

Speed control of a sugar cane belt conveyor with a fuzzy controller

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Abstract. This paper describes the experience attained by the authors in the design of a fuzzy controller for speed control of an induction motor in field oriented, that drives a sugar cane belt conveyor, without making the compensations in the d-q axes. The Mamdani type fuzzy controller was implemented which utilizes speed error and the rate of change of the speed error as input variables and the current component in the q-axis as output variable. The simulation results reached show that the behavior of the control system under sudden changes of load and reference are better than those results obtained using PID classic.

Keywords: Fuzzy control, Speed control, Induction motor, field oriented control Simulation, PI controller.

1 Introduction

The function of a raw sugar factory is to produce sugar from the juice of sugar canes delivered to the factory. On arrival at the plant, the sugar cane is transported on belt conveyors to the shredder where it is prepared for the removal of juice by the extraction station. The shredder prepares the cane by smashing it up into small pieces. The extraction process is done by crushing mills. The prepared cane from the shredder is passed through a series of mills called the milling train as a whole. The mills squeeze the cane to separate the juice which contains the sugar from its fibrous part.

The feeding conveyor is moved by an electric motor with winding rotor and double or triple stages of speed reduction. In this process the control of speed takes place by insertion of external resistances in the rotor circuit, it is a discrete control and introduces strong electric losses and heating. On the other hand the presence of gearboxes introduces mechanical losses. Both situations contribute to reduce the efficiency of these systems, being one of the fields that can be improved.

To achieve a high performance of the AC motor drives the vector control is used [1]. The decoupling characteristics of vector controlled induction motor are adversely affected by the parameter changes in the motor [2].

Actually in a wide range of power the induction machine is fed with an inverter with semiconductor devices acting as voltage source using Pulse Width Modulation techniques (PWM) whose commutation frequency is usually in the range 3KHz -12 KHz. [3].

Since this converters are used with powers up to 1000 kW (and higher) and one of the main applications is the position servomechanism of high dynamic behavior, nowadays it is possible to reach a quick control of the stator currents with sinusoidal references of stator current in closed loop. For it, the stator currents can be controlled by quick regulation loops, and the stator voltage or currents equations can be used, depending of motor capacity.

The motor control issues have been traditionally handled by proportional integral derivative controllers (PID). However, the fixed gain controllers are very sensitive to parameter variations, load disturbances, etc. So, the controller parameters have to be continuously adapted. The problem can be solved by several adaptive control techniques such as model reference adaptive control (MRAC) [4], sliding mode control (SMC) [5], variable structure control (VSC) and self tuning PI controllers [6], etc.

The design of all of the above controllers depends on the exactitude of the mathematical model of the system. However, it is often difficult to develop an accurate mathematical model of the system due to unknown load variation, unknown and unavoidable parameter variations due to saturation, temperature variations and system disturbances.

The necessity to obtain more accurate systems, facing with success their unavoidable disturbances and nonlinearities and the loads associated to them has propitiated the use of intelligent techniques: fuzzy control, neural nets, genetic algorithms and others [7], [8], [9], [10]. To solve the problem outlined in this work a fuzzy controller (FLC), is proposed, which is based on the Fuzzy Logic introduced at the first time by Zadeh [11].

The FLC has some advantages such as: (1) it does not need any exact system mathematical model; (2) it can handle nonlinearity of arbitrary complexity and (3) it is based on the linguistic rules with IF-THEN general structure which are deduced from the knowledge of an expert [12].

In the following section the mathematical models of the components of the system are described in terms of the controller's inputs and outputs. In the section 3 the developed fuzzy controller is analyzed in detail, explaining their structure and operation.

In the section 4 the simulation scheme is outlined and in the section 5 the results are examined in comparison with those obtained with the use of classic controllers PID. Finally, in section 6 the conclusions of this work are exposed.

2 Mathematical Model of System Components

2.1 Induction motor model.

The model that will be used in this work is determined by the equations which define the dynamic behavior of the machine in oriented field, in this case in the reference system of the axes d (direct) and q (transversal) [2].

$$\sigma\tau_s \frac{di_{sd}}{dt} + i_{sd} = \frac{u_{sd}}{R_s} + \sigma\tau_s\omega_{mr}i_{sq} - (1-\sigma)\tau_s \frac{di_{mr}}{dt} \quad (1)$$

$$\sigma\tau_s \frac{di_{sq}}{dt} + i_{sq} = \frac{u_{sq}}{R_s} - \sigma\tau_s\omega_{mr}i_{sd} - (1-\sigma)\tau_s\omega_{mr}i_{mr} \quad (2)$$

$$\tau_r \cdot \frac{di_{mr}}{dt} + i_{mr} = i_{ds} \quad (3)$$

$$0 = i_{qs} - (\omega_{mr} - \omega_r) \tau_r \cdot i_{mr} \quad (4)$$

Where:

σ : Bondel's dispersion coefficient

τ_s : Stator's time constant (s)

τ_r : Rotor's time constant (s)

ω_{mr} : Speed of the reference axis (1/s)

i_{sd} : Current component in d axis (A)

i_{sq} : Current component in q axis (A)

u_{sd} : Voltage component in d axis (V)

u_{sq} : Voltage component in q axis (V)

L_m : Per phase magnetizing inductance (H)

i_{mr} : Magnetizing current (A)

The previous equations represent the conversion of u_{sd} and u_{sq} in i_{sd} and i_{sq} and in this case they are the consequence of feeding the motor with a voltage source. That is to say that they are the equations of the induction motor in a reference system

that rotates at the speed of the rotor magnetic flux (dynamics of the induction motor in field oriented) [13].

Equations of electromagnetic torque

$$T_e = \frac{3}{2} \frac{P}{2} \frac{L_m}{L_r} \cdot \lambda_r \cdot i_{qs} = \frac{3}{2} \frac{P}{2} \frac{L_m^2}{L_r} \cdot i_{mr} \cdot i_{qs} \quad (5)$$

Where:

λ_r : component of rotor magnetic flux

P : number of poles of the rotor

Equation of mechanical part

$$J \frac{d\omega}{dt} + B\omega = T_e - T_l \quad (6)$$

Where J is the total inertial torque, ω is the axis rotation speed, B is the friction, T_e is the machine torque and T_l is the load torque. The equation of mechanical part as a function of electric speeds is:

$$\frac{1}{P} J \frac{d\omega}{dt} + B\omega = P k i_{mr} i_{sq} - T_l \quad (7)$$

The blocks diagram of the motor fed with a voltage source (See Fig. 1) can be obtained from the previous model and the interrelation among its equations.

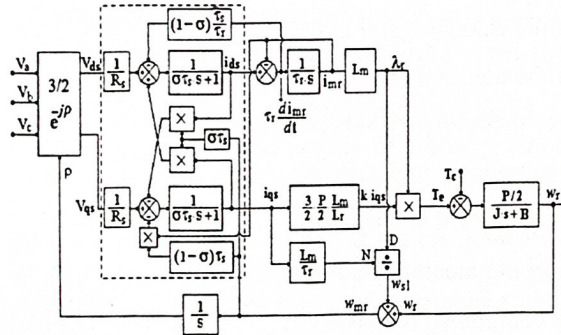


Fig. 1. Induction motor in field oriented fed with voltage source.

2.2 Mathematical model of cane belt conveyor

The cane belt conveyor consists of a long horizontal tract located below the floor level which transports the cane to the feeding conveyor and is built with steel splints. A scheme is shown in Fig. 2.

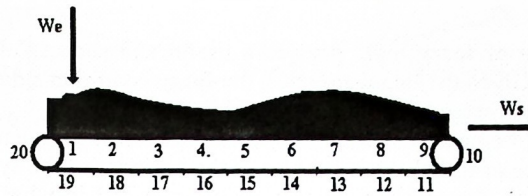


Fig. 2. Schematic representation of a belt conveyor.

When there is variation of speed due to fluctuations in the load or in the reference of the motor, it will present a dynamic that should be kept in mind in the model of the conveyor.

The static and dynamic behavior of the drive is determined by the mechanical equation of the system. When all the components that contribute both to the generation of the moment of the motor and to the resistant moment are known, the behavior of the group can be expressed simply by means of the equations of the Newton classic mechanics.

Thus, the equation (8) that appears developed in [14] is taken as dynamic model of the sugar cane conveyor. The model is represented in schematic form in Fig. 3.

$$T_l(s) = \frac{W_o r}{\eta i} \frac{1}{s} + \frac{m_{eq} r^2}{n i^2} s \omega(s) \quad (8)$$

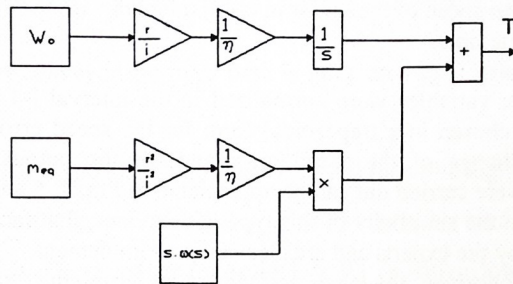


Fig. 3. Model equivalent of the sugar cane conveyor.

Where:

W_o : Traction force in stationary state

η : Efficiency of the system transmission

m_{eq} : Equivalent mass

r : ratio of toothed wheel

i : transmission relationship among the axis that moves the toothed wheel and motor axis

T_l : Load torque

3 Design of FLC

The mechanisms of fuzzy logic provide a useful and successful tool to implement linguistic rules. Given the linguistic rules, the fuzzy controller's development does not demand too much time and its cost is not high.

The fact that the controller is carried out by means of linguistic rules makes easy the understanding of its behavior. In short, if the behavior of the system in closed loop is not satisfactory, determining the responsible rule and in what address it must be modified is usually possible [15].

In this work, a fuzzy controller of Mamdani type was designed to control the speed of the group motor-conveyor and the "Fuzzy Logic" Toolbox was used as tool. This controller should provide the control of the current i_q that is required in order that the motor reaches the reference speed.

Two input linguistic variables were considered: The speed error ($e\omega(k)$) and the rate of change of the speed error ($ce\omega(k)$) and an output variable: the current of the axis q (i_q). These variables were defined respectively as:

$$e\omega(k) = \omega_r(k) - \omega(k) \quad (9)$$

$$ce\omega(k) = e\omega(k) - e\omega(k-1) \quad (10)$$

where:

ω_r : reference speed

ω : the rotation speed of the motor in each moment

k : the discrete time.

The linguistic variables were normalized in the interval $[-1 \ 1]$. The membership functions were chosen in a trapezoidal form for the speed error and in a triangular form for the change of the speed error and for the output. The corresponding partitions that were carried out can be appreciated in Fig. 4, 5 and 6. Such an election was done due to the simplicity of this type of functions, that facilitates the validation and correction by the experts and are also easier to implement.

As it can be observed, the labels assigned to the different sets have been created in an abbreviated form, using the initials, with the purpose of facilitating their notation and understanding.

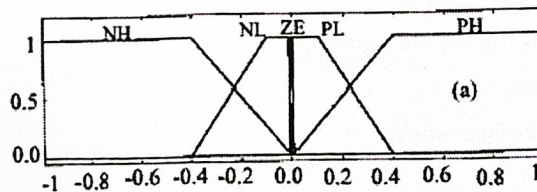


Fig. 4. Speed error

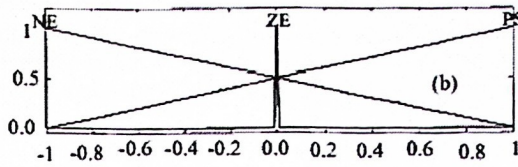


Fig. 5. Rate of change of the speed error

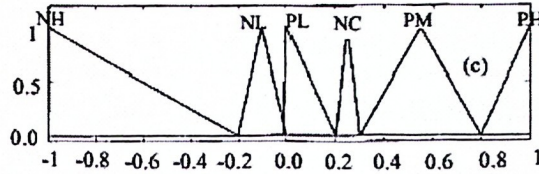


Fig. 6. The current of the axis q i_q

The fuzzy controller includes a certain number of rules that can usually be expressed by linguistic statements like:

$$\text{If } x_1 \text{ is } A_1^i \text{ and } x_2 \text{ is } A_2^i \text{ and } \dots \text{ and } x_{n_x} \text{ is } A_{n_x}^i \text{ then } z_1 \text{ is } Z_1^i, z_2 \text{ is } Z_2^i, \dots, z_{n_y} \text{ is } Z_{n_y}^i \quad (11)$$

where A_j^i is the fuzzy set of the input j (n_x is the number of inputs) and Z_j^i is the fuzzy set of the output j (n_y is the number of outputs) both relative ones to the rule i .

For the group motor-conveyor the rules base is integrated by 7 rules that are shown next:

- 1) If $e\omega(k)$ is PH (positive high) then i_q is PH (positive high)
- 2) If $e\omega(k)$ is PL (positive low) then i_q is PM (positive medium)
- 3) If $e\omega(k)$ is ZE (zero) and $ce\omega(k)$ is PS (positive low) then i_q is PL (positive low)
- 4) If $e\omega(k)$ is ZE (zero) and $ce\omega(k)$ is NE (negative) then i_q is NC (no change)
- 5) If $e\omega(k)$ is ZE (zero) and $ce\omega(k)$ is ZE (zero) then i_q is NC (no change)
- 6) If $e\omega(k)$ is NL (negative low) then i_q is NL (negative low)
- 7) If $e\omega(k)$ is NH (negative high) then i_q is NH (negative high)

The membership functions, fuzzy sets for the input/output variables and the rules used in this work are selected by trial and error to obtain the optimum drive performance. Zadeh's compositional operator "sup-min" was used for the fuzzy reasoning and the

centroid method was used for the defuzzification. The output is obtained by means of the following expression:

$$\text{Output} = \frac{\sum_{i=1}^n x_i \mu(x_i)}{\sum_{i=1}^n \mu(x_i)} \quad (12)$$

Where n is the total number of rules and $\mu(x_i)$ denotes the degree of membership for the rule i . This method is the most frequently used one and it also guarantees a soft behavior of the control.

4 Control Scheme. Proposed Configuration

The basic configuration of the drive consists of an induction motor fed by a current controlled voltage source inverter. The speed error and the rate of change of the speed error are processed by the fuzzy controller to generate the appropriate electromagnetic torque in the motor [16].

In order to obtain the system model for simulation, the configuration selected was the Current Controlled Voltage Inverter Source. In this case, the inverter feeds the motor with voltage and allows using the non compensated motor's equation. At the motor control schemes with compensation to variables decoupling, compensation's blocks are placed before coordinates transformations and the inverter is fed by voltage without motors current's feedback. These are feed backing to flux model.

Fig. 7. shows the simulation scheme developed for the validation experiments.

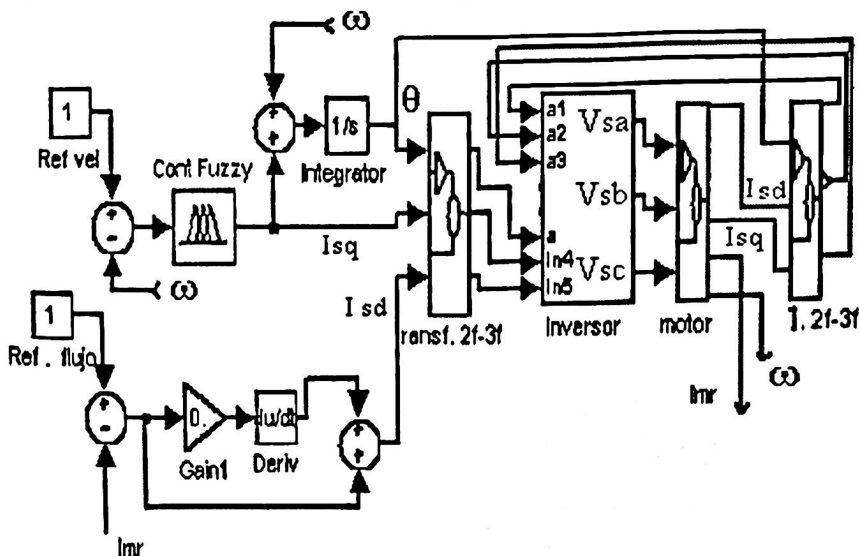


Fig. 7. Simulation scheme of the fuzzy control of an induction motor.

The reference currents of each phase are compared with the current values to carry out a control Bang-Bang for drive the power semiconductors of each branch of the inverter bridge to generate the voltage to feed the motor. The corresponding blocks are used to carry out the transformations of coordinates.

5 Simulation Experiments

To carry out the simulation experiments, the package SIMULINK[®]-MATLAB[®] was used as tool and the models that appear in epigraph 2 were taken to simulate the process. The fuzzy inference system was implemented by means of the fuzzy logic toolbox based in the structure shown in epigraph 3. The simulation scheme used can be seen in Fig. 7.

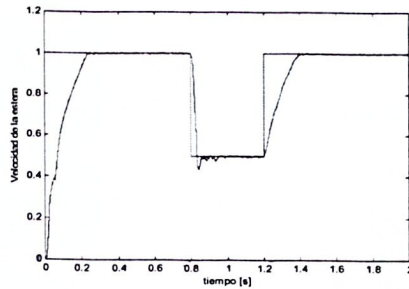


Fig. 8. Response to changes in the reference with fuzzy controller.

Motor power and belt conveyor parameters have been determinates for real conditions at the feeder belt conveyor drive in a Cuban sugar factory [14]. Simulations variable's results matches with experimental tests at referred drive conditions.

The following pictures show the response of the system to changes in the reference signal and in the load with PID controller and with fuzzy controller for comparison.

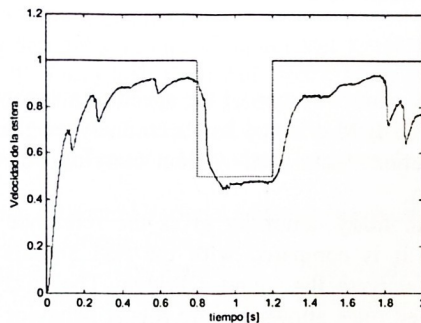


Fig. 9. Response to changes in the reference with PID controller.

The responses of the system to changes in the reference signal with fuzzy controller and with PID controller respectively are shown in Fig. 8 and Fig. 9. There you can appreciate how the response of the control system with fuzzy control is faster without presenting stationary state error. The response of the system with both types of regulators to disturbance in the load can be seen in Fig. 10 and Fig. 11. It can be appreciated that the fuzzy controller's response is better because the response is faster and more accurate. In all the cases the PI controller is tuned to give optimum response.

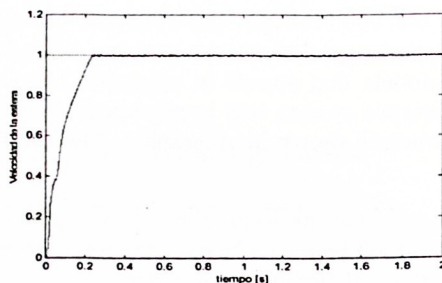


Fig. 10. Response to step in the reference signal and in the load disturbance with fuzzy controller.

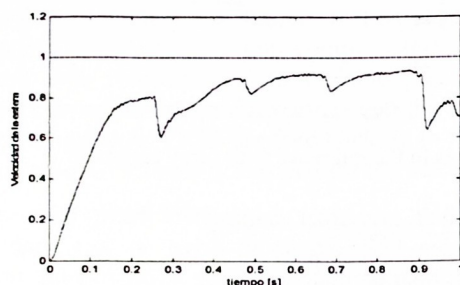


Fig. 11. Response to step in the reference signal and in the load disturbance with PID controller.

6 Conclusions

The behavior of a fuzzy control system of the speed of a sugar cane conveyor driven by an induction motor in field oriented has been analyzed. In the simulation of the motor the voltage equations were used without carrying out the decoupling of the variables in the axes d-q.

The speed loop with fuzzy controller gives the reference current signal to the bridge inverter where it is compared with the real signals of the motor. Their difference is used to activate the inverter bridge. The fuzzy controller designed according to the outlined rules allows a more robust behavior of the control system when facing variations of parameters and external disturbances that the classic PID controller.

The use of a classical PI algorithm for the control of the AC motor drives made evident the necessity of using the decoupling of the variables in the axes d-q, which is completely unnecessary when using the fuzzy controller. It is also necessary to keep in mind that there are nonlinearities in the model such as the hysteresis for drive the power semiconductors.

Due to the improvement of speed control this result makes it possible to minimize time waste in the process and to eliminate or minimize the continuous and much stressed starting process of the motor and then the process efficiency must be higher.

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