Fuzzy Sliding-Mode Control for a five drive web-winding System

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Abstract: In this contribution, a control scheme based on multi input multi output Fuzzy Sliding Mode control (MIMO-FSMC) for linear speed regulation of winding system is proposed. Once the decoupled model of the winding system is obtained, a smooth control function with a threshold was chosen to indicate how far the state from to the sliding surface is. However, the magnitude of this control function depends closely on the upper bound of uncertainties, and this generates chattering. So, this magnitude has to be chosen with great care to obtain high performances. Usually the upper bound of uncertainties is difficult to known before motor operation, so, a Fuzzy Sliding Mode controller is investigated to solve this difficulty, a simple Fuzzy inference mechanism is used to reduce the chattering phenomenon by simple adjustments. A simulation study is carried out and shows that the proposed fuzzy sliding mode controllers have great potential for use as an alternative to the conventional sliding mode control.

Keywords: winding system, induction machine Proportional-integral (PI), sliding mode control, Fuzzy logic.

I. Introduction

The systems handling web material such as textile, paper, polymer or metal are very common in the industry. The modelling and the control of web handling systems have been studied already for several decades [1].The increasing requirement on control performance, however, and the handling of thinner web material led us to search for more sophisticated control strategies. One of the objectives in such systems is to increase web velocity as much as possible, while controlling web tension over the entire production line. This requires decoupling between web tension and speed, so that a constant tension can be maintained during speed changes [2] [3]. Since the decentralized PI control method can be applied easily and is widely known, it has an important place in control applications, where many industrial web transport systems have used this type of controllers [4]. But this method is insensitive to parameter changes. A H_∞ robust control strategy for web tension control and linear transport velocity control are presented in [5], an adaptive algorithm to compensate web tension disturbances caused by the eccentricity and non-circularity of the reel and rolls in web winding systems is presented in [6]. In this work the design of fuzzy sliding-mode (FSMC) to control a winding system are proposed in order to improve the performances of the control system, which are coupled mechanically, and Synthesis of the robust control and their application to synchronize the five sequences and to maintain a constant mechanical tension between the rollers of the system [7]. The advantage of an FSMC is its robustness and ability to handle the non-linear behaviour of the system. In this contribution, based on fuzzy variable structure

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control concept, the authors introduced a control scheme for the design and the tuning of fuzzy logic controllers with an application to winding system. To show the benefits of the proposed fuzzy sliding mode control algorithm, simulation results comparing the performance of the proposed fuzzy model based control with that of conventional sliding mode control are presented. The results obtained confirm that the proposed control structure improves the performance and the robustness of the drive system.
The model of the winding system and in particular the model of the mechanical coupling are developed and presented in Section II. Section III shows the development of sliding mode controllers design for winding system. The proposed Fuzzy sliding mode control is given in the section IV. Section V shows the Simulation results using MATLAB SIMULINK of different studied cases. Finally, the conclusions are drawn in Section VI.

2. System Models

In the mechanical part, the motor M1 carries out unreeling, M3 drives the fabric by friction and M5 is used to carry out winding, each one of the motors M2 and M4 drives two rollers via gears “to grip” the band (Figure 1). Each one of M2 and M4 could be replaced by two motors, which each one would drive a roller of the stages of pinching off. The elements of control of pressure between the rollers are not represented and not even considered in the study. The stage of pinching off can make it possible to isolate two zones and to create a buffer zone. [8, 9].

The objective of these systems is to maintain the tape speed constant and to control the tension in the band.

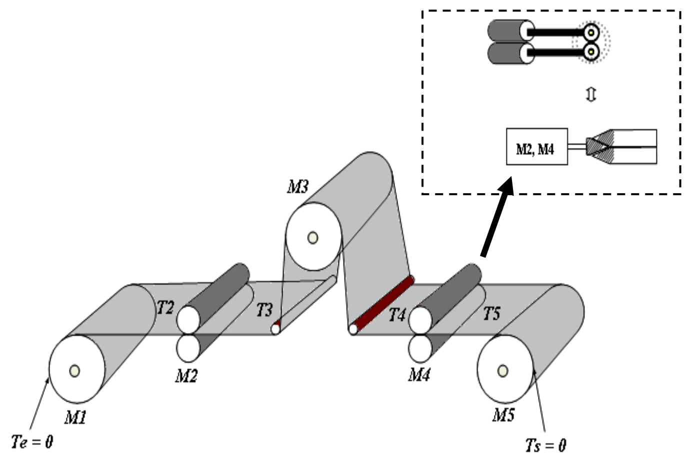

Figure 1. Five motors web transport system

The used motor is a three phase induction motor type (IM) supplied by an inverter voltage controlled with Pulse Modulation Width (PWM) techniques. A model based on circuit equivalent equations is generally sufficient in order to make control synthesis. The dynamic model of three-phase, Y-connected induction motor can be expressed in the d-q synchronously rotating frame as [13]:

$$\begin{cases} \dfrac{di_{ds}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 .R_r \right).i_{ds} + \sigma.L_s.\omega_e.i_{qs} + \dfrac{L_m.R_r}{L_r^2}.\phi_{dr} + \dfrac{L_m}{L_r}.\phi_{qr}.\omega_r + V_{ds} \right) \\ \dfrac{di_{qs}}{dt} = \dfrac{1}{\sigma.L_s}.\left(-\sigma.L_s.\omega_e.i_{ds} - \left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 .R_r \right).i_{qs} - \dfrac{L_m}{L_r}.\phi_{dr}.\omega_r + \dfrac{L_m.R_r}{L_r^2}.\phi_{qr} + V_{qs} \right) \\ \dfrac{d\phi_{dr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{ds} - \dfrac{R_r}{L_r}.\phi_{dr} + (\omega_e - \omega_r)\phi_{dr} \\ \dfrac{d\phi_{qr}}{dt} = \dfrac{L_m.R_r}{L_r}.i_{qs} - (\omega_e - \omega_r)\phi_{dr} - \dfrac{R_r}{L_r}.\phi_{qr} \\ \dfrac{d\omega_r}{dt} = \dfrac{P^2.L_m}{L_r.J}.(i_{qs}.\phi_{dr} - i_{ds}.\phi_{qr}) - \dfrac{f_c}{J}.\omega_r - \dfrac{P}{J}.T_l \end{cases} \quad (1)$$

Where σ is the coefficient of dispersion and is given by:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (2)$$

The tension model in web transport systems is based on Hooke's law, Coulomb's law, [8, 9] mass conservation law and the laws of motion for each rotating roll.

A. Hooke's law

The tension T of an elastic web is function of the web strain ε

$$T = ES\,\varepsilon = ES\,\frac{L - L_0}{L_0} \quad (3)$$

Where E is the Young modulus, S is the web section, L is the web length under stress and L0 is the nominal web length (when no stress is applied).

B. Coulomb's law

The study of a web tension on a roll can be considered as a problem of friction between solids, see [8] and [9].

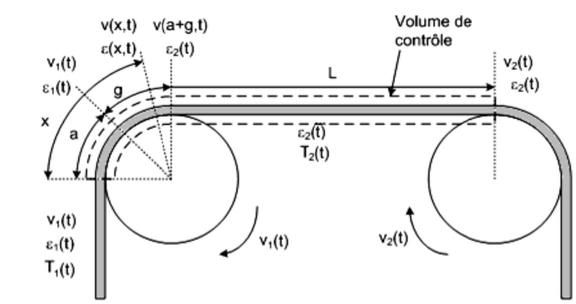

Figure 2. Web tension on the roll

The roll, the web tension is constant on a sticking zone of arc length a and varies on a sliding zone of arc length g (cf. Figure 2, where Vk(t) is the linear velocity of the roll k). The web tension between the first contact point of a roll and the first contact point of the following roll is given by:

$$\begin{cases} \varepsilon(x,t) = \varepsilon_1(t) & \text{if} \quad x \le a \\ \varepsilon(x,t) = \varepsilon_1(t)e^{\mu(x-a)} & \text{if} \quad a \le x \le a+g \\ \varepsilon(x,t) = \varepsilon_2(t) & \text{if} \quad a+g \le x \le L_t \end{cases}$$

Where μ is the friction coefficient, and Lt = a + g + L. The tension change occurs on the sliding zone. The web velocity is equal to the roll velocity on the sticking zone.

C. Mass conservation law

Consider an element of web of length $L = L_0\,(1+\varepsilon)$

With a weight density ρ, under an unidirectional stress. The cross section is supposed to be constant. According to the mass conservation law, the mass of the web remains constant between the state without stress and the state with stress

$$\rho SL = \rho_0 SL_0 \Rightarrow \frac{\rho}{\rho_0} = \frac{1}{1+\varepsilon} \tag{4}$$

D. Tension model between two consecutive rolls.

The equation of continuity, cf. [8], applied to the web gives:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V)}{\partial x} = 0 \tag{5}$$

By integrating on the variable x from 0 to Lt (cf. Figure 2), taking into account (4), and using the fact that a + g << L, we obtain

$$\frac{d}{dt}\left(\frac{L}{1+\varepsilon_2}\right) = \frac{V_1}{1+\varepsilon_1} - \frac{V_2}{1+\varepsilon_2}.$$

Therefore:

$$-L\frac{d\varepsilon_2}{dt} = V_1\frac{(1+\varepsilon_2)^2}{1+\varepsilon_1} - V_2(1+\varepsilon_2). \tag{6}$$

This equation can be simplified by using the approximation

$$\varepsilon_1 << 1 \quad and \quad \varepsilon_2 << 1$$

$$\frac{(1+\varepsilon_2)^2}{1+\varepsilon_1} \approx (1-\varepsilon_1)(1+2\varepsilon_2) \tag{7}$$

And using Hook's law, we get:

$$L_{k-1}\frac{dT_k}{dt} \cong ES(V_k - V_{k-1}) + T_{k-1}V_{k-1} - T_k(2V_{k-1} - V_k). \tag{8}$$

k = 2, 3, 4, 5.

where L_{K-1} is the web length between roll k−1 and roll k, T_K is the tension on the web between roll k−1 and roll k, V_K is the linear velocity of the web on roll k, Ω_K is the rotational speed of roll k, R_K is the radius of roll k, E is the Young modulus and S is the web section.

E. Roll velocity calculation

The law of motion can be obtained with a torque balance:

$$\frac{d(J_k\Omega_k)}{dt} = R_k(T_{k+1} - T_k) + Cem_k + C_f \tag{9}$$

Where $\Omega_k = V_k / R_k$, is the rotational speed of roll k Cem_k is the motor torque (if the roll is driven) and C_f is the friction torque.

F. Complete model of the five motors system

Figure 1 shows a typical five motors system with winder, unwinder, and three tractors. The complete model of this system is given by the following equations:

$$L_1\frac{dT_2}{dt} = ES(V_2 - V_1) - T_2V_2.$$

$$L_2\frac{dT_3}{dt} = ES(V_3 - V_2) + T_2V_2 - T_3V_3.$$
$$L_3\frac{dT_4}{dt} = ES(V_4 - V_3) + T_3V_3 - T_4V_4.$$
$$L_4\frac{dT_5}{dt} = ES(V_5 - V_4) + T_4V_4 - T_5V_5. \tag{10}$$

$$\frac{d(J_1(t)\Omega_1)}{dt} = R_1(t)T_2 + C_{em1} - f_1(t)\Omega_1.$$
$$\frac{d(J_2\Omega_2)}{dt} = R_2(T_3 - T_2) + C_{em2} - f_2(t)\Omega_2.$$
$$\frac{d(J_3\Omega_3)}{dt} = R_3(T_4 - T_3) + C_{em3} - f_3(t)\Omega_3.$$
$$\frac{d(J_4\Omega_4)}{dt} = R_4(T_5 - T_4) + C_{em4} - f_4(t)\Omega_4.$$
$$\frac{d(J_5(t)\Omega_5)}{dt} = R_5(t)(-T_5) + C_{em5} - f_5(t)\Omega_5. \tag{11}$$

G. State space representation

The nonlinear state-space model is composed of (10) for the different web spans and of (11) for the different rolls. Under the assumption that Jk Rk (k = 2, 3, 4, 5) is varying only slowly, which is the case for thin webs, Vk can be chosen as a state variable in (11), leading to the following linear model:

$$E_m \dot{X} = A(t)X + BU \qquad Y = C(t)X \tag{12}$$

Where

$$X^T = [(T_2 \quad T_3 \quad T_4 \quad T_5 \quad J_1(t)\Omega_1 \quad J_2\Omega_2 \quad J_3\Omega_3 \quad J_4\Omega_4 \quad J_5(t)\Omega_5)]$$

$$Y^T = [T_2 T_3 T_4 T_5 V_1], \tag{13}$$

$$U = [u_1\ u_2\ u_3\ u_4\ u_5] \tag{14}$$

$$A(t) = \begin{bmatrix} -V_2 & 0 & 0 & 0 & -ES\frac{R_1(t)}{J_1(t)} & ES\frac{R_2}{J_2} & 0 & 0 & 0 \\ V_2 & -V_3 & 0 & 0 & 0 & -ES\frac{R_2}{J_2} & ES\frac{R_3}{J_3} & 0 & 0 \\ 0 & V_3 & -V_4 & 0 & 0 & 0 & -ES\frac{R_3}{J_3} & ES\frac{R_4}{J_4} & 0 \\ 0 & 0 & V_4 & -V_5 & 0 & 0 & 0 & ES\frac{R_4}{J_4} & ES\frac{R_5}{J_5} \\ R_1(t) & 0 & 0 & 0 & -\frac{f_1(t)}{J_1(t)} & 0 & 0 & 0 & 0 \\ -R_2 & R_2 & 0 & 0 & 0 & -\frac{f_2(t)}{J_2(t)} & 0 & 0 & 0 \\ 0 & -R_3 & R_3 & 0 & 0 & 0 & -\frac{f_3(t)}{J_3} & 0 & 0 \\ 0 & 0 & -R_4 & R_4 & 0 & 0 & 0 & -\frac{f_4(t)}{J_4} & 0 \\ 0 & 0 & 0 & -R_5(t) & 0 & 0 & 0 & 0 & -\frac{f_5(t)}{J_5(t)} \end{bmatrix},$$

$$E_m = \begin{bmatrix} L_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & L_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & L_4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C=\begin{bmatrix}1&0&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0&0\\0&0&1&0&0&0&0&0&0\\0&0&0&1&0&0&0&0&0\\0&0&0&0&\dfrac{R_1(t)}{J_1(t)}&0&0&0&0\end{bmatrix}$$

$$B=\begin{bmatrix}0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\0&0&0&0&0\\K_1&0&0&0&0\\0&K_2&0&0&0\\0&0&K_3&0&0\\0&0&0&K_4&0\\0&0&0&0&K_5\end{bmatrix},$$

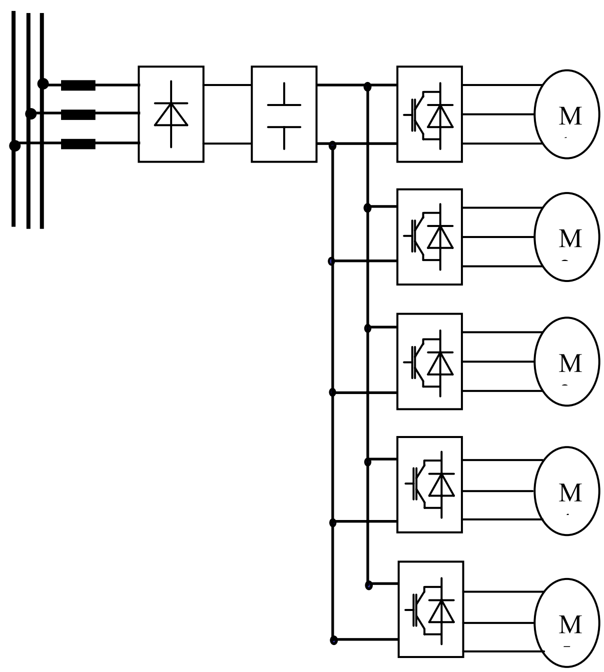

Figure 3. Electrical part of the five drive system

3. Sliding Mode Control

The sliding mode control consists in moving the state trajectory of the system toward a predetermined surface called sliding or switching surface and in maintaining it around this latter with an appropriate switching logic. In the case of the nth-order system, the sliding surface could be defined as [12]:

$$S(x)=\left(\frac{\partial}{\partial t}+\lambda\right)^{r-1}.e(x) \quad , \quad \lambda>0 \tag{15}$$

Concerning the development of the control law, it is divided into two parts, the equivalent control Ueq and the attractivity or reachability control Us. The equivalent control is determined off-line with a model that represents the plant as accurately as possible. If the plant is exactly is exactly identical to the model used for determining Ueq and there are no disturbances, there would be no need to apply an additional control Us. However, in practice there are a lot of differences between the model and the actual plant. Therefore, the control component Us is necessary which will always guarantee that the state is attracted to the switching surface by satisfying the condition $\dot{S}(x).S(x)<0$ [12,13]. Therefore, the basic switching law is of the form:

$$U=U_{eq}+U_{sw} \tag{16}$$

U_{eq} is the equivalent control, and U_{sw} is the switching control. The function of U_{eq} is to maintain the trajectory on the sliding surface, and the function of U_{sw} is to guide the trajectory to this surface.
Let the sliding surface vector be given by:

$$S=\begin{bmatrix}S_1 & S_2 & S_3 & S_4 & S_5\end{bmatrix}$$

With Usw=-M (.) sgn(S (.))
M(S): The magnitude of the attractivity control law Usw and sgn: the sign function

In a conventional variable structure control, Un generates a high control activity. It was first taken as constant, a relay function, which is very harmful to the actuators and may excite the unmodeled dynamics of the System. This is known as a chattering phenomenon. Ideally, to reach the sliding surface, the chattering phenomenon should be eliminated [12,13]. However, in practice, chattering can only be reduced.

The first approach to reduce chattering was to introduce a boundary layer around the sliding surface and to use a smooth function to replace the discontinuous part of the control action as follows :

$$\begin{cases} U_{sw}=\dfrac{K}{\varepsilon}.S(x) & if \quad |S(x)|<\varepsilon \\ U_{sw}=K.\operatorname{sgn}(S(x)) & if \quad |S(x)|>\varepsilon \end{cases}$$

The constant K is linked to the speed of convergence towards the sliding surface of the process (the reaching mode). Compromise must be made when choosing this constant, since if K is very small the time response is important and
the robustness may be lost, whereas when K is too big the chattering phenomenon increases.

4. Fuzzy Sliding Mode Control (FSMC)

The disadvantage of sliding mode controllers is that the discontinuous control signal produces chattering dynamics; chatter is aggravated by small time delays in the system. In order to eliminate the chattering phenomenon, different schemes have been proposed in the literature [15, 16, 17, 18, 19]. However, this does not solve the problem completely. In this

section, a fuzzy sliding surface is introduced to develop a sliding mode controller, where the parameters λ_i are adjusted by a fuzzy system mechanism to reduce the chattering phenomenon.
Consider the class of nonlinear time varying systems described by the equations

$$x_j^n = f_j(X_1,....,X_m) + b_j(X_1,...,X_m)u_j + d_j(t) \quad (17)$$

$$y_j = x_j \quad (18)$$

Where $X_j = \left[x_j, \dot{x}_j, ..., x_j^{(n-1)}\right]^T$ are the j-th components of the state vector?

$\wedge = \left[X_1, ..., X_m\right]^T$

u_j is the j-th control input

y_j is the j-th system output

In (17) the function f_i, the control gain b_j and the disturbance d_j are assumed to be unknown. The dynamics of (17) describe a large number of nonlinear systems encountered in practice, including a vast class of controllable nonlinear systems that could be converted into (17) by using appropriate transformations.

Then we can write a state space representation of (17) in terms of $e_j = r - x_j$, and its derivatives:

$$\begin{cases} \dot{e}_{j1} = e_{j2} \\ \dot{e}_{j2} = e_{j3} \\ \vdots \\ \dot{e}_{jn-1} = e_{jn} \\ \dot{e}_{jn} = -f_j(\wedge) - b_j(\wedge)\, u_j - d_j(t) \end{cases} \quad (19)$$

Where

$$e_{j1} = e_j, ..., e_{jn} = e_j^{(n-1)}$$

and

$$x_{j1} = x_j, ..., x_{jn} = x_j^{(n-1)}$$

Now let

$$E_j = \left[e_{j1}, ..., e_{jn}\right]^T$$

and

$$E = \left[E_1, ..., E_n\right]^T$$

Then we can rewrite (19) as follows:

$$\begin{cases} \dot{e}_{j1} = e_{j2} \\ \dot{e}_{j2} = e_{j3} \\ \vdots \\ \dot{e}_{jn-1} = e_{jn} \\ \dot{e}_{jn} = -f_j(E) - b_j(E)\, u_j - d_j(t) \end{cases} \tag{20}$$

Where $f_j(E)$ is a shifted replica of $f_j(\Lambda)$. The systems of nonlinear equations in (20) are highly coupled. Considering the nonlinear coupling terms in (20) as disturbances, we can introduce the sliding mode into the system and reject the disturbance by the various design procedures based on the invariance property of the sliding mode. Therefore, the coupled systems of (20) can be written as q set of m independent differential equations as follows:

$$\begin{cases} \dot{e}_{j1} = e_{j2} \\ \dot{e}_{j2} = e_{j3} \\ \vdots \\ \dot{e}_{jn-1} = e_{jn} \\ \dot{e}_{jn} = -f_j(E_j) - b_j(E_j)\, u_j - D_j(E,t) \end{cases} \tag{21}$$

Where $D_j(E,t)$ is the sum of the disturbances $d_j(t)$ and all the nonlinear coupling terms in (20) or equivalently

$$D_j(E,t) = -d_j(t) + \sum_{\substack{i=1 \\ j\neq 1}}^{m} a_i h_i(E_j,t) + b_i g_i(E_i,t) \tag{22}$$

Where a_i and h_i are in general time varying and b_i and g_i, are the nonlinear

Define a set of sliding surfaces S_j in the E_j space by the equations

$$S_j(E_j) = C_j E_j = 0 \qquad j = 1,\dots,m \tag{23}$$

Finally the proposed MIMO sliding Mode Fuzzy control law is

$$U = U_{eq} + U_{sw-f} \tag{24}$$

$$U_{eq}(x,t) = -D(t,x)^{-1}.F(t,x) \tag{25}$$

$$U_{sw-f}(x,t) = -\alpha_i.[sat(\frac{S_{1\_f}}{\phi_1} \quad \frac{S_{2\_f}}{\phi_2} \quad \frac{S_{3\_f}}{\phi_3} \dots \frac{S_{i\_f}}{\phi_i}) \tag{26}$$

$S_i, i = 1,2,\dots,5$ as

$$S_{i\_f} = \dot{e} + \lambda_{i\_f}.\, e_i \tag{27}$$

Where $e_i = \frac{1}{s+\lambda_{i\_f}} S_i$ are tracking errors and λ_{i-f} are positive scalar design parameters which control the bandwidth of the closed-loop system.

Thus, the tracking error eventually enters neighborhoods of e_i =0, the sizes of which are inversely proportional to λ_i . Therefore, if λ_i is larger, tracking errors are smaller.

$$\lambda_{i\_f} = \frac{\sum_{j=1}^{r_i} u_i^j \lambda_i^j}{\sum_{j=1}^{r_i} u_i^j} \tag{28}$$

In order to improve tracking performance while avoiding chattering under physical limitations, effort is made to improve the sliding mode controller via fuzzy logic. In this work, individual Mamdani fuzzy systems are used to adjust control bandwidths λ_i based on the corresponding tracking errors.

The fuzzy system rule base for control bandwidths λ_i is defined as follows;

The fuzzy sets R1, R2, R3, R4, R5, and R6 are characterized by the membership functions shown in Figure 04 where

d1=-0.04, d2=-0.03, d3=-0.02, d4=-0.01
d5=-0.005, d6=0.005, d7=0.01, d8=0.02,
d9=0.03, d10=0.04

Since only five fuzzy subsets, R1, R2, R3, R4, R5 and R6, are defined for e_i , the fuzzy inference mechanism contains five rules for the FLC output. The resulting fuzzy inference rules for the output variable λ_i^j are as follows:

$$\begin{aligned} &\text{Rule 1: IF } e_i \in R_i^1 \quad THEN \quad \lambda_i = \lambda_i^1, \\ &\text{Rule 2: IF } e_i \in R_i^2 \quad THEN \quad \lambda_i = \lambda_i^j, \\ &\\ &\text{Rule j: IF } e_i \in R_i^j \quad THEN \quad \lambda_i = \lambda_i^j, \\ &j = 1,....,r_i \end{aligned} \tag{29}$$

Where e_i is the tracking error for the *ith* system variable, and r_i is the total number of rules for the *ith* system variable. In (2.29), R_i^j is the *jth* fuzzy set on the *ith* universe of discourse, characterized by membership function $\mu_i^j(e_i)$.

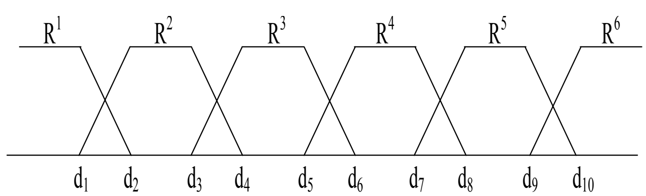

Figure 4. Input membership function of the fuzzy system.

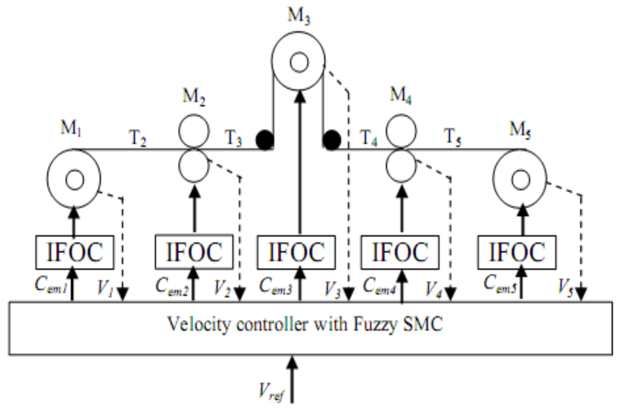

Figure 5. Block diagram for multi motors web winding system with MIMO-FSMC control.

5. Simulation Results

The winding system we modeled is simulated using MATLAB SIMULINK software and the simulation is carried out on 10s.

To evaluate system performance we carried out numerical simulations under the following conditions:

- Start with the linear velocity of the web of 5m /s.
- The motor M1 has the role of Unwinder a roll radius R1 (R1 = 2.25 m).
- The motors M2, M3, M4 are the role is to pinch the tape.
- The motor M5 has the role of winding a roll of radius R5. The aims of the STOP block is to stop at the same time the different motors of the system when a radius adjust to a desired value (for example R5 = 0.8 m), by injecting a reference speed zero.

The comparison between the two controllers FSMC-SISO and FSMC-MIMO is achieved in the two cases:

- Comparison of the control performances: it has been made by the comparison of the average speeds of the five motors Vavg, for each controller this average is expressed by the equation (47).
- Comparison of synchronism between the speeds of the five motors: in this point one makes a comparison between the deviation standard of speeds of five motors Vstd, for each controller this average is expressed by the equation (48).

$$V_{avg} = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{47}$$

$$V_{std} = \left(\frac{1}{n}\sum_{i=1}^{n}(V_i - V_{avg})^2\right)^{\frac{1}{2}} \tag{48}$$

As shown in Figure (6-8). An improvement of the linear speed is registered, and has follows the reference speed for both PI controller and FSMC control, but in case of PI controller, the overshoot in linear speed of Unwinder is 25%. Figure (7) and Figure (8) show that with the FSMC MIMO controller the system follows the reference speed after 0.3 sec, in all motors, however, in the FSMC SISO and PI controller the system follows after 1.3 sec and 2 sec respectively.

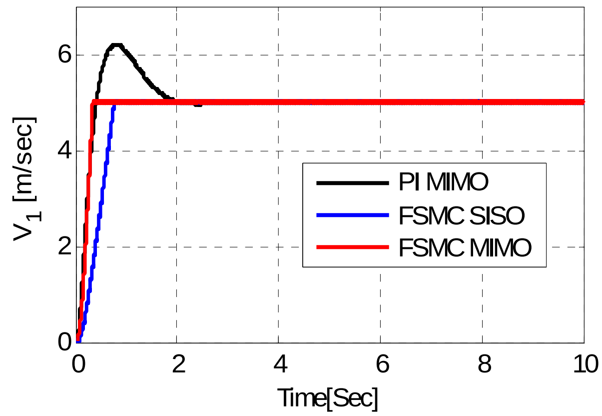

Figure 6. The linear speed of unwinder M1

From the Figures (5-7), we can say that: the effect of the disturbance is neglected in the case of the FSMC MIMO controller. It appears clearly that the classical control with PI controller is easy to apply. However the control with fuzzy sliding mode MIMO controllers offers better performances in both of the overshoot control and the tracking error.

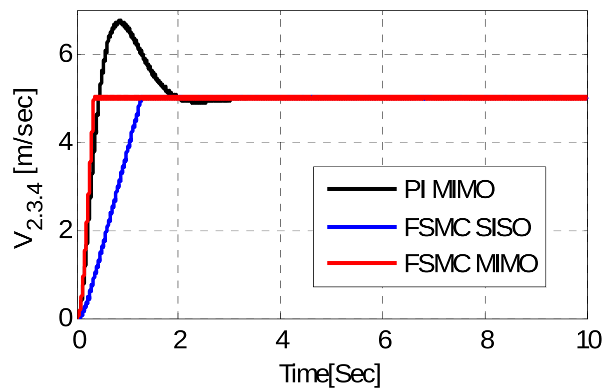

Figure 7. The linear speed of motors M2, M3 and M4

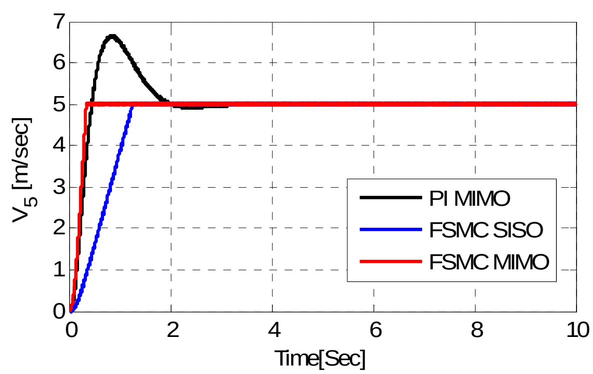

Figure 8. The linear speed of winder M5

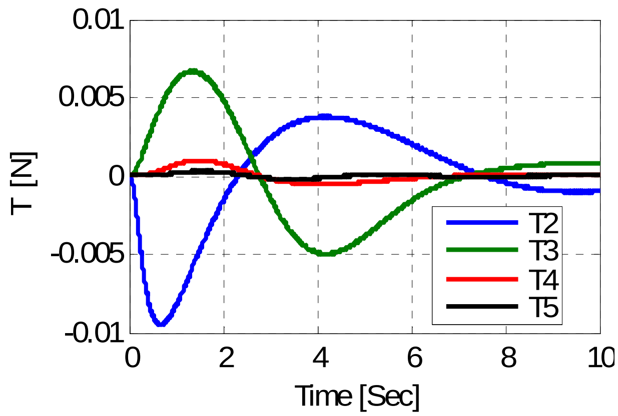

Figure 9. The Tension between two rolls With PI Controller

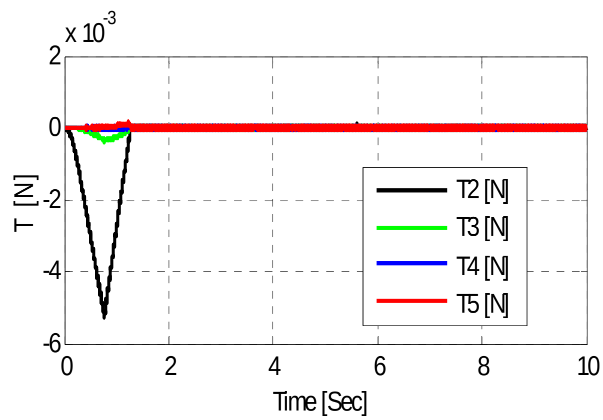

Figure 10. The Tension between two rolls With FSMC-SISO Controller

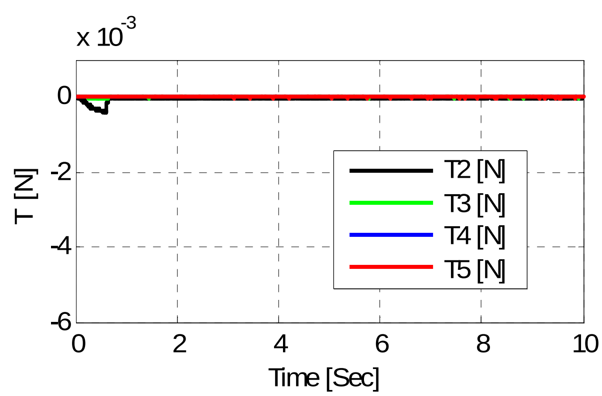

Figure 11. The Tension between two rolls With FSMC-MIMO Controller

Figure 9 shows that applying PI controller, the duration of the oscillations of the tension between rolls is 2 to 7 sec, with an amplitude equals 0.01 while, when applying FSMC-MIMO controller these values are enhanced and become 0.5 sec and 0.00025 N respectively is shown in Figure 11.

Figure 12 and Figure 13 shows the comparison between the FSMC-MIMO controller, the FSMC-SISO controller and the PI- MIMO controller. After this comparison we can judge that the FSMC-MIMO controller presents a clean improvement to the level of the performances of control, compared to the PI-MIMO controller, the synchronism between the five motors is improved with FSMC-MIMO controller compared to FSMC-SISO controller.

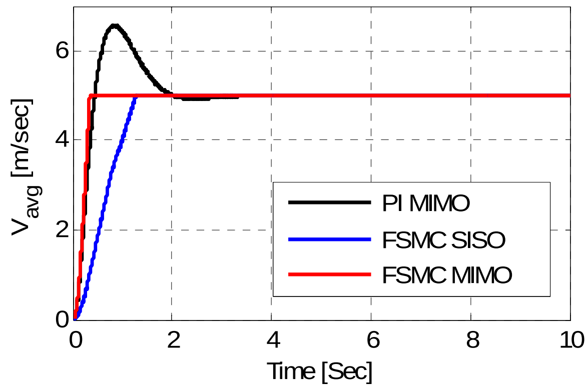

Figure 12. Comparison between the FSMC MIMO, FSMC SISO and PI MIMO with average speeds of five motors

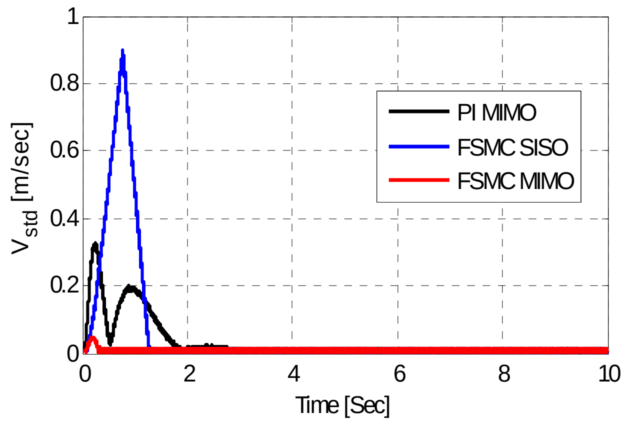

Figure 13. comparison between the FSMC MIMO, FSMC SISO and PI MIMO with the deviation standard of speeds of five motors

4. Conclusion

The sliding mode control of the field oriented induction motor was proposed. To show the effectiveness and performances of the developed control scheme, simulation study was carried out. Good results were obtained despite the simplicity of the chosen sliding surfaces. The robustness and the tracking qualities of the proposed control system using sliding mode controllers appear clearly.

Furthermore, in order to reduce the chattering, due to the discontinuous nature of the controller, fuzzy logic controllers were added to the sliding mode controllers.

These gave good results as well and simplicity with regards to the adjustment of parameters.

The simulations results show the efficiency of the FSMC-MIMO controller technique, however the strategy of FSMC-MIMO Controller brings good performances, and she is more efficient than the FSMC-SISO controller and classical PI-MIMO controller.

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