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MODELLING OF INDUCTION MOTOR & CONTROL OF SPEED USING HYBRID CONTROLLER TECHNOLOGY

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ABSTRACT

This paper presents a novel design of a Takagi-Sugeno fuzzy logic control scheme for controlling some of the parameters, such as speed, torque, flux, voltage, etc. of the induction motor. Induction motors are characterized by highly non-linear, complex and time-varying dynamics and inaccessibility of some of the states and outputs for measurements, and hence it can be considered as a challenging engineering problem. The development of advanced control techniques has partially solved induction motor's speed control problems; because they are sensitive to drive parameter variations and the performance may deteriorate if conventional controllers are used. Fuzzy logic based controllers are considered as potential candidates for such an application. Further, the Takagi-Sugeno control strategy coupled with rule based approach in a fuzzy system when employed to the induction motor yields excellent results compared to the other methods as this becomes a hybrid & integrated method of approach. Such a mixed implementation leads to a more effective control design with improved system performance, cost-effectiveness, efficiency, dynamism, & reliability. The closed loop speed control of the induction motor using the above technique thus provides a reasonable degree of accuracy which can be observed from the results depicted at the end. Simulink based block model of induction motor drive is used for the simulation purposes & its performance is thereby evaluated for the speed control. The simulation results presented in this paper show the effectiveness of the method developed & have got a wide number of advantages in the industrial sector & can be converted into a real time application using some interfacing cards.

Keywords: *TS Model*, *Fuzzy Logic*, *Controller*, *Simulink*, *Matlab*, *Induction motor*, *Closed loop*, *Parameter*, *Robustness.*

1. INTRODUCTION

Recent years have witnessed rapidly growing popularity of fuzzy control systems in engineering applications. The numerous successful applications of fuzzy control have sparked a flurry of activities in the analysis and design of fuzzy control systems [13]. Fuzzy logic based flexible multi-bus voltage control of power systems was developed by Ashok *et.al.* in [35]. In the last few years, fuzzy logic has met a growing interest in many motor control applications due to its non-linearities handling features and independence of the plant modeling. The fuzzy controller (FLC) operates in a knowledge-based way, and its knowledge relies on a set of linguistic if-then rules, like a human operator. Ramon *et.al.* [31] presented a rule-based fuzzy logic controller applied to a scalar closed loop induction motor control with slip regulation & they also compared their results with those of a PI controller. They used a new linguistic rule table in FLC to adjust the motor control speed.

The design and implementation of industrial control systems often relies on quantitative mathematical models of the plants (say, induction motors, generators, dc motors, etc), the controllers, etc. At times, however, we encounter problems for which controller design becomes very difficult and expensive to obtain. In such cases, it is often necessary to observe human experts or experienced operators of the plants or processes and discover rules governing their actions for automatic control [12]. In this context, the fuzzy logic concepts play a very important role in developing the controllers for the plant as this controller does not require that much complicated hardware & uses only some set of rules.

Recently, there has been observed an increasing interest in combining artificial intelligent control tools with classical control techniques [5]. The principal motivations for such a hybrid implementation is that with fuzzy logic, neural networks & rough sets issues, such as uncertainty or unknown variations in plant parameters and structure can be dealt with more effectively, hence improving the robustness of the control system. Conventional controls have on their side well-established theoretical backgrounds on stability and allow different design objectives such as steady state and transient characteristics of the closed loop system to be specified. Several works were contributed to the design of such hybrid control schemes which was shown by various researchers in [8]-[10].

There are a number of significant control methods available for induction motors including scalar control, vector or field-oriented control, direct torque and flux control, sliding mode control, and the adaptive control [11]. Scalar control is aimed at controlling the induction machine to operate at the steady state, by varying the amplitude and frequency of the fundamental supply voltage [18]. A method to use of an improved V/f control for high voltage induction motors was proposed in [19]. The scalar controlled drive, in contrast to vector or field-oriented controlled one, is easy to implement, but provides somewhat inferior performance. This control method provides limited speed accuracy especially in the low speed range and poor dynamic torque response.

Two researchers, Takagi & Sugeno developed a excellent control scheme for control of various applications in the industrial sector. This controller had many advantages over the other methods discussed so far. Many researchers started using their models for their applications. Zie, Ling & Jhang [15] presented a TS model identification method by which a great number of systems whose parameters vary dramatically with working states can be identified via Fuzzy Neural Networks (FNN). The suggested method could overcome the drawbacks of traditional linear system identification methods which are only effective under certain narrow working states and provide global dynamic description based on which further control of such systems may be carried out.

Since, the induction motor is a complex non-linear system, the time-varying parameters entail an additional difficulty during the controller design [33]. Vector control methods have been proposed by various researchers to simplify the speed control of induction motors so they can be controlled like a separately excited dc machine. Indirect vector control methods decouple the motor current components by estimating the slip speed, which requires a proper knowledge of the rotor time constant [34]. Classical control systems like PI, PID control have been used, together with vector control methods, for the speed control of induction machines. The main drawbacks of the linear control approaches were the sensitivity in performance to the system parameters variations and inadequate rejection of external perturbations and load changes [33].

As an attempt to solve all these deficiencies, problems & difficulties encountered in designing the controller as mentioned in the above paragraphs, we have tried to devise a control strategy using the Takagi-Sugeno fuzzy scheme for the speed control of IM in our paper which has yielded excellent results & this has been applied to the control of electrical drive systems (induction motor). The results of our work have showed a very low transient response and a non-oscillating steady state response with excellent stabilization.

The structure of the work (flow / organization of the paper) presented in this research paper is organized in the following sequence. A brief review of the literature survey of the related work was presented in the previous paragraphs in the introductory section. Section 2 presents the mathematical modelling of the induction motor. Review about the Takagi-Sugeno control scheme used in the design of the controller in our case is presented in section 3. The TS based fuzzy controller design is presented in section 4. The section 5 shows the development of the simulink model for the speed control of the induction motor. The graphical results of the simulation & the discussion are presented in section 6. This is followed by the conclusions in the concluding section, references & the author biographies.

2. MODELLING OF INDUCTION MOTOR

In the control of any power electronics drive system (say a motor), to start with a mathematical model of the plant is required. This mathematical model is required further to design any type of controller to control the process of the plant. The induction motor model is established using a rotating (d, q) field reference (without saturation) concept [17].

The power circuit of the 3-ϕ induction motor is shown in the Fig. 1. The equivalent circuit used for obtaining the mathematical model of the induction motor is shown in the Fig. 2. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period. This calculated voltage is then synthesized using the space vector modulation. The stator & rotor voltage equations are given by [17]

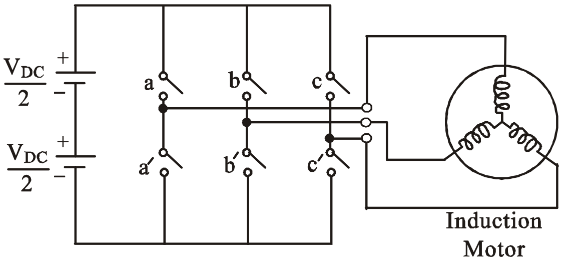
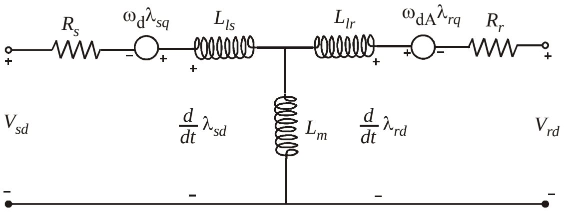


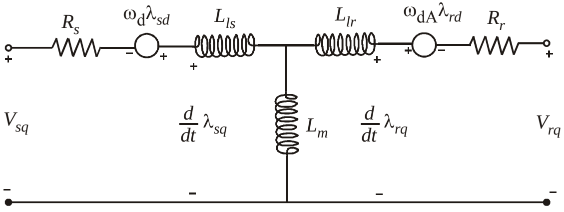
Fig. 1 : Power circuit connection diagram for the IM

$$V_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_d \lambda_{sq}, \qquad (1)$$

$$V_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_d \lambda_{sd}, \qquad (2)$$



(a) *d*-axis



(b) *q*-axis

Fig. 2 : Equivalent circuit of induction motor in *d* - *q* frame

$$V_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{dA} \lambda_{rq}, \qquad (3)$$

$$V_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} - \omega_{dA} \lambda_{rd}, \qquad (4)$$

where V_{sd} and V_{sq}, V_{rd} and V_{rq} are the direct axes & quadrature axes stator and rotor voltages. The squirrel-cage induction motor considered for the simulation study in this paper, has the *d* and *q*-axis components of the rotor voltage zero. The flux linkages to the currents are related by the Eq. (5) as

$$\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} = M \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix}; \; M = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}. \qquad (5)$$

The electrical part of an induction motor can thus be described by a fourth-order state space model (4 × 4), which is given in Eq. (6), by combining equations (1) - (5) as

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \frac{1}{L_m^2 - L_r L_s} \times \left(A \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_r & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} \right), \qquad (6)$$

where, *A* is given by

$$A = \begin{bmatrix} L_r R_s & \omega_{dA} L_m^2 - \omega_s L_r L_s & -L_m R_r & -L_r L_m (\omega_s - \omega_{dA}) \\ -(\omega_{dA} L_m^2 - \omega_s L_r L_s) & L_r R_s & L_r L_m (\omega_s - \omega_{dA}) & -L_m R_r \\ -L_m R_s & L_s L_m (\omega_s - \omega_{dA}) & L_s R_r & \omega_s L_m^2 - \omega_{dA} L_r L_s \\ -L_s L_m (\omega_s - \omega_{dA}) & -L_m R_s & -(\omega_s L_m^2 - \omega_{dA} L_r L_s) & L_s R_r \end{bmatrix}. \qquad (7)$$

By superposition, i.e., adding the torques acting on the *d*-axis and the *q*-axis of the rotor windings, the instantaneous torque produced in the electromechanical interaction is given by

$$T_{em} = \frac{P}{2}\left(\lambda_{rq} i_{rd} - \lambda_{rd} i_{rq}\right). \qquad (8)$$

The electromagnetic torque expressed in terms of inductances is given by

$$T_{em} = \frac{P}{2} L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right). \qquad (9)$$

The mechanical part of the motor is modeled by the equation [17] as

$$\frac{d}{dt}\omega_{Mech} = \frac{T_{em} - T_L}{J_{eq}} = \frac{\frac{P}{2} L_m \left(i_{sq} i_{rd} - i_{sd} i_{rq} \right) - T_L}{J_{eq}}, \tag{10}$$

where,

J_{eq} = Equivalent MI,

$\omega_{dA} = \omega_{slip} = \omega_s - \omega_m$,

$\omega_m = \frac{P}{2}\omega_{mech}$, $\omega_d = \omega_s$,

$L_s = L_{sl} + L_m$, $L_r = L_{rl} + L_m$

This IMs mathematical model is further used to design a controller using TS-fuzzy control strategy.

3. TAKAGI-SUGENO CONTROL SCHEME

In this section, a brief review of the Takagi and Sugeno control strategy to control various system parameters of the plants is presented. Takagi and Sugeno [2] - [4] proposed a new type of fuzzy model (TS model) which has been widely used in many disciplines, especially in the control of dynamical systems, such as induction motors, DC motors, AC motors, etc. This fuzzy model is described by IF-THEN fuzzy rules which represent local linear input-output relations of a non-linear system. The main feature of a Takagi-Sugeno fuzzy model is to express the local dynamics of each fuzzy implication (rule) by a linear system model. The overall fuzzy model of the system is achieved by fuzzy "blending" of the linear system models. These TS models use fuzzy rules with fuzzy antecedents and functional consequent parts, thereby qualifying them as mixed fuzzy or non-fuzzy models [13]. Such models can represent a general class of static or dynamic non-linear mappings via a combination of several linear models.

In this context, the TS control model which is being used by us to design the controller for the speed control of induction motor is explained as follows. In general, TS models are represented by a series of fuzzy rules of the form [14]

$$\begin{array}{l} R_k : \text{IF}\{\text{x is A}^k\}, \text{THEN}\{y_1 = h_1^k(x)\} \\ \text{AND ..... AND}\{y_m = h_m^k(x)\} \end{array}, \tag{11}$$

where $h_j^k(x), j = 1,......,m$ are polynomial functions of the inputs and represent local models used to approximate the response of the system in the region of the input space represented by the antecedent $\mathbf{A}^k$.

Fuzzy models relying on such rules are referred to as singleton fuzzy models [14]. This class of fuzzy models can employ all the other types of fuzzy reasoning mechanisms, because they represent a special case of each of the above-described fuzzy models. Parameter varying systems which possess *m* working state characteristic variables, *q* inputs and single output can be described by the TS fuzzy model consisting of *R* rules, where the i^{th} rule can be represented as [15]

$$\begin{array}{l} \text{Rule } i: \text{if } z_1 \text{ is } A_1^{i,k_1}, z_2 \text{ is } A_2^{i,k_2}, \wedge, \text{and } z_m \text{ is } A_m^{i,k_m}, \\ \quad \text{then, } y^i = a_1^i x_1 + a_2^i x_2 + \wedge + a_q^i x_q, \\ \quad i = 1, 2, \wedge, ...R. \ \ k_j = 1, 2, \wedge, ... r_j, \end{array} \tag{12}$$

where, *R* is the number of rules in the TS fuzzy model, $z_j \ (j = 1, 2, 3, ..., \Lambda, ...m)$ is the j^{th} characteristic variable, which reflects the working state of the systems and can be selected as input, output or other variables affecting the parameters of the system dynamics.

Here, $x_l \ (l = 1, 2, 3, ..., \Lambda, ...q)$ is the l^{th} model input and y^i is the output of the i^{th} rule. For the i^{th} rule, A_j^{i,k_j} is the k_j^{th} fuzzy sub-set of z_j. a_l^i is the coefficient of the consequent terms. r_j is the fuzzy partition number of z_j.

For simplicity of induction, we let $r_j = r$ and *r* is determined by both the complexity and the accuracy of the model. Once a set of working state variables $(z_{10}, z_{20}, ..., \Lambda, .., z_{m0})$ and the model input variables $(x_{10}, x_{20}, ..., \Lambda, .., x_{q0})$ are available, then the output of the TS model under such working states can be calculated by the weighted-average of each y^i as [15]

$$y = \sum_{i=1}^{R} \frac{\mu^i y^i}{\sum_{i=1}^{R} R}, \tag{13}$$

where y^i is determined by consequent equation of the i^{th} rule. The truth-value μ^i of the i^{th} rule can be calculated as [15]

$$\mu^i = \bigwedge_{j=1}^{m} A_j^{i,k_j}\left(z_{j0}\right). \tag{14}$$

Furthermore, Eq. (13) can be rewritten as [15]

$$y = \frac{\left(\sum_{i=1}^{R} \mu^i a_1^i x_1 + \Lambda + \sum_{i=1}^{R} \mu^i a_q^i x_q \right)}{\sum_{i=1}^{R} \mu^i}, \tag{15}$$

which is nothing but the final output of the system and is the weighted average of all the rule outputs (from *i* to *R*). From Eq. (15), one can see that the TS fuzzy model can be expressed as an ordinary linear equation under certain working states, since the truth-value μ^i is only determined by the working state variables. As μ^i varies with the working state, TS fuzzy model becomes a coefficient-varying linear equation. For all possible varying ranges of the various parameters, the TS fuzzy model reflects the relationships between these model parameters and the working states. Thus, the global dynamic characteristics of the parameter varying systems can be represented [15].

4. CONTROLLER DESIGN

A controller is a device which controls each & every operation in the system making decisions. From the control system point of view, it is bringing stability to the system when there is a disturbance, thus safeguarding the equipment from further damages. It may be hardware based controller or a software based controller or a combination of both. In this section, the development of the control strategy for control of various parameters of the induction machine such as the speed, flux, torque, voltage, stator current is presented using the concepts of Takagi-Sugeno based fuzzy control scheme, the block diagram of which is shown in the Fig. 3.

To start with, we design the FLC, then combine with the TS scheme, finally to obtain the hybrid controller. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables & emerged as a consequence of the 1965 proposal of fuzzy set theory by Lotfi Zadeh. Linguistic variables, defined as variables whose values are sentences in a natural language (such as large or small), may be represented by the fuzzy sets. Fuzzy set is an extension of a ‘crisp’ set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow partial membership, which means that an element may partially belong to more than one set.

A fuzzy set *A* of a universe of discourse *X* is represented by a collection of ordered pairs of generic element $x \in X$ and its membership function $\mu : X \rightarrow [\,0 \quad 1]$, which associates a number $\mu_A(x) : X \rightarrow [\,0 \quad 1]$, to each element *x* of *X*. A fuzzy logic controller is based on a set of control rules called as the fuzzy rules among the linguistic variables. These rules are expressed in the form of conditional statements. Our basic structure of the fuzzy logic coordination controller to damp out the oscillations in the power system consists of 3 important parts, viz., fuzzification, knowledge base - decision making logic (inference system) and the de-fuzzification, which are explained in brief in further paragraphs.

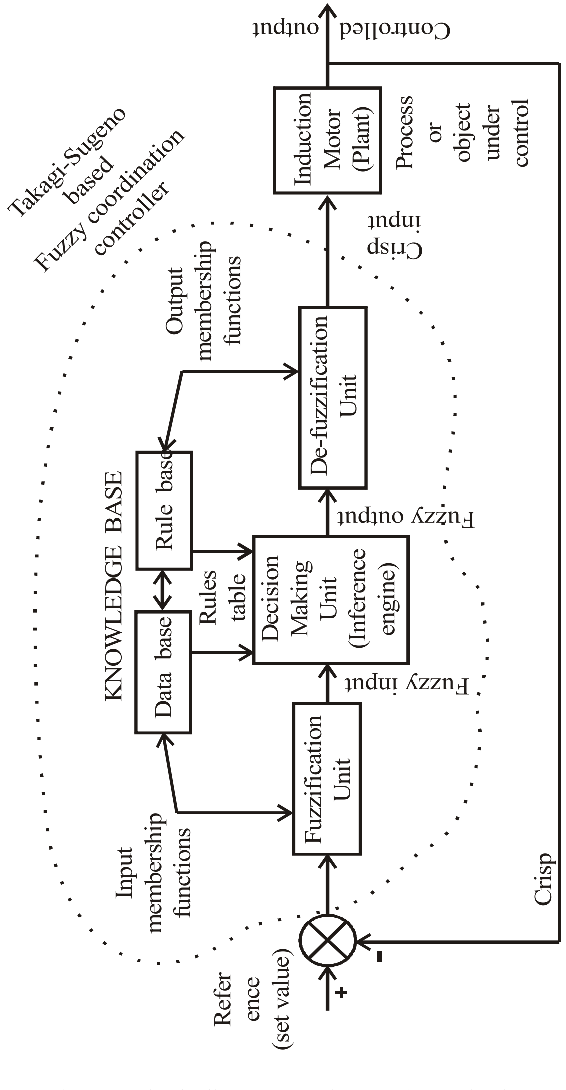


Fig. 3 : Block diagram of the TS-fuzzy logic control scheme of the IM

The inputs to the FLC, i.e., the error & the change in error is modeled using the Eq. (16) as

$$\begin{aligned} e(k) &= \omega_{ref} - \omega_r \\ \Delta e(k) &= e(k) - e(k-1) \end{aligned} \tag{16}$$

where ω_{ref} is the reference speed, ω_r is the actual rotor speed, is the $e(k)$ error and $\Delta\ e(k)$ is the change in error.

The internal structure of the fuzzy coordination unit with the TS control scheme is shown in the Fig. 3. The necessary inputs to the decision-making unit blocks are the rule-based units and the data based block units. The fuzzification unit converts the crisp data into linguistic variables. The decision making unit decides in the linguistic variables with the help of logical linguistic rules supplied by the rule base unit and the relevant data supplied by the data base. The output of the decision-making unit is given as input to the de-fuzzification unit and the linguistic variables are converted back into the numeric form of data in the crisp form.

The decision-making unit uses the conditional rules of 'IF-THEN-ELSE', which can be observed from the algorithm mentioned in the algo for developing the fuzzy rules below. In the fuzzification process, i.e., in the first stage, the crisp variables, the speed error & the change in error are converted into fuzzy variables or the linguistics variables. The fuzzification maps the 2 input variables to linguistic labels of the fuzzy sets. The fuzzy coordinated controller uses the linguistic labels. Each fuzzy label has an associated membership function. The inputs are fuzzified using the fuzzy sets & are given as input to fuzzy controller. The rule base for the decision-making unit is written as shown in the table I. The developed Takagi-Sugeno fuzzy rules (7 × 7 = 49) included in the fuzzy coordinated controller.

E ΔE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	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	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table I : Rule base for controlling the speed

The control decisions are made based on the fuzzified variables. The inference involves a set of rules for determining the output decisions. As there are 2 input variables & 7 fuzzified variables, the fuzzy logic coordination controller has a set of 49 rules for the fuzzy logic based TS controller. Now, the 49 output variables of the inference system are the linguistic variables and they must be converted into numerical output, i.e., they have to be de-fuzzified. This process is what is called as de-fuzzification. Defuzzification is the process of producing a quantifiable result in fuzzy logic.

The defuzzifcation transforms fuzzy set information into numeric data information. This defuzzification process along with the operation of fuzzification is critical to the design of fuzzy systems as both of these operations provide nexus between the fuzzy set domain and the real valued scalar domain. There are so many methods to perform the deffuzification, viz., centre of gravity method, centre of singleton method, maximum methods, the marginal properties of the centroid methods & so on. In our work, we use the centre of gravity method. The output of the defuzzification unit will generate the control commands which in turn is given as input (called as the crisp input) to the plant through the inverter. If there is any deviation in the controlled output (crisp output), this is fed back & compared with the set value & the error signal is generated which is given as input tot he TS-fuzzy controller, which in turn brings back the output to the normal value, thus maintaining stability in the system. Finally, the controlled output signal, i.e., y is given by Eq. (17) as

$$y = \left(\sum_{i=1}^{R} \mu^i a_1^i x_1 + .. + \Lambda + .. + \sum_{i=1}^{R} \mu^i a_q^i x_q \right) \Bigg/ \sum_{i=1}^{R} \mu^i , \quad (17)$$

This controlled output y is nothing but the final output of the controller and is the weighted average of all the rule based outputs. From Eq. (17), one can see that the TS fuzzy model can be expressed as an ordinary linear equation under certain working states since the truth-value μ^i is only determined by the working state variables. The main advantage of designing the TS based fuzzy coordination scheme to control the speed of the IM is to increase the dynamic performance & provide good stabilization.

5. DEVELOPMENT OF SIMULINK MODEL

The block model of the induction motor system with the controller was developed using the power system, power electronics, control system, signal processing toolboxes & from the basic functions available in the Simulink library in Matlab / Simulink. In this paper, plots of voltage, torque, speed, load & flux, etc are plotted as functions of time with the controller and the waveforms are observed on the corresponding scopes after running the simulations. The entire system modeled in Simulink is a closed loop feedback control system consisting of the plants, controllers, samplers, comparators, feedback systems, the mux, de-mux, summers, adders, gain blocks, multipliers, clocks, sub-systems, integrators, state-space models, sub-systems, the output sinks (scopes), the input sources, etc. The developed simulink model for the control of various parameters of the SCIM is shown in the Fig. 4.

6. SIMULATION RESULTS & DISCUSSIONS

Simulink model with the controller for the speed control of IM is developed in Matlab 7 as shown in the Fig. 4. The simulation is run for a specific amount of time (say 2 to 3 secs) in Matlab 7 with a reference speed of 100 rads / sec $\left\{ \text{i.e., } (100 \times 60) / 2\pi \right\} = 955$ rpm & with a load torque of 2 N-m.

Note that the fuzzy coordinated TS controller consists of 3 basic blocks viz., fuzzification, inference, and the de-fuzzification blocks as shown in the Fig. 4. A set of 49 fuzzy rules are written and called in the form of a file in the developed Simulink model with the controller. While the simulation is run, the 2 fuzzy inputs are then given to the controller (Takagi-Sugeno-fuzzy), where the output is obtained thereafter. The response curves of flux, load, torque, terminal voltage, and speed & stator currents v/s time are observed on the respective scopes & are shown in the Figs. 5 - 9 respectively after importing the scope data into the workspace and plotting them.

From the simulation results shown in the Figs. 5 to 9, it is observed that the stator current does not exhibit any overshoots, undershoots, the response of the flux, torque, terminal voltage, speed & stator currents, etc. takes lesser time to settle & reach the desired value compared to the results presented in [1]. It was observed in [1] using the Mamdani control strategy for the same set speed & the 49 rules, the speed reaches its desired set value (becomes stable) at 1.4 seconds, whereas in this paper using the TS-fuzzy control for the same mathematical model & for the same set speed & for the same 49 rules, the speed reaches its desired set value at 0.7 seconds.

This shows the effectiveness of the developed controller. It is also observed that with the controller, the response characteristics curves take less time to settle & reach the final steady state value compared to that in [1].

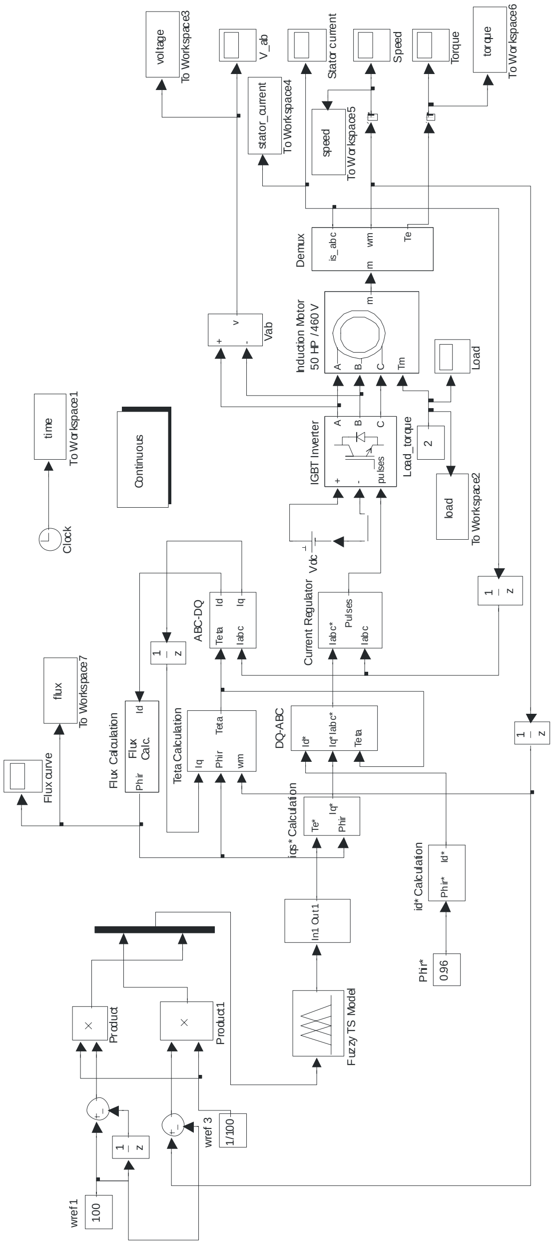


Fig. 4 : The developed simulink model with the TS based Fuzzy logic controller

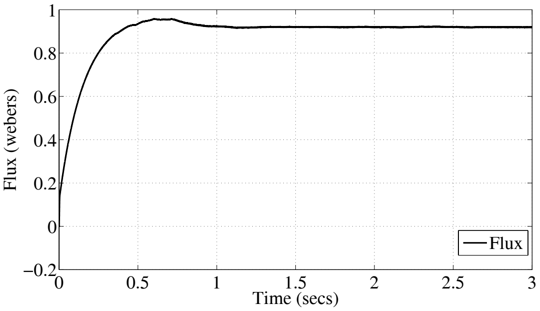


Fig. 5 : Plot of flux vs. time

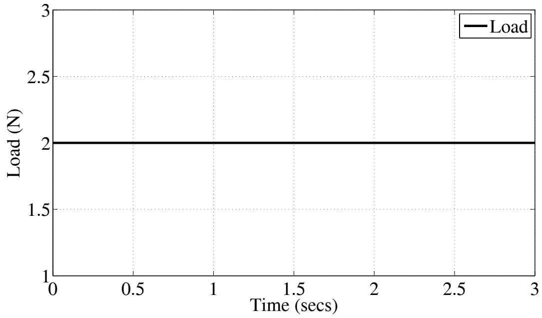


Fig. 6 : Plot of load vs. time

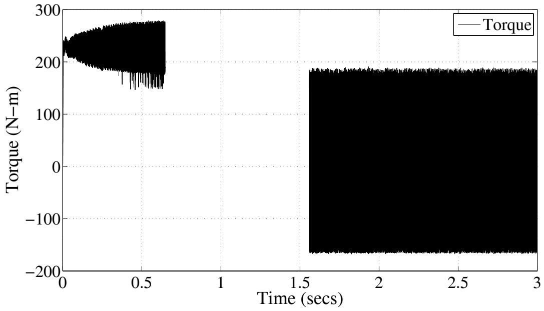


Fig. 7 : Plot of Torque vs. time

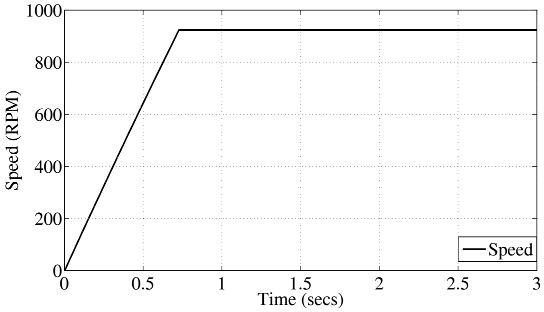


Fig. 8 : Plot of speed vs. time

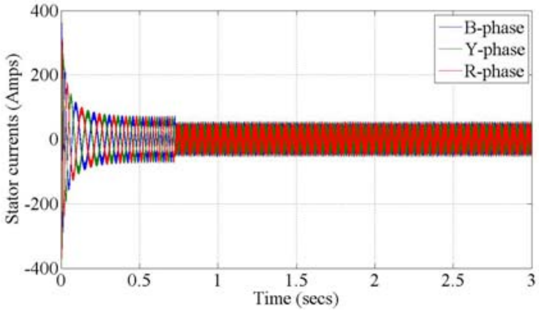


Fig. 9 : Plot of 3-ϕ stator currents vs. time (colored)

7. CONCLUSIONS

A systematic approach of achieving robust speed control of an induction motor drive by means of Takagi-Sugeno based fuzzy control strategy has been investigated in this paper. Simulink models were developed in Matlab 7 with the TS-based fuzzy controllers (hybrid controller) for the speed control of IM. The control strategy was also developed by writing a set of 49 fuzzy rules according to the TS control strategy. The main advantage of designing the TS based fuzzy coordination scheme to control the speed of the IM is to increase the dynamic performance & provide good stabilization. Simulations were run in Matlab 7 & the results were observed on the corresponding scopes. Graphs of speed, torque, stator current, flux, etc. vs. time were observed.

The outputs takes less time to stabilize, which can be observed from the simulation results. But, from the incorporation of the TS based fuzzy coordination system in loop with the plant gave better results there by stabilizing the plant very quickly. The developed control strategy is not only simple, reliable, and may be easy to implement in real time applications, but also cost-effective as when this control scheme is implemented in real time, the size of the controller will become very small. Collectively, these results show that the TS-fuzzy controller provides faster settling times, has very good dynamic response & good stabilization.

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