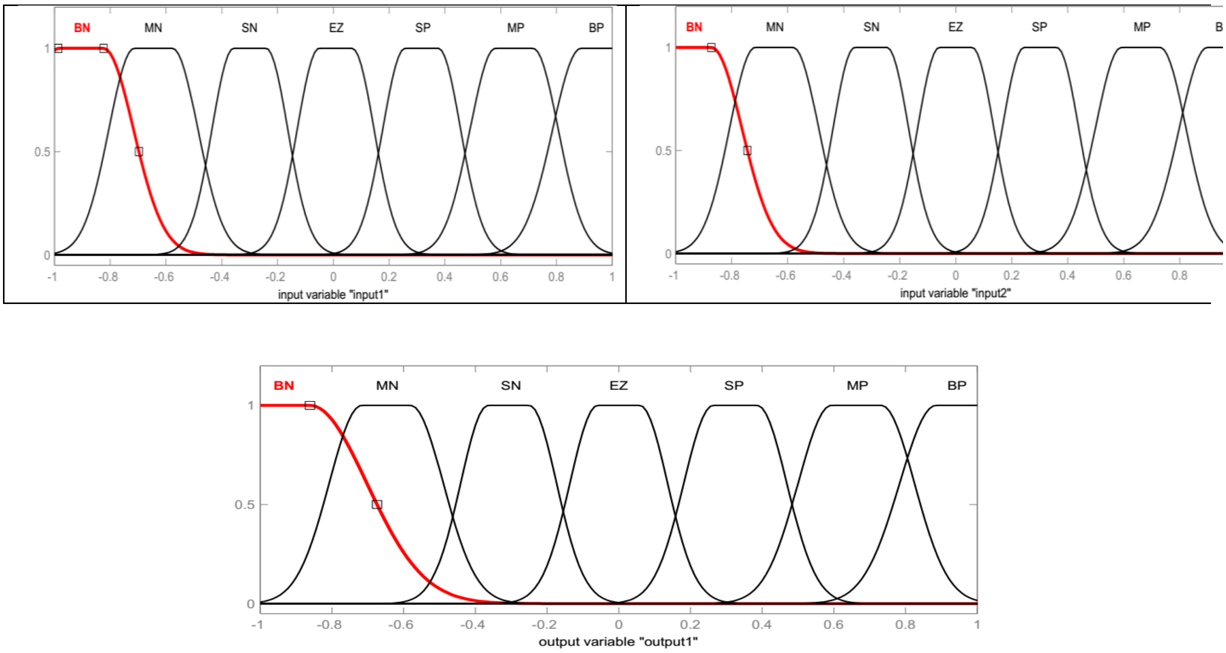

Figure 3. Membership functions of fuzzy sliding controller

8. SIMULATION RESULTS

In this section, simulation results are presented to show the performance of the proposed Fuzzy Sliding Mode Controller, meanwhile, the proposed control method has been compared with the conventional SMC [21], [22], and classical PI control method [23], [24].
In order to evaluate the performance of the indirect speed vector control with adjustment by a PI regulator, Sliding mode regulator and Fuzzy Sliding mode regulator we performed numerical simulations under the following conditions:

- Speed set point change from 200 to -200rad / s at the instant 3s
- Variation of the mechanical load from 0 to -10 Nm between times 1 and 2s.

Figure 4 shows the IM speed setting by the indirect vector controladjustment by a PI regulator, with load variation, supplied with voltage by a three-level inverter. Figure 5 shows mesured speed and speed reference of PI regulator. The results show using the decoupled model gives satisfactory results:

- The speed of rotation follows the reference speed with exceeding of 7.20 rad/s.
- The control ensures good regulation with disturbance rejection of 13 rad/s.
-

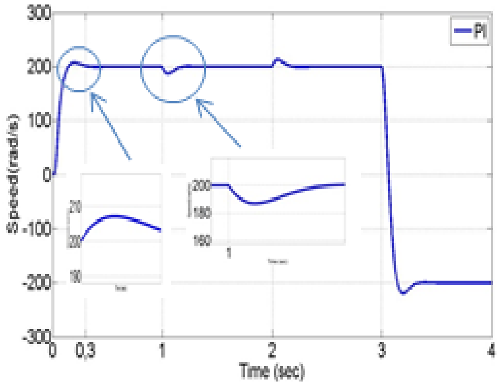

Figure 4. Speed of IMwith PI controller

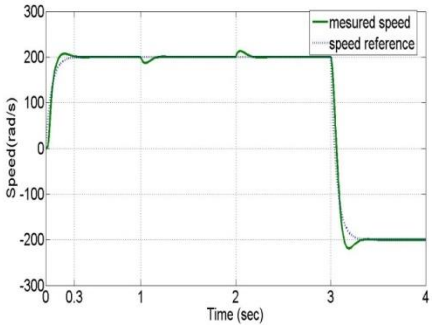

Figure 5. Mesured speed and speed reference of PI

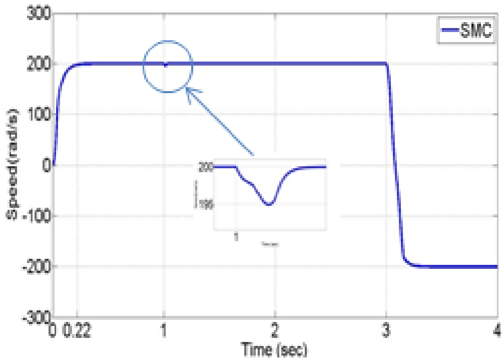

Figure 6. Speed of IM with SMC controller

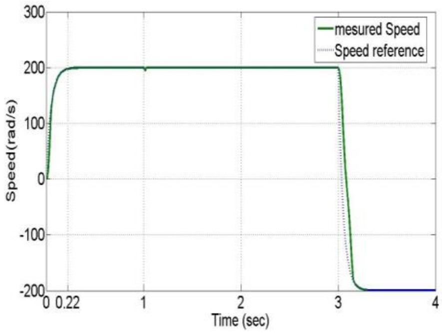

Figure 7. Mesured speed and speed reference of SMC

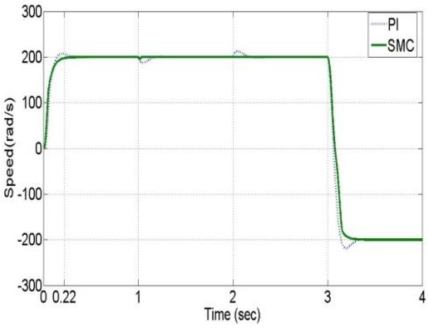

Figure 8. Difference between the PI and SMC

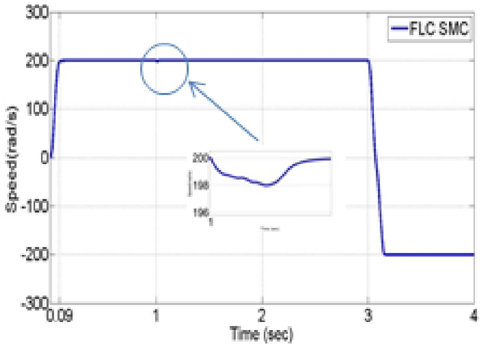

Figure 9. Speed of IM with FSMC

Figure 6 shows the IM speed setting by the indirect vector control adjustment by Sliding mode regulator, with load variation, supplied with voltage by a three-level inverter. Figure 7 shows mesured speed and speed reference of sliding mode regulator. Figure 8 shows the difference between the PI regulator and Sliding mode regulator. The results show that the regulation by a Sliding mode regulator gives satisfactory results:

- The speed of rotation follows the reference speed without exceeding.
- The control ensures good regulation with disturbance rejection of 5 rad/s.
- A response time of 0.22ms to reach the balanced state.

Figure 9 shows the IM speed setting by the indirect vector control adjustment by Fuzzy Sliding mode regulator, with load variation, supplied with voltage by a three-level inverter. Figure 10 shows mesured speed and speed reference of fuzzy sliding mode regulator. Figure 11 shows the difference between the Sliding mode regulator and Fuzzy Sliding mode regulator. The results show that the regulation by a fuzzy Sliding mode regulator gives satisfactory results:

- The speed of rotation follows the reference speed without exceeding.
- The control ensures good regulation with disturbance rejection of 2 rad/s.
- A response time of 0.09 ms to reach the balanced state.

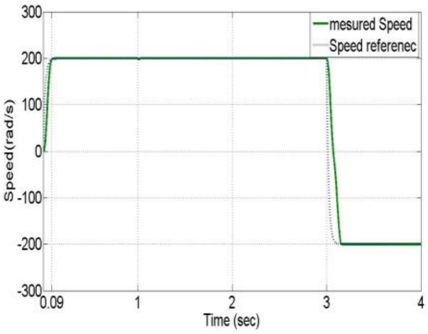

Figure 10.mesured speed and speed reference of FSMC

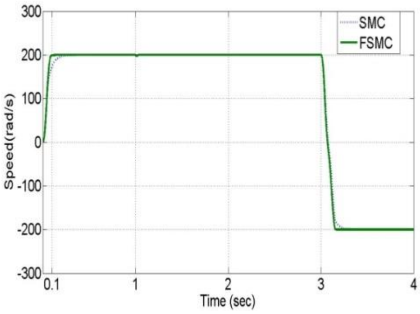

Figure 11. Difference between the SMC and FSMC

9. CONCLUSION

In this paper, we proposed a hybrid control of an induction machine. This command combines the advantages of two techniques considered robust and which are the control by sliding mode and the fuzzy control. This structure aims to exploit the robustness and the speed of the sliding mode during the transient regime and the flexibility of the fuzzy controller during the steady state. The simulation results show that the hybrid control by sliding mode and fuzzy logic gives better results compared to the other commands studied previously.

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