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TRIPLE DRIVE PAPER SYSTEM SPEEDS CONTROL USING ROBUST MULTIVARIABLE FUZZY LOGIC CONTROLLER

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Abstract

Speeds control of the multi-machines system (MMS) takes a great interest of the scientists in the relevant industry, the real time industrial control systems usually are multidimensional structure, according to the artificial intelligent many researches on the industrial control was carried. The aim of this work is to develop a novel fuzzy logic controller called multi-input multi-output fuzzy logic controller (MIMO-FLC) affect on a winding-unwinding system (Rolling-Unrolling) forming MMS process. This paper introduces a MIMO-FLC applied on speeds regulation of the triple drive paper system, to deal with multivariable control processes, MMS is a non-linear, time varying multi-input multi-output system whose states generally vary with operating conditions, for these reasons control requires a multivariable controller, in our case it is a multivariable fuzzy logic controller. Simulations were approved on MATLAB-SIMULINK environment and show clearly the robustness and the capability of the MIMO-FLC to ensure the system stability improvement with no over tracking and no steady state error with perfected rising time. The results confirm that multi-machines system speeds control process is best achieved using the proposed multivariable fuzzy logic controller.

Keywords: Triple drive paper system, winding-unwinding system, multi-input multi-output fuzzy logic control, multivariable fuzzy logic controller, MIMO-FLC MMS speeds control.

1 INTRODUCTION

Most electrical industry applications in the drives field require the use of several electric machines and needs many controllers that occupied an important place in most of electromechanical systems [1]. In electrical drive applications, the multi-machines systems are more frequently used, such as in the textile industry [2], paper industry [3] and autonomous mobile robotics.

In industry, the paper, plastic and other thin elastic materials are often employed for the manufacturing of commercial products by employing a continuous process [4]. In this case, paper or any other material is typically unrolled of a large roll by using a series of rollers and a rewinder, formant what is called enchainment. The main goal of enchainment is the process affectation to transfer the material with a maximum speed and a possible minimum damages.

The paper can be rolled onto a cylindrical shaft for storage and easy supply to later processing stages such as testing, cutting, and lamination. Alternatively, the material would require very large manufacturing facilities or cutting of the material into smaller sections. In addition to tension, the velocity of the paper passing through a processing stage is of paramount importance. If the velocity is not within specifications, product quality is again compromised [5], for this reason the control will be necessary.

The mathematical model present the mechanical tension realization, assessment [6], and the sequence speed in a winder. The recent progress achieved in the order and the electric machinery food makes these tools much more flexible and easy to control. One can find more fluently today several motors; each convicted a task, in a process, and whose speed is now adjusted nearly continuously, directly according to the studied application. The requirements in terms of the dynamic performances and regulation changed with the development of regulating methods and the control efficiency. Initially, a strong coupling existed between the mechanical loads, all bound the same machine; besides, this coupling could not be mastered in a rigorous way. Therefore, the regulation will impose certain mechanical load synchronization. With the use of several motors in sequence, the regulation is more precise and the other types of couplings can be taken in consideration in the synthesis of global control.

Thus, the couplings between the different machinery and their process by order became a considerable research task. On the other hand, although being part of the chain of conversion of the energy, the mechanical coupling moves away a little the pure electric genius to meet the border between the automatic, mechanics and the electrotechnics. It is about searching for new knowledge, to pass by a new training, entirely linked the mechanical load and its specific coupling.

The control problem is particularly difficult because of the nonlinearities of the model [1, 2, 4, 7], strong and weak interactions among the subsystems, the uncertainties in the parameters and various disturbances that can act upon the system.

The majority of process industries are nonlinear, multi- input multi-output (MIMO) systems. The control of these systems is met with a number of difficulties due to process interactions, dead time and process nonlinearities [2, 7]. The difference between MIMO systems control and Single-Input Single-Output (SISO) systems control is based on an estimation and compensation of the process interaction among each degree of freedom. It is obvious that the difficulty of MIMO systems control is how to overcome the coupling effects among each degree of freedom. To obtain good performance, coupling effect cannot be neglected. Hence SISO system control scheme is not easy to implement on complicated MIMO systems [8, 9]. In addition, the control rules and controller computation will grow exponentially with respect to a number of considered variables. Therefore, intelligent control strategy is gradually drawing attention.

The multi-machines system is a time varying non-linear system. The performance of these controllers is limited, since they don’t account for variation in the system parameters, and periodic tuning is necessary. There is, therefore, a practical motivation for considering fuzzy control. Fuzzy set theory was introduced by Zadeh in 1965 [10]. In 1974, Mamdani introduced a fuzzy algorithm in control field. Since that date, fuzzy set theory is employed for introducing and developing fuzzy models and controllers to control complex dynamic systems. Having uncertain data and/or nonlinearities, there arises some difficulties to build such fuzzy scheme. Based on generalized modus ponens strategy, two models have been proposed, Mamdani’s model [11] and Takagi-Sugeno model [12]. The latter simplified the output of a fuzzy rule of the former to a set of weighted singletons; however, using the Mamdani’s model improves the final outcome and controls multi-dimensional dynamic system with ease. The latter was single-loop and multi-loop control schemes that lack generality for controlling such complex processes.

This paper introduces an MMS speeds control using a multi-dimensional fuzzy logic controller based on Mamdani’s model to overcome this problem. The proposed scheme interacts with the variation of speeds states of the MMS that may change with operating conditions. Deriving fuzzy rules of the proposed scheme gives the corner stone to avoid redundant rules. Expertise, control actions, engineers and modeling techniques are the main strategies to obtain these fuzzy rules, however, precision becomes difficult to obtain if the process complexity increases. To construct a strong rule base for the controller, much effort have been conducted [13, 14], however, Wang and Mendel method [15] is the simplest and most effective to deal with this problem as will be shown in Section 3.

This paper is organized as follows: Section 2 briefly describes the model of the multi-machines rolling-unrolling system in its simplest form. The proposed multidimensional fuzzy controller is detailed in Section 3. Computer simulation results are given in Section 4 and Section 5 concludes the paper.

2 MULTI-MACHINES ROLLING-UNROLLING SYSTEM MODELING

This section is dedicated to the presentation and the multi-machines system modeling. In the industry of paper [16, 17] the winding systems are frequently present. Fig. 1 presents the test system constituted by three motors forming the winding system, every motor has an independent alimentation and an indirect field oriented control (IFOC) [18, 19]; the motors are coupled mechanically by a band whose tension is adjustable by the control of the last motors. This system is composed of two different parts; Fig. 2 shows the mechanical part and Fig. 3 shows the electrical part.

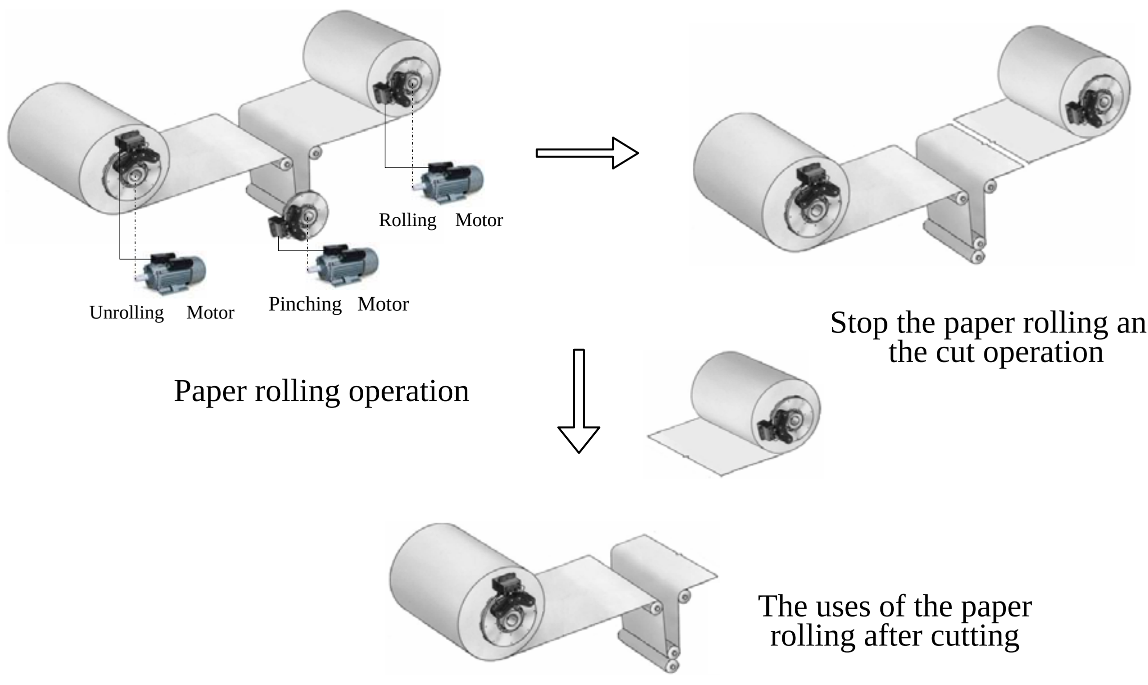


Figure 1: The winding system test constituted by three motors

2.1 MECHANICAL PART DESCRIPTION

In the mechanical part, the motor M_1 does the unwinding, the motor M_3 does the winding and the motor M_2 entails two rollers through the intermediary of gearings for the pinch of the band (Fig.2). The elements of controls pressure between the rollers are not represented, nor considered in the survey. The stage of pinch can permit to isolate two zones and to create a zone tampon [16]. The objective of these systems is to maintain the tape speed constant and to control the tension in the band.

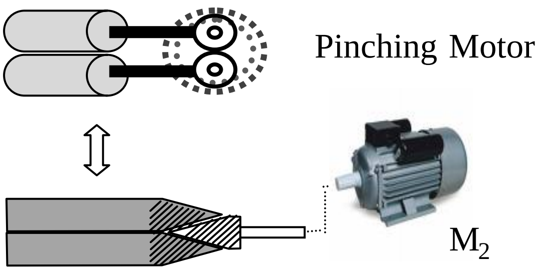


Figure 2: Pinching motor drive

2.2 ELECTRICAL PART DESCRIPTION

The tests band is composed by three three-phase asynchronous motors; in Fig. 3 the motors drives are connected each one to a three-phase alimentation and an IFOC [18, 19]. The engines (M_1, M_2 and M_3) are supplied by inverters in order to vary speed. The trained material is regarded as an elastic band. The asynchronous motors used are powerful.

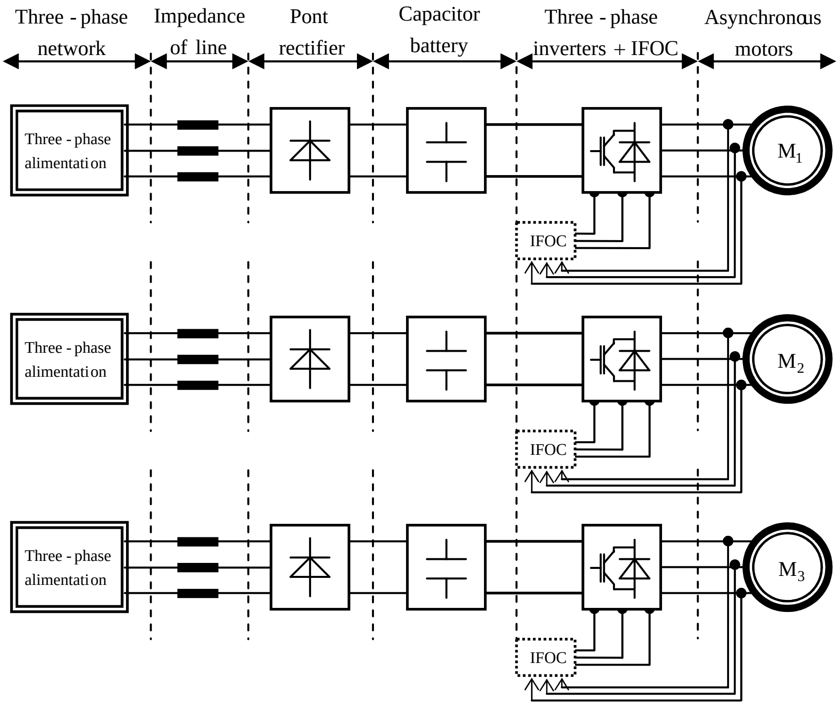


Figure 3 : Electrical part for an MMS with three motors

2.3 ROLLING-UNROLLING SYSTEM MODELING

The three phase induction motor modeling was approached in detail by Dong Hwa Kim [19]. As one could note, the various treatments are carried out in phase of run. It is therefore imperative to have effective organs of unrolling and rolling. These two devices, the rolling and the unrolling, are symmetrical (Fig. 4). After installation on the unrolling motor of a matter roller (paper), a band of product left and leaves towards the remainder the process.

The first role of the unrolling appears here: matter injection in the system. During the operating cycle, the quantity of matter on the roller decreases, its mass and its ray is thus not constant. In the same manner, the roller recovers the treated product; with starting, the carrying roller is empty, it fills progressively of advance. In order to guarantee a rolling up of good quality, linear velocity on arrival on the roller must be constant, the tension load imposed on material also.

In the same way, if one wants to ensure a good treatment of the product, the unrolling motor must deliver the product at constant speed and tension. When the unrolling motor is empty, the chain must stop; it is time to put a new roller. That is to say *l* the axial length of the paper rolling. The important relations for kinematics of the paper rolling can be developed as follows (Fig. 4) [20, 21].

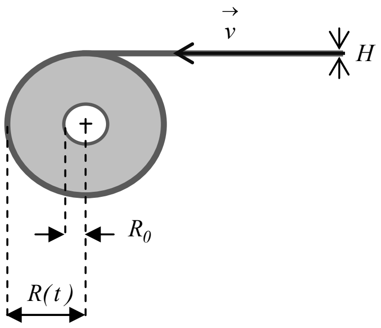


Figure 4 : Model of a paper roller

Ray *R(t)* and masses *m*: Let us regard the profile of the roller as an initial disc of ray R_0 , a crown of interior ray R_0 and external *R(t)* (Fig. 4).

$$R(t)=\sqrt{R_0^2+\frac{H}{\pi}\int_0^t V dt} \tag{1}$$

$$\dot{R}(t)=\frac{H}{2\pi}\frac{V}{R(t)} \tag{2}$$

$$\ddot{R}(t)=\frac{H}{2\pi R(t)}(\dot{V}-\frac{H}{2\pi}\frac{V^2}{R^2(t)}) \tag{3}$$

$$m=m_0+\rho\pi(R^2(t)-R_0^2)l \tag{4}$$

$$\dot{m}=\rho HlV \tag{5}$$

Rotation angle:

$$\theta=\int_0^t \frac{V}{R(t)}dt \tag{6}$$

$$\dot{\theta}=\frac{V}{R(t)} \tag{7}$$

$$\ddot{\theta}=\frac{1}{R(t)}(\dot{V}-\frac{H}{2\pi}\frac{V^2}{R^2(t)}) \tag{8}$$

Inertia of mass *J(t)*: Let us recall that the inertia of a hollow roll depends on its rays internal and external, on its density ρ and its height, here the width of the roll is *l*.

$$J=\frac{\pi\rho l}{2}(R^4-R_0{}^4) \tag{9}$$

The inertia of a roller unrolling or rolling is the sum of its vacuum inertia J_0 and of variable inertia according to the ray *R(t)*.

$$J(t)=J_0+\frac{\pi\rho l}{2}(R^4(t)-R_0{}^4) \tag{10}$$

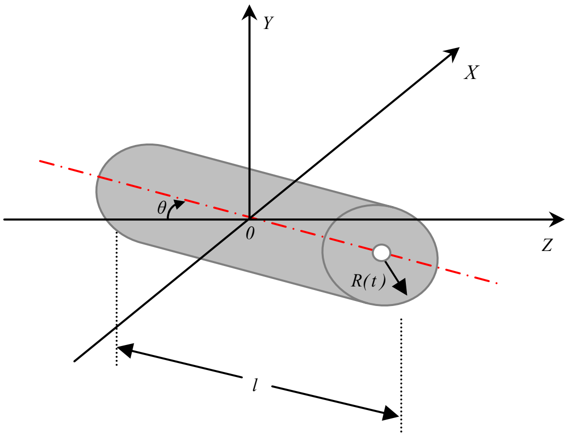


Figure 5 : Sight prospect for a paper roller

2.4 MATERIAL MODELING BETWEEN TWO CONSECUTIVE ROLLERS

The various models for the fabric or the band in the material transport systems in leafs are based on three laws [4, 6].

- The law of Hooke, model the elasticity of the bond between the enchainment;
- The law of Coulomb, which gives the variation of mechanical tension due to the friction and the force of contact between the fabric and the roller;
- Law of conservation of mass, which expresses the interconnection between the speed of band and its constraint.

Several modeling studies have been proposed to describe the tension behavior of a paper in different winding processes [22, 23, 24]. All those theoretical models are, in large measure, based on the Hooke's equation, given by (11), which expresses the linear relationship between the traction evolution, δT_i, and the elongation, δe of an elastic stick.

$$\delta T_i = \frac{EA}{l}\delta e \tag{11}$$

With:

l Distance between motors axes (m),
E Young's modulus (N/m^2),
A Cross-section of the strip (m^2).

In such a winding system, the elastic film moves from an unwinding motor to a rewinding motor. Consequently, the elongation is time-variant, and can be expressed in terms of a linear velocity difference, as defined by (12):

$$\frac{dT_i}{dt} = \frac{EA}{l}(V_{i+1}(t) - V_i(t)) \tag{12}$$

with i denoting the index of the motor,
Based on this last expression, an empirical tension equation is proposed in [23]:

$$\frac{d\Delta(T_i(t))}{dt} + \frac{V}{l}\Delta T_i(t) = \frac{EA}{l}\Delta V_i(t) \tag{13}$$

$$\Delta T_i(t) = T_i(t) - \Delta T_{i-1}(t) \tag{14}$$

$$\Delta V_i(t) = V_{i+1}(t) - V_i(t) \tag{15}$$

where V is the average linear velocity of the strip. Around the nominal operating condition, V is generally constant. Accordingly, (13) can be approximated as a first-order differential equation with constant coefficients. The interest of this formula in comparison to (12) is in pointing out the tension interaction between the motor i and its precedent by introducing the previous tension T_{i-1} in the computation of T_i. By taking account of other physical phenomena, such as the invariability of mass and the balance of the momentum, [24] proposes a nonlinear equation defined by (14).

$$\frac{d}{dt}\left(\frac{\xi}{\xi+T_i(t)}l\right)=\frac{\xi}{\xi+T_{i-1}(t)}\Delta V_{i-1}(t)-\frac{\xi}{\xi+T_i(t)}\Delta V_i(t) \tag{16}$$

$$l\frac{dT_i}{dt}=EA(V_i-V_{i-1})+T_{i-1}V_{i-1}-T_iV_i \tag{17}$$

where ξ is the related modulus of elasticity.

2.5 ENCHAINMENT SPEED ON EACH ROLLER

Supposing that the enchainment does not slip on the roller, the enchainment speed is equal at the linear speed of roller [16, 25, 26]. The speed dynamic equation V_i of the i^{th} roller can be obtained by the equilibrium equation of couple:

$$\frac{d(J_i\Omega_i)}{dt}=R_i(T_{i+1}-T_i)+C_{emi}+C_f \tag{18}$$

$$\Omega_i=V_i/R_i \tag{19}$$

Where T_{i+1} and T_i are the tensions in material between each pair of rollers, C_f is the sum of the friction couples. We note according to the equation (18) that inertia J_i and the ray R_i are related to time. J_i and R_i augment with time for the rolling roller and diminish with time for the unrolling roller.

2.6 COMPLETE MODEL OF ROLLING-UNROLLING USED FOR THREE MOTORS

The complete model of our experimental installation can be established while using (17) to indicate the mechanical tension in each segment and (18) to indicate the speed of each roller. Fig. 6 shows the various variables in the model of our experimental rolling-unrolling system. The inputs are the control signals u_1, u_2 and u_3 (command tensions). The outputs are the linear velocity V_1 and the enchainment tensions T_2 and T_3. The control signals are the reference couple of the asynchronous motors. In a centralized arrangement of command, the enchainment speed is commanded by the traction motor and the enchainment tension is commanded by the motors of rolling and unrolling. The equations (17) and (18) can be expressed in the form of state equations:

$$\begin{aligned} L\dot{X} &= A(t)X+BU \\ Y &= C(t)X \end{aligned} \tag{20}$$

with:

$$X^T=[T_2 \quad T_3 \quad J_1(t)\Omega_1 \quad J_2\Omega_2 \quad J_3(t)\Omega_3]$$

and:

$$Y^T=[T_2 \quad T_3 \quad V_1]$$

$$A(t)=\begin{bmatrix} -V_2 & 0 & -EA\dfrac{R_1(t)}{J_1(t)} & EA\dfrac{R_2}{J_2} & 0 \\ V_2 & -V_3 & 0 & -EA\dfrac{R_2}{J_2} & EA\dfrac{R_3(t)}{J_3(t)} \\ R_1(t) & 0 & -\dfrac{f_1(t)}{J_1(t)} & 0 & 0 \\ -R_2 & R_2 & 0 & -\dfrac{f_2(t)}{J_2} & 0 \\ 0 & -R3(t) & 0 & 0 & -\dfrac{f_3(t)}{J_3(t)} \end{bmatrix} \quad L=\begin{bmatrix} l_1 & 0 & 0 & 0 & 0 \\ 0 & l_2 & 0 & 0 & 0 \\ 0 & 0 & l_3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix};$$

$$C(t)=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \dfrac{R_1(t)}{J_1(t)} & 0 & 0 \end{bmatrix}; \quad B=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ K_1 & 0 & 0 \\ 0 & K_2 & 0 \\ 0 & 0 & K_3 \end{bmatrix}; \quad U=[u_1 \quad u_2 \quad u_3]$$

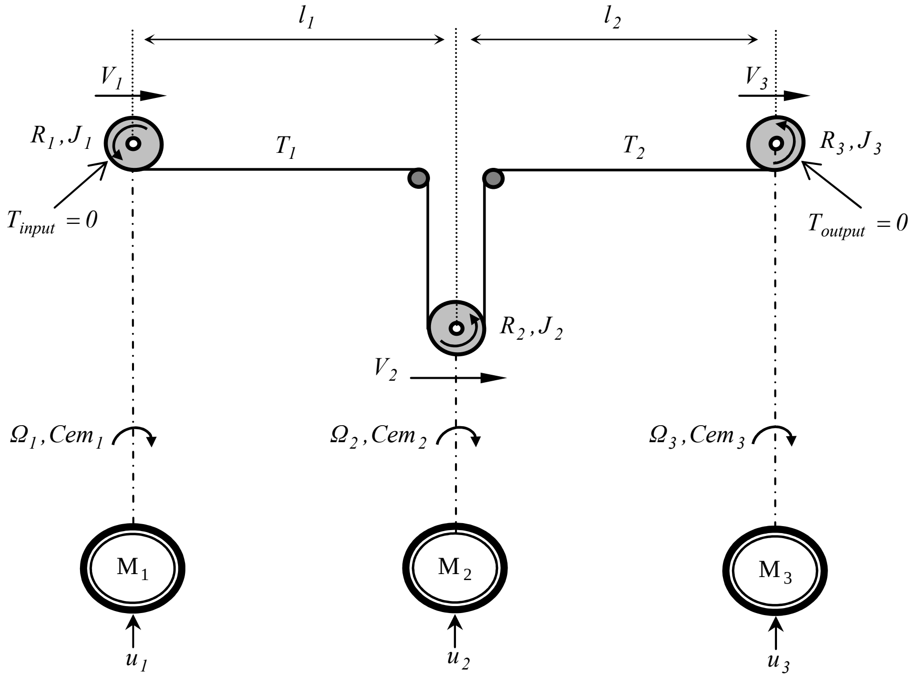


Figure 6 : Complete model of rolling-unrolling for three motors

The equations of the motors and the tensions are:

$$\frac{d(J_1(t)\Omega_1)}{dt} = R_1(t)T_2 + C_{em1} - f_1(t)\Omega_1$$

$$l_1\frac{dT_2}{dt} = EA\,(V_2 - V_1) - T_2V_2$$

$$\frac{d(J_2\Omega_2)}{dt} = R_2(T_3 - T_2) + C_{em2} - f_2(t)\Omega_2$$

$$l_2\frac{dT_3}{dt} = EA\,(V_3 - V_2) + T_2V_2 - T_3V_3$$

$$\frac{d(J_3(t)\Omega_3)}{dt} = R_3(t)(-T_3) + C_{em3} - f_3(t)\Omega_3$$

3 MULTIVARIABLE FUZZY CONTROLLER STRUCTURE

Fuzzy set theory has been successfully applied in a number of control applications [8, 12, 27, 28, 29, 30] based on the SISO system point of view without system model consideration. In this paper, the MIMO fuzzy control strategy is used to multi-machines system speeds control. The block diagram of the MIMO fuzzy control scheme is shown in Fig. 7. The design procedure of the fuzzy control strategy is used to control each degree of freedom of this MIMO system individually. Then, an appropriate coupling fuzzy logic controller (FLC) is designed to compensate for the coupling effects of system dynamics among each degree of freedom.

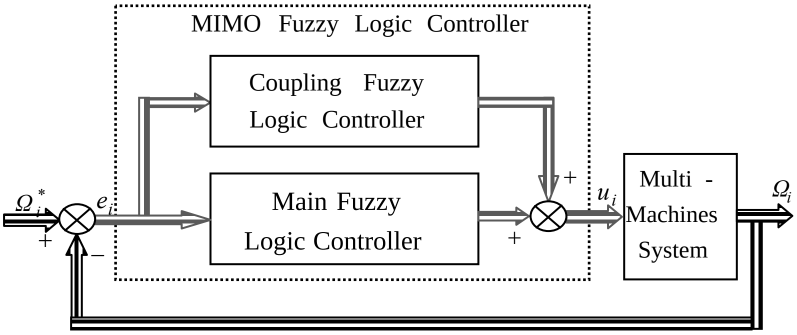


Figure 7 : Block diagram of the MIMO fuzzy control scheme

An ordinary fuzzy controller that usually operates with system output error and error change was chosen as the main controller to control each degree of freedom of the MIMO systems. Here, the input variables of the conventional fuzzy controller for among each degree of freedom of a MIMO system were defined individually as

$$e_i(k) = \Omega_i^*(k) - \Omega_i(k) \tag{21}$$

$$\Delta e_i(k) = e_i(k) - e_i(k-1) \tag{22}$$

where $e_i(k)$ is the position error of the i^{th} degree, $\Delta e_i(k)$ is used for change in error of the i^{th} degree, $\Omega^*_i(k)$ is the reference input (Rotation speed reference of the roller *i*) of the i^{th} degree and $\Omega_i(k)$ represents the i^{th} position output of each degree of freedom (real Rotation speed of the roller *i*) of this MIMO system at the k^{th} sample.

The relationship between the scaling factors (G_e, $G_{\Delta e}$, G_u) are the input and output variables of the FLC is

$$e_{iN} = G_e \times e_i, \quad \Delta e_{iN} = G_{\Delta e} \times \Delta e_i, \quad \Delta u_i = G_{\Delta u} \times \Delta u_{iN} \tag{23}$$

Selection of suitable values for G_e, $G_{\Delta e}$ and G_u are made based on the knowledge about the process to be controlled and sometimes through trial and error to achieve the best possible control performance. This is so because, unlike conventional no fuzzy controllers to appointment, there is no well-defined method for good setting of scaling factor's for FLC's. The SFs are the significant parameters of FLC because changing the SFs changes the normalized universe of discourse, the domains, and the membership functions of input/output variables of FLC.

All membership functions (MFs) for controller inputs (e_i and Δe_i) and incremental change in controller output (Δu_i) are defined on the common normalized domain (Per Unit) [-1, +1]. We use symmetric triangles (except the two MFs at the extreme ends) with equal base and 50% overlap with neighboring MFs as shown in Fig. 8. This is the most natural and unbiased choice for MFs.

By way of the above design process, the actual control input voltage for the main fuzzy controller can be written as

$$u_i(k) = u_i(k-1) + \Delta u_i(k) \tag{24}$$

In (24), k is the sampling instant and $\Delta u_i(k)$ is the incremental change in controller output, which is determined by the rules of the form (IF-THEN) If e_i is E_i and Δe_i is ΔE_i, Then Δu_i is ΔU_i. The rule base for computing is a standard one [8, 12, 29] as shown in Tab. I.

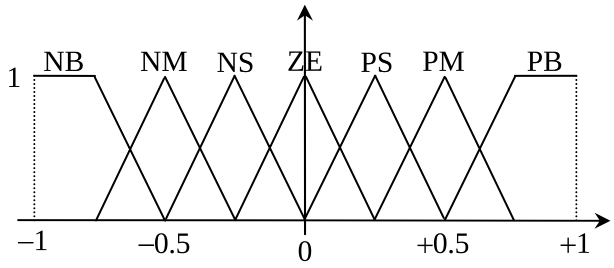


Figure 8 : Membership functions for e_i, Δe_i and Δu_i

NB-Negative Big, **NM**-Negative Medium, **NS**-Negative Small, **ZE**-Zero Error, **PS**-Positive Small, **PM**-Positive Medium, **PB**-Positive Big.

Table I : Rules base

Δe_i / e_i	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

The fuzzy control rules of the coupling fuzzy controller are similar to the main fuzzy controller. The output of the coupling fuzzy controller is chosen directly as the coupling control input voltage. The main reason is that there is a different coupling effect for each sampling interval and it does not have an accumulating feature. The coupling effect is incorporated into the main fuzzy controller for each step to improve system performance and robustness. Fig. 9a illustrates the structure of MIMO fuzzy control scheme. Fig. 9b shows Simulation of the MMS speeds control using the MIMO fuzzy controller.

Therefore, the total control input voltage of the MIMO fuzzy controller is represented as

$$U_i(k) = u_i(k) + U(k)_{i\to l} \quad , \quad i \neq l \tag{25}$$

where $u_i(k)$ expresses the system control input voltage of the i^{th} degree of a main fuzzy controller. $U(k)_{l\to i}$ represents the coupling effect control of the l^{th} degree relative to the i^{th} degree of the coupling fuzzy controller.

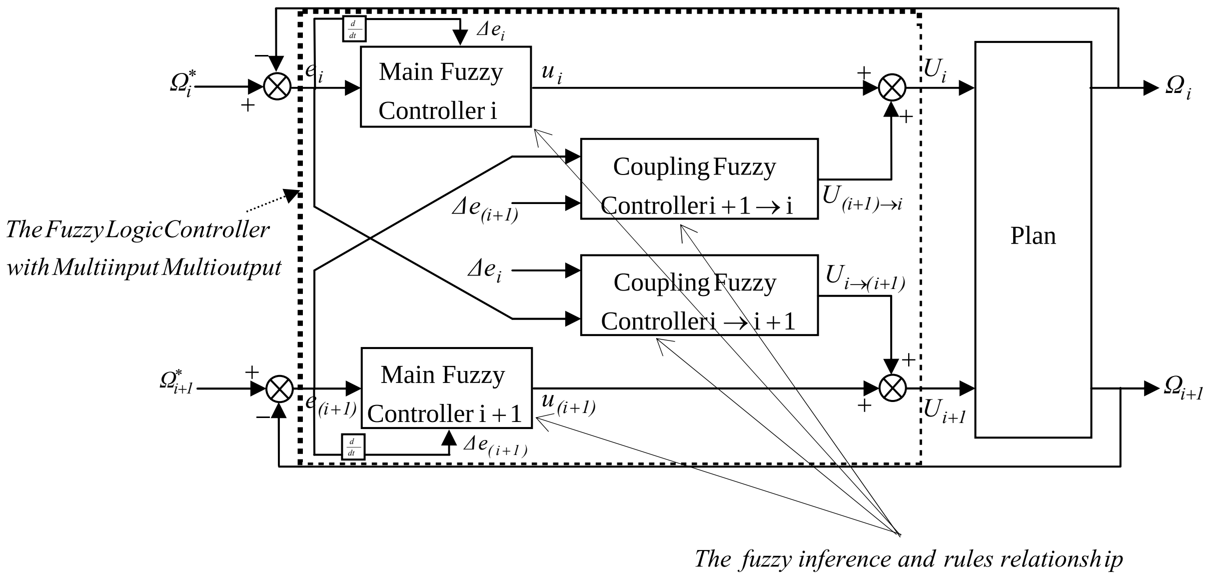


Figure 9a : Structure of MIMO fuzzy control scheme

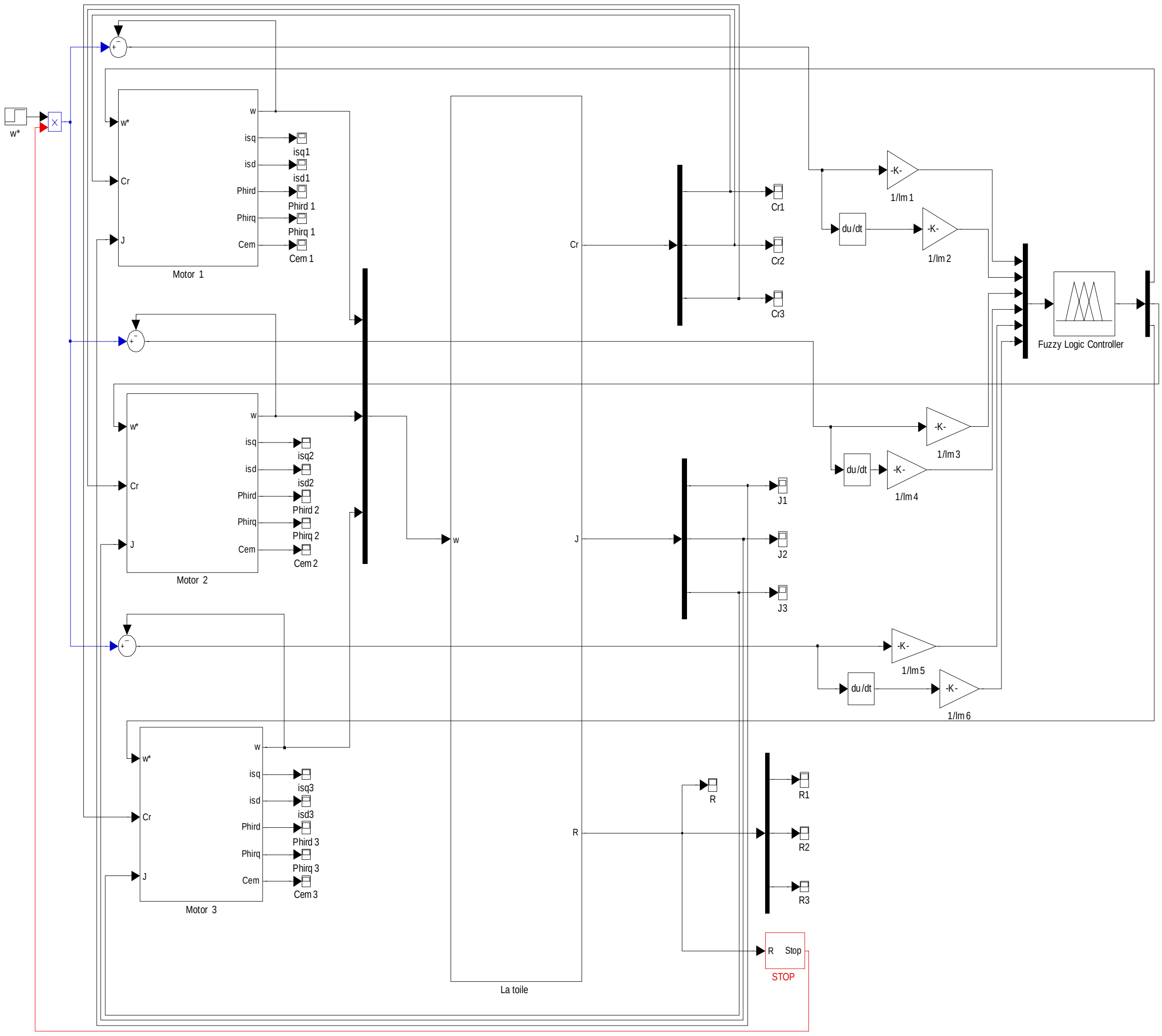


Figure 9b : The MMS speeds control using the MIMO fuzzy controller in Simulink

4 COMPUTER SIMULATION RESULTS

From the state equations, we can construct the model with the environment MATLAB 7.6 (R2008a) in Simulink version 7.1. To evaluate the performances of the system we carried out digital simulations under the following conditions:

- Starting with level speed application of 50 rad/sec.
- The motor M_1 role to unrolling the roller of ray R_1 (R_1=2.25 m).
- The motor M_2 makes the pinching of the band.
- The motor M_3 role to rolling the roller of ray R_3.
- To turn off slightly the several motors at the same time of system until where the ray to regulate reached a desired value (example: R_3=0.8 m), by injecting a null speed reference.
- The simulation results are obtained for 22 seconds range time.

The Fig. 10, Fig. 11 and Fig. 12 demonstrate that the adjustment using MIMO-FLC gives satisfactory results:

- The three motors rotational speeds (Ω_1, Ω_2 and Ω_3) follow the reference speed.
- The currents (i_{sq} and i_{sd}) for the three motors are well limited to its acceptable values.
- The fluxes (Φ_{rq} and Φ_{rd}) for the three motors are maintained at their desired values (indeed decoupling is maintained).
- It is noticed that the electromagnetic couple C_{em} follows the resistive torque value C_r.
- It is also noticed that the inertia moment J reduce with the reduction in the ray R and augment with its augmentation.

The general objective of the transport processes, winding and unwinding guarantees that the unit works in harmony and synchronism, especially to ensure a good quality of the treatment and rewinding of the product.

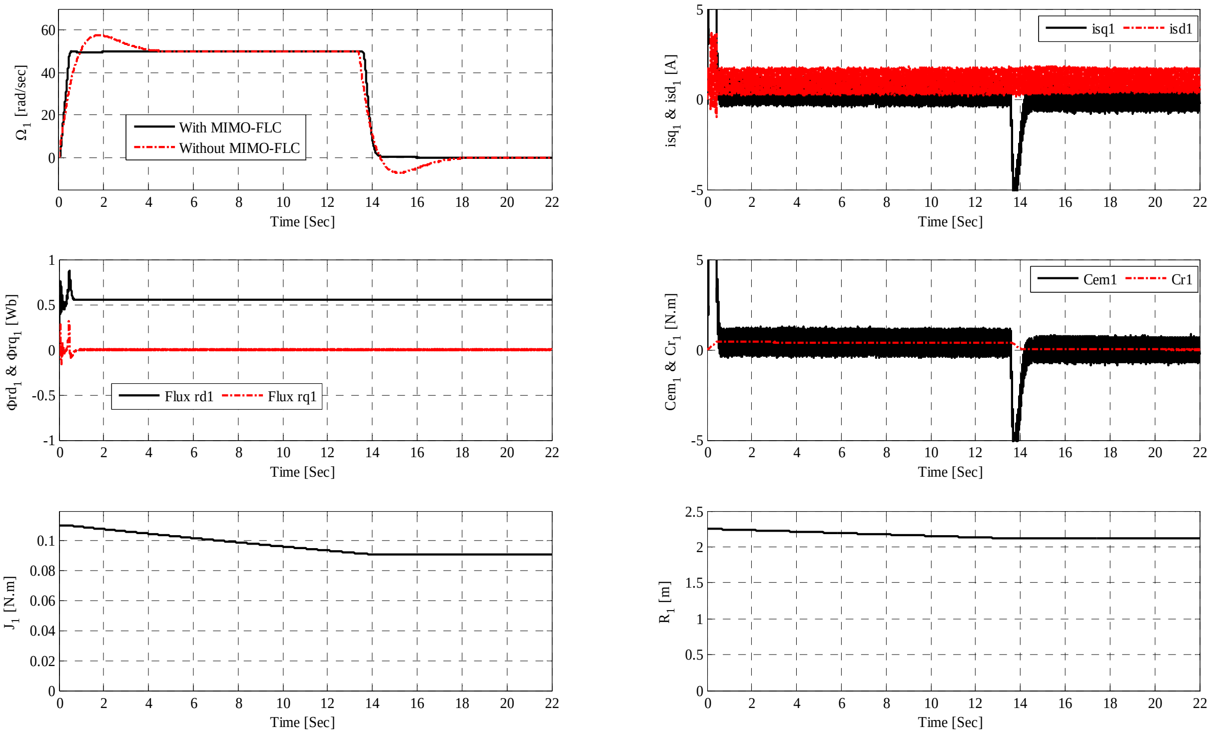


Figure 10 : Simulation results of the first motor M_1 (unrolling motor)

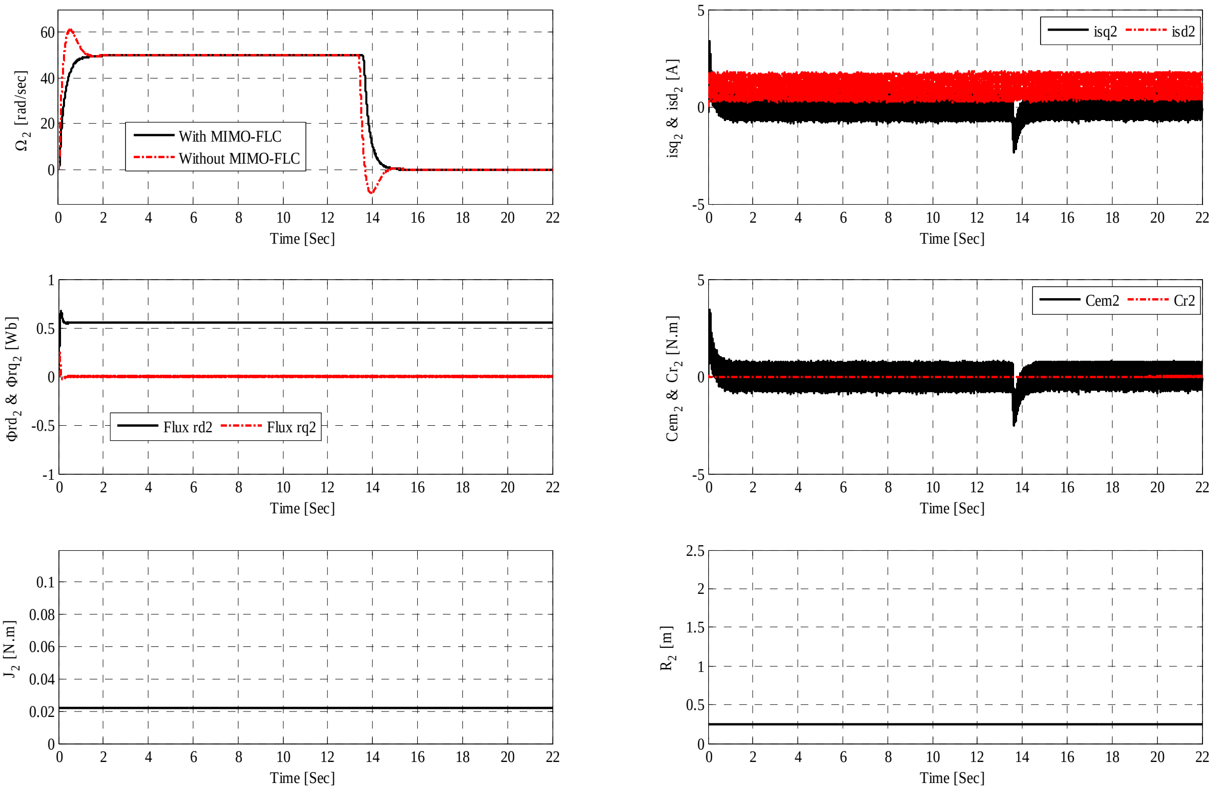
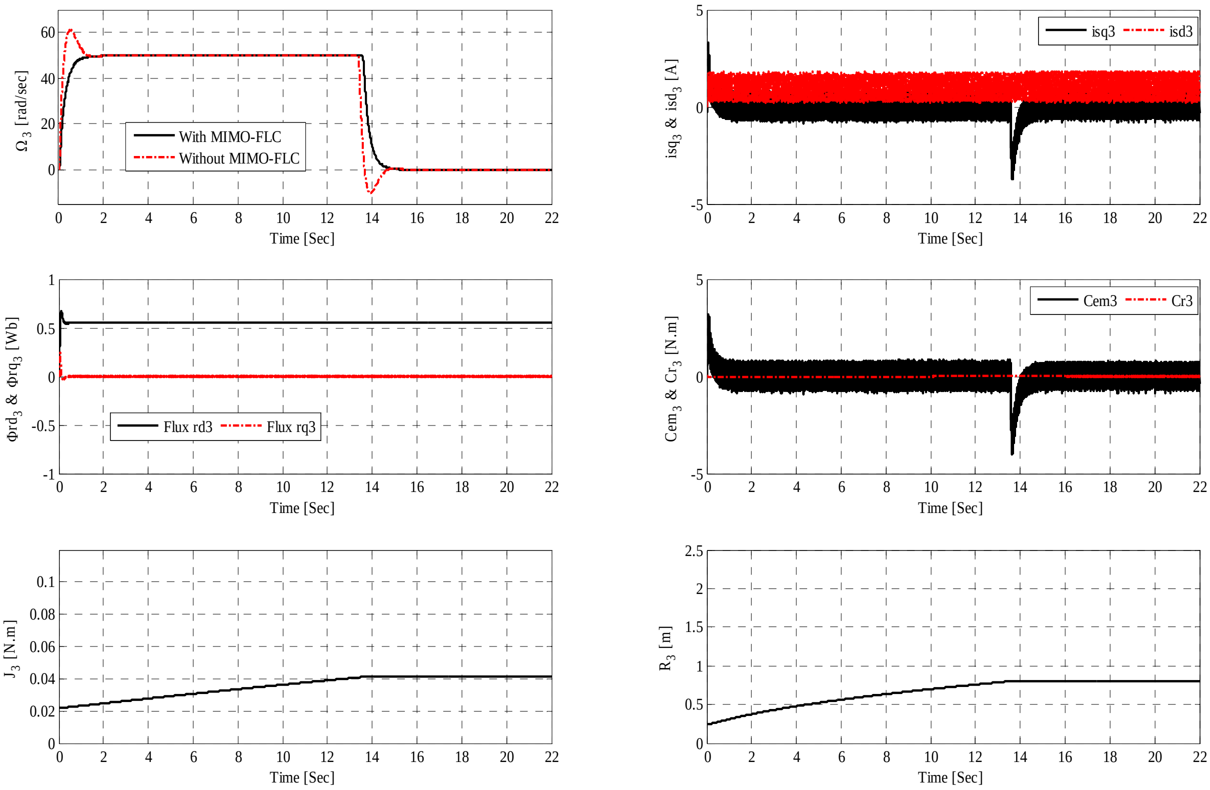


Figure 11 : Simulation results of the second motor M_2 (pinching motor)



Figue 12 : Simulation results of the third Motor M_3 (rolling motor)

5 CONCLUSION

In this paper, the speeds of three motors forming a multi-machines system are controlled by multi-input multi-output fuzzy logic controller. Winding system in particular was presented, significant improvement of the systems and of the controls of these systems is still both possible and desirable to satisfy the need for higher processing speeds and increased constraints on accuracy. Development for these systems is not limited to global control structures, but calls for research development in many fields for control engineers: improve drive systems and their performance in disturbed or degraded operating conditions; improve state estimators for induction motor drives; develop design methods and controllers that can be easily accepted by the control engineers; and many others. Moreover, the richness of problems and the complexity of winders make then a very interesting case study for education of control engineers and in related fields.

The problems of the multi-machines system are expressed in terms of couplings between these motors. The mechanical coupling between the rollers is surely the most concrete case. In industry, the knowledge of the coupling and its effects requires an immersion in the industrial context. The delimitation of the subject to industry appears only in the choice of an application; the study of the coupling remains valid for a broad ranges of industrial applications containing rolling-unrolling.

Our principal contributions relate to:

- The developments of a multi-machines system model compose by three motors, which are coupled mechanically by a band whose tension is adjustable.
- The development of the MIMO-FLC laws and their application to synchronize the three enchainments and to maintain a mechanical tension constant between the rollers of the system.
- The MIMO-FLC controller is the best which presented satisfactory performances and possesses good robustness (no overshoot, minimal rise time, Steady state error = 0).

This work enabled us to contribute a technological share for the multi-motors system of high efficiency. The simulation results show well the system steps and the operation stages. The MIMO-FLC advantages are the effects compensation of non linearity, to ensure a good internal and high stability performance of the system with a negligible starting error.

APPENDIX

Table II : Parameters of the asynchronous motors

Designations	Abbreviation	Value	Units
Nominal power	P_n	3.5	kw
Nominal voltage	V_n	380	V
Nominal power-factor	$\cos\varphi_n$	0.8	—
Nominal Speed	N_n	1200	tr/min
Nominal frequency	f	60	Hz
Nominal current	I_n	8.31	A
Stator resistance	R_s	4.85	Ω
Rotor resistance	R_r	3.805	Ω
Cyclic inductance stator	L_s	0.374	H
Cyclic Inductance rotor	L_r	0.374	H
Mutual Inductance	L_m	0.358	H
Many pairs of poles	P	2	—
Inertia Moment	J	1.011	kg/m^2
Coefficient of friction	f_c	0.01	N.m.sec/rad

Table III : Used symbols

Symbols	Designations	Units
d and q	Axes direct and into quadratic.	—
x_d and x_q	Components in the reference mark (d-q).	—
Φ_{rd} and Φ_{rq}	Rotor fluxes following the axes direct and into quadratic.	Wb
i_{ds} and i_{qs}	Stator currents following the axes direct and into quadratic.	A
θ	Rotation angle	rad
C_{em} and C_r	Electromagnetic couple and Resistive torque.	N.m
e	Variation enters speed w and reference speed w^*.	rad/sec
m_0	Mass of core.	Kg
m	Total mass of the paper roller.	Kg
R_0	Ray of the core.	m
V	Tape speed of paper.	m/ sec
H	Thickness of paper.	m
J_0	Vacuum inertia.	kg.m^2
E	Band Young modulus.	N/m^2
A	Enchainment section.	m^2
$A(t),B,C(t),L$	Diagonal matrices of the parameters.	—
ρ_i $(i=2,3)$	Material voluminal density.	kg/m^3
V_i (i=1,3)	Linear velocity of roller i.	m/ sec
Ω_i (i=1,3)	Rotation speed of the roller i.	rad/ sec
R_i (i=1,3)	Ray of the roller i of paper.	m
J_i (i=1,3)	Inertia moment of the roller i.	kg.m^2
f_i (i=1,3)	Coefficient of viscous friction of the roller i.	N.m. sec /rad
T_i (i=2,3)	Mechanical tension enters the rollers i and $i+1$.	N
l_i (i=1,2)	Enchainment length enters the rollers i and $i+1$.	m

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