Abstract—This paper proposes an effective algorithm approach to hybrid control systems combining fuzzy logic and conventional control techniques of controlling the speed of induction motor assumed to operate in high-performance drives environment. The introducing of fuzzy logic in the control systems helps to achieve good dynamical response, disturbance rejection and low sensibility to parameter variations and external influences. Some fundamentals of the fuzzy logic control are preliminary illustrated. The developed control algorithm is robust, efficient and simple. It also assures precise trajectory tracking with the prescribed dynamics. Experimental results have shown excellent tracking performance of the proposed control system, and have convincingly demonstrated the validity and the usefulness of the hybrid fuzzy controller in high-performance drives with parameter and load uncertainties. Satisfactory performance was observed for most reference tracks.

Keywords—Fuzzy controller, high-performance, induction motor, intelligent control, robustness.

I. INTRODUCTION

DUE to the recent advances in power electronic devices and microprocessors, high performance control and estimation for induction motor are very fascinating and a new alternative in robotics and mechatronic A.C drives[1]-[3]. This induction motor has many chances for application in controlled drives due to its inherent low cost, simplicity, high torque per volume and useful flux-weakening capability. However, high-performance industrial applications such as steel wills, robotics, machine tools, and electric vehicles, their control remains a challenging problem because they exhibit significant non-linearities and many of the parameters, mainly the rotor resistance vary with the operating conditions today [8]-[9].

The motor flux and motor speed can be controlled independently. FOC methods are attractive but suffer from one major disadvantage. Field orientation control FOC of induction motor is one the most important topics in the variable speed drive area. They are sensitive to plant parameters variations and an incorrect flux measurement or estimation peed at low speed. One of the possible approach to robustly control in the case of plant uncertainties and unknown external disturbances is the application of modern control method such artificial intelligence techniques. Therefore, desired to develop a controller that has the ability to adjust its own parameters and even structure online, according to the environment in which it works to yield satisfactory control performance. An interesting alternative that could be investigated is the use of fuzzy logic control strategy. In the last decade, FLC has attracted considerable attention as a tool for a novel control approach because of the variety of advantages that it offers over the classical control techniques. In recent years, FLC was proposed for high-performance drives employing induction, synchronous reluctance and conventional DC machines [4]-[7]-[9]. Conventional control techniques require accurate mathematical models describing the dynamics of the system under study. These techniques result in tracking error when the load varies fast and overshoot during transients [4]-[5]. In this paper, a hybrid control system combing fuzzy logic and conventional control techniques, is proposed and applied to high-performance tracking of an induction motor. The paper is structured as follows. Section 2 describes a mathematical of induction motor drive; Section 3 gives the structure of the proposed hybrid fuzzy system. The basic concepts of the fuzzy sun-sets theory and the configuration of the control system are discussed in section 4, 5. Sections 6 and 7 provide the simulation results and conclusions, respectively.

II. INDUCTION MOTOR DIFFERENTIAL EQUATIONS

The dynamics of the induction motor in the $d-q$ motor reference frame fixed to the stator has a form of the following nonlinear differential equations (Morini, Peseda and Valogy, 1993).
where \( \sigma = 1 - \frac{L_d^2}{L_{m}} \)

\( i_s, v_s, \psi_s, R, L \) denote the stator current and voltage vector components, the rotor flux linkage, resistance and inductance respectively. The subscripts s and r stand for stator and rotor, d and q are the components of a vector with respect to a synchronously rotating frame. \( \omega_m, \omega_e \) are the angular speed of coordinate system and the angular speed of rotor shaft respectively. \( \sigma \) is the dispersion coefficient, \( p \) denotes the number of pole pairs, \( J \) is the total rotor inertia and \( T_l \) is the load torque.

### III. PROPOSED HYBRID FUZZY CONTROL SYSTEM

The conventional controllers, such as the Proportional Integral and Derivative (PID) require a mathematical model representing the system under control [5]. This can be a major limiting factor for systems with unknown varying dynamics such as inertia variations, components and magnetic saturation, parameter drifts and noisy environments. For most of the basic electric drive applications, these unknown conditions in addition to system nonlinearities can be ignored. High accuracy is not usually imperative. However, for high performance drive applications, disregarding these unknowns may lead to unacceptable tracking performance. Thus, the need for other types of controllers that can account for non-linearities requires adaptable conditions in real time. Other methods are now being employed, such as the hybrid fuzzy logic controller, in order to achieve a desired performance level for a high performance motor drive. These controllers, as currently demonstrated by a number of experimenters, show encouraging results [2]-[4]-[10]. In order to get control schemes that would be less sensitive to parameter variations than traditional linear PI controllers, we consider the hybrid controller structure shown in Fig. 1.

### IV. FUZZY LOGIC CONTROLLER

Fuzzy logic control design methodologies are justified because imprecision of the mathematical model used previously. Rule-based controllers try accounting the human’s knowledge about how to control a system without requiring a mathematical model [10]-[13]. The main preference of the fuzzy logic is that is easy to implement control that it has the ability of generalisation. The approach of the basic structure of the fuzzy logic controller system is illustrated in Fig. 2.

In the system presented in this study, Mamdani type of fuzzy logic is used for speed controller [10]. The command signals to the speed controller are the error \( \varepsilon(\omega) \) and change rate of error \( '\Delta e(\omega)'. \) Speed error \( e(\omega) \) is calculated with comparison between reference speed command \( \omega_{ref} \).
and speed signal feedback $\omega$. Speed error and speed error changing are fuzzy controller inputs, so must speed error changing $\Delta e$ be calculated. Input variables require be normalized which range of membership functions specify them. The output of the fuzzy controller $u(k)$ is given by:

$$u(k) = F_f \left( e(k) - \Delta e(k) \right) \quad (2)$$

Where $F_f$ is a non linear function determined by fuzzy parameters, $e(k)$, $\Delta e(k)$ are the error and change-of-error respectively. A type of those controllers is fuzzy PI controller whose input is the error $e(k)$.

$$e(k) = \omega_r^* - \omega(k) \quad (3)$$

where $\omega_r^*$ is the reference model and $\omega(k)$ is the process output at time $k$. The fuzzy logic controller was used to produce and adaptive control so that the motor speed $\omega(k)$ can accurately track the reference command $\omega_r^*$. In Fig. 2, normalisation factors have been shown with $K_1$ and $K_2$. Fuzzy logic controller is based on three well known blocs: Fuzzyfication bloc, block of rule bases and defuzzyfication block, whose function is following briefly explained. The fuzzyfication stage transforms crisp values from a process into fuzzy sets. The second stage is the fuzzy rule bases which expresses relations between the input fuzzy sets of linguistic description rules $A$, $B$ and the output fuzzy set $C$ in the form of "IF $A$ and $B$ THEN $C$", and the defuzzyfication stage transforms the fuzzy sets in the output into crisp control signals. As fuzzy system, we are considering a fuzzy PI PD controller. The control algorithm is represented by fuzzy rules [3]-[7]-[10]. The first step in designing the fuzzy controller is to generate the fuzzy rules based on the knowledge of the expert. According to the expert, three situations can be distinguished for the motor speed, namely, above, around and below the desired reference speed. The linguistic representation of the motor speed with respect to a given desired reference speed can be easily translated into a linguistic characterisation of the system error. By defining the system error between the measured speed and the desired speed, the propositions, higher, around and beneath the desired reference speeds are otherwise expressed as Positive, Zero and Negative errors. Furthermore, for given system state variables, the expert can express how he would act if he was controlling the system. For example, a typical rule reads as follows:

**Rule_1**: IF speed error is Positive Small (PS), AND rate of change in speed error is negative small (NS) THEN change in motor voltage (Output of fuzzy controller is Zero (Z))

The second step consists of modifying the rule-base in order to satisfy the requirements induced by the proposed strategy. The fuzzy controller has to produce a null action when the system has a normal behaviour. In other words, a dead zone has to be generated by the fuzzy controller, thus defining the zone where PI control is used. Furthermore, a null fuzzy action is desired when the system is not oscillatory and the overshoot very reduced. Nonetheless, the system is anomalous when it has oscillatory or tends to overshoot. Consequently, anomalous behaviour is defined as speed errors being zero and its change being not zero. Thus, the following set of rules:

IF speed error is Zero (Z), AND rate of change in speed error is another value, THEN control is null.

For the proposed fuzzy controller, the universe of discourse is first partitioned into the five linguistic variables NB, NS, ZE, PS, PB, triangular membership functions are chosen to represent the linguistic variables and fuzzy singletons for the outputs are used. The fuzzy rules that produce this control action is reported in Table I.

### Table I 

<table>
<thead>
<tr>
<th>Error</th>
<th>Delta Error</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>PB</td>
<td>PS</td>
<td>NB</td>
</tr>
<tr>
<td>NS</td>
<td>NS</td>
<td>ZE</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>ZE</td>
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<tr>
<td>ZE</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PS</td>
<td>NS</td>
</tr>
<tr>
<td>PS</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>NS</td>
<td>NB</td>
<td>NB</td>
</tr>
<tr>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

This implies an inference engine based on 5 implications rules for each of the speed error and its variation, thus a total 25 combinations take place. One can see on Table I, the rules sets of the fuzzy controller. Fig. 3 shows an example of Mamdani’s fuzzy inference [10], assuming that applicable fuzzy rules are:

**Rule_1**: IF e(k) is PS AND $\Delta e(k)$ is PM , THEN u(k) is PS;

**Rule_2**: IF e(k) is PM AND $\Delta e(k)$ is PS , THEN u(k) is PM

where e(k), $\Delta e(k)$, u are the speed error, the change rate of speed error and the control action, respectively. The inference law is given as:

$$\mu_f(u) = \mu_{u(\Delta e)}(1 - \text{Min} (\mu_{e(e)}(e), \mu_{\Delta e(\Delta e)}(\Delta e), \mu_{\Delta u(u)}(u))) \quad (4)$$

$\mu_f(u)$ design the fuzzy control action.

![Fig. 3 Mamdani’s fuzzy inference](image-url)

The controller treats each measurement as a fuzzy singleton and fuzzifies it using the fuzzy sets shown in Fig. 4 where NB: Negative Big, PB: Positive Big, NS: Negative Small, PS: Positive Small and ZE: Zero Equal.
Triangular shapes were chosen as the membership functions due to the linear equation in evaluation of membership functions and the output of the fuzzy controller is illustrated in Fig. 3.

V. CONFIGURATION OF THE PROPOSED CONTROL SYSTEM

Block diagram of implemented drive using fuzzy controller consists of the components illustrated in Fig. 5. The software environment used of these simulation experiments is Matlab with Simulink Toolboxes.

VI. SIMULATION RESULTS

To demonstrate the proposed hybrid fuzzy control scheme success, it has been tested by simulation, in order to evaluate the performances under a variety of operating conditions. The numerical values for the tested induction motor are summarized in Table II. The controller algorithm is housed inside the personal computer with Pentium-4 microprocessor and all numerical values of the simulation model are obtained either by measurements. The software environment used of these simulation experiments is Matlab-software with Simulink Toolboxes. For all simulations performed in this paper, the best gain, found experimentally to be $k_p = 0.56$ and $k_i = 10.04$.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>RATING OF TESTED INDUCTION MOTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated values</td>
<td>Power 4 kW</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Voltage Δ/Υ</td>
<td>220/380 V</td>
</tr>
<tr>
<td>Current Δ/Υ</td>
<td>15/8.6 A</td>
</tr>
<tr>
<td>Motor Speed</td>
<td>1440 rpm</td>
</tr>
<tr>
<td>pole pair (p)</td>
<td>2</td>
</tr>
<tr>
<td>Rated parameters</td>
<td>Rs 1.2 Ω</td>
</tr>
<tr>
<td></td>
<td>Rr 1.8 Ω</td>
</tr>
<tr>
<td></td>
<td>Ls 0.1554 H</td>
</tr>
<tr>
<td></td>
<td>Lr 0.1564 H</td>
</tr>
<tr>
<td></td>
<td>M 0.15 H</td>
</tr>
<tr>
<td>Constant</td>
<td>J 0.013 kg,m²</td>
</tr>
</tbody>
</table>

After designing the best stand alone PI and fuzzy controllers, all effectiveness of combining the two controllers to produce a hybrid design is demonstrated. Simulation results are given for motor speed tracking with the desired speed changing from the level to another (square-wave reference track with amplitude 150 rad/s). Figs. 6 and 7 show the speed trajectory when the desired speed changes from one value to another, using the PI controller and the Fuzzy controller, respectively. The measured speed is superimposed on the specified desired speed in order to compare tracking accuracy. Clearly, the fuzzy controller reduces both the overshoot and extent of oscillations under the same operating conditions. As shown in Fig. 6, the PI controller exhibits some overshoot or oscillations as the measured speed approaches the desired speed. To demonstrate the robustness of the proposed controller a different type of trajectory was considered in this test. Figs. 8, 9, 10, 11 show the results, in the case of a combined square-sinusoidal and square-triangular references speed track, for which $\omega_*(k)$ has an amplitude of 150 (rad/s) and wavelength of 1.0 (sec). High tracking accuracy is observed at all speed. One can see from these figures that the results using fuzzy controller, were very successful.
To illustrate the effectiveness of the switching strategy further, the hybrid controller was applied to control the motor under variable load torque. It is observed from Figs.12,13,14, that the hybrid controller closely tracks the motor speeds, even under changing conditions. Rejection of external disturbances is also achieved. Compared with the motor speed response with variable load, it can be seen that the undesirable oscillatory response is clearly evident.

All test results show that the proposed hybrid fuzzy control strategy is very effective in tracking the selected tracks at all time, while the system transients are effectively reduced. The results presented in Figs. 10, 11, 12, 13, 14 show that the proposed control system works correctly. The plots of these figures show the performance as the proposed scheme of hybrid-fuzzy controller for variety of step changes in the desired set point. It can be observed that, the application of external force of 10 (N.m) to induction motor, the control and set-point following are satisfactory.
In order to examine the robustness of the proposed control scheme, we assume that the parameters of rotor resistance \( R_r \) and load inertia \( J \) have been perturbed from their nominal values.

![Diagram](image1)

Fig. 12 Results of speed evolution after reference track step and inertia load changes

![Diagram](image2)

Fig. 13 Results of speed control after reference track and inertia changes, under load

![Diagram](image3)

Fig. 14 Speed step response under load and rotor resistance changes

The parameters of stator resistance, inductances and viscous friction \( f \) maintain their nominal values. It is evident that the speed response of the proposed control scheme is not significantly affected by these variations. One can see from these all figures the results were very successful and the obtained results confirm the validity of the proposed control scheme. These figures reveal that the proposed controller based on the hybrid fuzzy scheme was superior to the conventional controllers, such as the Proportional Integral PI-type. The controller envisaged is capable of maintaining a high tracking accuracy even in the presence of sudden disturbances such as load of electric transients.

VII. CONCLUSION

We have proposed a simple, yet effective, switching control strategy for tracking application of an induction motor drive. The proposed control system was analysed and implemented and its effectiveness in tracking application was verified. From the above results it is clear that the proposed controller despite of its simple structure has all of the futures of a high precision speed controller for operating in the whole of speed range and for any loading and environmental conditions. The proposed control scheme had a good speed response regardless of parameter variation or external force. The results are promising and further studied on similar schemes will be carried out. Satisfactory performance was observed for most reference tracks.

REFERENCES


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