MULTI-MACHINES SYSTEM SPEEDS CONTROL USING MULTI-INPUT MULTI-OUTPUT FUZZY LOGIC CONTROLLER

Boumediène ALLAOUA Abdellah LAOUFI Brahim MEBARKI Brahim GASBAOUI
Faculty of the Sciences and the Technology, Department of the Technology, Bechar University,
B.P 417 BECHAR (08000), ALGERIA
elec_allaoua2bf@yahoo.fr

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 multi-machines 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 controller multivariable, in our case it is a multivariable fuzzy logic controller. Simulations were approved on MATLAB-SIMULINK environment and show clearly 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.

Key words: Multi-machines system, winding-unwinding system, multi-input multi-output fuzzy logic control, multivariable fuzzy logic controller, MIMO-FLC MMS speeds control.

1. Introduction.
Most electrical industrial 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 used, such as 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 manufacture 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 affection 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 realization and the assessment of mechanical tension [6] and speed of sequence in a winder represented by a mathematical model will be gotten. The recent progress achieved in the order and the electric machinery food makes these of the tools of as much more flexible and easy to control. One finds 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 of course with the development of regulating methods and of controls besides and more efficient. In the departure, 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 regulating will impose certain mechanical load synchronization. With the use of several motors of sequence, the regulating are more precise and the other types of couplings can be taken in consideration in the synthesis of controls it global.

Thus, the couplings between the different machinery and their processed by the order became a considerable research axis. 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 of 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 the 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 non-linear system, time varying. 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 introduced by Zadah 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, 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 take 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 is 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 can be 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.

1. Multi-machines rolling-unrolling system modeling.

This section is dedicated for the presentation and the multi-machines system modeling. In the industry of paper [16, 17] the winding systems are very present. Fig. 1 present the test system constitutes three motors forming the winding system, every motor has a 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 two different parts; Fig. 2 shows the mechanical part and Fig. 4 shows the electrical part.

Fig. 1  The winding system test constitutes three motors.
2.1 Mechanical part description.
In the mechanical part, the motor M1 does the unwinding, the motor M3 does the winding and the motor M2 entails two rollers through the intermediary of gearings for the pinch of the band (Fig. 3). 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.

![Pinching Motor](image)

Fig. 3 Pinching motor drive.

2.2 Electrical part description.
The tests band compose three three-phase asynchronous motors; in Fig.4 the motors drives are connected each one to a three-phase alimentation and an IFOC [18, 19]. The engines (M1, M2 and M3) are supplied by inverters in order to vary speed. The trained material is regarded as an elastic band. The asynchronous motors used are powerful.

![Electrical part](image)

Fig. 4 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 it, 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. 5). 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. 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 speed and tension constants. When the unrolling motor is empty, the chain must stop; time to put a new roller. That is to say l the axial length of the paper rolling. The important relations kinematics of the paper rolling can be developed as follows (Fig. 5) [20, 21].

![Model of a paper roller](image)

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. 5).

\[
R(t) = \sqrt{R_0^2 + \frac{H}{\pi} \int_0^t Vdt} \\
\text{•} \quad \dot{R}(t) = \frac{H}{2\pi} \frac{V}{R(t)} \\
\text{•} \quad \ddot{R}(t) = \frac{H}{2\pi R(t)} \left( V - \frac{H}{2\pi} \frac{V^2}{R^2(t)} \right) \\
\quad \text{m} = m_0 + \rho \pi (R^2(t) - R_0^2) l \\
\quad \text{m} = \rho l V H
\]

Rotation angle:

\[
\theta = \frac{1}{l} \int_0^t \frac{V}{R(t)} dt
\]
\[ \theta = \frac{V}{R(t)} \]  
\[ \ddot{\theta} = \frac{1}{R(t)} \left( V^2 - \frac{H}{2\pi R^2(t)} \right) \]  
Inertia of mass \( J(t) \): Let us recall that the inertia of a hollow roll depends on its rays internal and external, of its density \( \rho \) and its height, here the width of the roll is \( l \).
\[ J = \frac{\pi \rho l}{2} (R^4 - R_0^4) \]  
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 \( R(t) \).
\[ J(t) = J_0 + \frac{\pi \rho l}{2} (R^4(t) - R_0^4) \]  

\[ \delta T_i = \frac{EA}{l} \delta e \]  
with 
\( l \) Distance between motors axes (m), 
\( E \) Young’s modulus (N/m²), 
\( A \) Cross-section of the strip (m²).

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):
\[ \frac{dT_i}{dt} = \frac{EA}{l} (V_{i+1}(t) - V_i(t)) \]  
With \( i \) Index of the motor,

Based on this last expression, an empirical tension equation is proposed in [23]:
\[ \frac{dT_i}{dt} = \frac{EA}{l} \Delta V_i(t) \]  
\[ \Delta T_i(t) = T_i(t) - \Delta T_{i-1}(t) \]  
\[ \Delta V_i(t) = V_{i+1}(t) - V_i(t) \]  

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] propose a nonlinear equation defined by (14).

\[ \frac{d}{dt} \left( \frac{\xi}{\xi + T_i(t)} \right) = -\frac{\xi}{\xi + T_i(t)} \Delta V_i(t) - \frac{\xi}{\xi + T_i(t)} \Delta V_f(t) \]  
\[ \frac{dT_i}{dt} = EA \left( V_i - V_{i-1} \right) + T_{i-1} V_{i-1} - T_i V_i \]  
where \( \xi \) 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:
\[ \frac{d(J_i \dot{\Omega}_i)}{dt} = R_i (T_{i+1} - T_i) + C_{emi} + C_f \]  
\[ \dot{\Omega}_i = \frac{V_i}{R_i} \]  
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 \( I_i \) 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. 7 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:

$$ L \dot{X} = A(t)X + BU $$

$$ Y = C(t)X $$

(20)

*Fig. 7 Complete model of rolling-unrolling for three motors.*

The equations of the motors and the tensions are:

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

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

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

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

$$ \frac{d(J_3(t)\Omega_3)}{dt} = R_2(t)(-T_3) + C_{em3} - f_3(t)\Omega_3 $$

$$ X^T = [T_2, T_3, V_1] $$

$$ A(t) = [\begin{bmatrix} -V_2 & 0 & -EA \frac{R_2(t)}{J_2} \frac{R_3(t)}{J_3(t)} \\ V_2 & -V_3 & 0 & -EA \frac{R_3(t)}{J_3(t)} \\ 0 & -R_3(t) & 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 \end{bmatrix}] $$

$$ B = \begin{bmatrix} l_1 & 0 & 0 & 0 \\ l_2 & 0 & 0 & 0 \\
0 & l_3 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 \end{bmatrix}; \ C(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\
0 & 0 & R_2(t) & 0 \\
0 & 0 & 0 & 0 \end{bmatrix}; $$

$$ U = [u_1, u_2, u_3] $$


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. 8. 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.

*Fig. 8 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

\[ e_i(k) = \Omega^*_i(k) - \Omega_i(k) \]  

(21)

\[ \Delta e_i(k) = e_i(k) - e_i(k-1) \]  

(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 (\( G_{e_i}, G_{u_i}, G_{e_{iN}} \)) are the input and output variables of the FLC is

\[ e_{iN} = G_e \times e_i, \quad \Delta e_{iN} = G_{e_i} \times \Delta e_i, \quad \Delta u_i = G_{u_i} \times \Delta u_{iN} \]  

(23)

Selection of suitable values for \( G_e, G_{u_i} \) and \( G_e \) 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 date, 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 \( \Delta e_i \)) and incremental change in controller output (\( \Delta u_i \)) 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. 9. 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

\[ u_i(k) = u_i(k - 1) + \Delta u_i(k) \]  

(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 \( E_j \) and \( \Delta e_i \) is \( \Delta E_j \). Then \( \Delta u_i \) is \( \Delta U_j \). The rule base for computing is a standard one [8, 12, 29] as shown in Table I.

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. 10.a illustrates the structure of MIMO fuzzy control scheme. Fig. 10.b 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

\[ U_i(k) = u_i(k) + U(k)_i, \quad i \neq l \]  

(25)

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

![Fig. 9 Membership functions for \( e_i, \Delta e_i \) and \( \Delta u_i \).](www.jee.ro)

<table>
<thead>
<tr>
<th>Rule Base</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>( AE_i )</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
</tr>
<tr>
<td>( e_i )</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>( NB )</td>
<td>NS</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
</tr>
<tr>
<td>( PS )</td>
<td>ZE</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td>( PB )</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>( PM )</td>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
</tbody>
</table>

Table I  Rules base.
The fuzzy inference and rules relationship

Fig. 10.a Structure of MIMO fuzzy control scheme.

Fig. 10.b The MMS speeds control using the MIMO fuzzy controller in Simulink.

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. 11, Fig. 12 and Fig. 13 demonstrate that the adjustment using MIMO-FLC gives satisfactory results:

- The three motors rotational speeds (\( \Omega_1 \), \( \Omega_2 \) and \( \Omega_3 \)) follow the reference speed.
- The currents (\( i_{sq} \) and \( i_{sd} \)) for the three motors are well limited to its acceptable values.
- The fluxes (\( \Phi_{rq} \) and \( \Phi_{rd} \)) 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 allows with insurance which the unit works in harmony and synchronism, especially to ensure a good quality of the treatment and rewinding of the product.

![Simulation results of the first motor M1 (unrolling motor).](image)

Fig. 11  Simulation results of the first motor \( M_1 \) (unrolling motor).
Fig. 12  Simulation results of the second motor M₂ (pinching motor).

Fig. 13  Simulation results of the third Motor M₃ (rolling motor).
5. Conclusions.

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 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 tension mechanical constant enters 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.

<table>
<thead>
<tr>
<th>Designations</th>
<th>Abbreviation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>( P_n )</td>
<td>3.5</td>
<td>kw</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>( V_n )</td>
<td>380</td>
<td>V</td>
</tr>
<tr>
<td>Nominal power-factor</td>
<td>( \cos \varphi_n )</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Nominal Speed</td>
<td>( N_n )</td>
<td>1200</td>
<td>tr/min</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>( f )</td>
<td>60</td>
<td>Hz</td>
</tr>
<tr>
<td>Nominal current</td>
<td>( I_n )</td>
<td>8.31</td>
<td>A</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>( R_s )</td>
<td>4.85</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>( R_r )</td>
<td>3.805</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Cyclic inductance stator</td>
<td>( L_s )</td>
<td>0.374</td>
<td>H</td>
</tr>
<tr>
<td>Cyclic Inductance rotor</td>
<td>( L_r )</td>
<td>0.374</td>
<td>H</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>( L_m )</td>
<td>0.358</td>
<td>H</td>
</tr>
<tr>
<td>Many pairs of poles</td>
<td>( P )</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Inertia Moment</td>
<td>( J )</td>
<td>1.011</td>
<td>kg/m^2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>( \varsigma )</td>
<td>0.01</td>
<td>N.m.sec/rad</td>
</tr>
</tbody>
</table>
### Table III  Used symbols.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Designations</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ and $q$</td>
<td>Axes direct and into quadratic.</td>
<td>—</td>
</tr>
<tr>
<td>$x_d$ and $x_q$</td>
<td>Components in the reference mark ($d$-$q$).</td>
<td>—</td>
</tr>
<tr>
<td>$\Phi_{d0}$ and $\Phi_{q0}$</td>
<td>Rotor fluxes following the axes direct and into quadratic.</td>
<td>Wb</td>
</tr>
<tr>
<td>$i_{ds}$ and $i_{qs}$</td>
<td>Stator currents following the axes direct and into quadratic.</td>
<td>A</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Rotation angle</td>
<td>rad</td>
</tr>
<tr>
<td>$C_{em}$ and $C_r$</td>
<td>Electromagnetic couple and Resistive torque.</td>
<td>N.m</td>
</tr>
<tr>
<td>$e$</td>
<td>Variation enters speed $w$ and reference speed $w^*$.</td>
<td>rad/sec</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Mass of core.</td>
<td>Kg</td>
</tr>
<tr>
<td>$m$</td>
<td>Total mass of the paper roller.</td>
<td>Kg</td>
</tr>
<tr>
<td>$r_0$</td>
<td>Ray of the core.</td>
<td>m</td>
</tr>
<tr>
<td>$V$</td>
<td>Tape speed of paper.</td>
<td>m/ sec</td>
</tr>
<tr>
<td>$H$</td>
<td>Thickness of paper.</td>
<td>m</td>
</tr>
<tr>
<td>$J_0$</td>
<td>Vacuum inertia.</td>
<td>kg.m²</td>
</tr>
<tr>
<td>$A$</td>
<td>Enchainment section.</td>
<td>m²</td>
</tr>
<tr>
<td>$A(t), B(t), L$</td>
<td>Diagonal matrices of the parameters.</td>
<td>—</td>
</tr>
<tr>
<td>$\rho_i$ (i=2,3)</td>
<td>Material voluminal density.</td>
<td>kg/m³</td>
</tr>
<tr>
<td>$V_i$ (i=1,3)</td>
<td>Linear velocity of roller $i$.</td>
<td>m/sec</td>
</tr>
<tr>
<td>$\Omega_i$ (i=1,3)</td>
<td>Rotation speed of the roller $i$.</td>
<td>rad/sec</td>
</tr>
<tr>
<td>$R_i$ (i=1,3)</td>
<td>Ray of the roller $i$ of paper.</td>
<td>m</td>
</tr>
<tr>
<td>$J_i$ (i=1,3)</td>
<td>Inertia moment of the roller $i$.</td>
<td>kg.m²</td>
</tr>
<tr>
<td>$f_i$ (i=1,2)</td>
<td>Coefficient of viscous friction of the roller $i$.</td>
<td>N.m. sec/rad</td>
</tr>
<tr>
<td>$T_i$ (i=2,3)</td>
<td>Mechanical tension enters the rollers $i$ and $i+1$.</td>
<td>N</td>
</tr>
<tr>
<td>$l_i$ (i=1,2)</td>
<td>Enchainment length enters the rollers $i$ and $i+1$.</td>
<td>m</td>
</tr>
</tbody>
</table>

### References


10. Mamadani, E.H.: Application of fuzzy algorithms for


