Ashok Kusagur [1]
S. F. Kodad [2]
B.V. Sankar Ram [3]

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Novel design of a Takagi-Sugeno fuzzy strategy for induction motor speed control

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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, current, 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 some of the induction motor's speed control problems; because they were 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 fuzzy logic rule based approach 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 & robustness. Due to the usage of the TS-FLC concept in closed loop with the plant, the dynamic characteristics of the AC drives increases as the developed strategy does not require the mathematical model of the controller unlike that of the conventional electrical drive controller, which uses the mathematical model, which is the highlight of the paper. The sudden fluctuation or change in speed & its effect on the various parameters of the dynamic system is also considered in this paper. The designed controller not only takes care of the sudden perturbations in load torque & speed, but also brings back the parameters to the reference or the set value in fraction of seconds, thus exhibiting the robustness behavior. In other sense, the designed controller is robust to parametric variations. 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 simulation results depicted at the end. Simulink based block model of induction motor drive was developed & used for the simulation purposes. Further, its performance is thereby evaluated for the control of various parameters. The method presented in this paper provides robustness of the induction machine towards the parametric variations compared to the conventional speed control of induction motor drives & has got a faster response time or settling times. 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. Nomenclature & Abbreviations

ϕ	Phase	AC	Alternating Current
s	Laplace domain	AI	Artificial Intelligence
z	Discrete domain	ANN	Artificial Neural Networks
d	Direct axis variable	DC	Direct Current
q	Quadrature axis variable	FIS	Fuzzy Inference System
V_{sd}	Direct axis stator voltage	FLC	Fuzzy Logic Controller
V_{sq}	Quadrature axis stator voltage	FNN	Fuzzy Neural Networks
V_{rd}	Direct axis rotor voltage	FOC	Field Oriented Control
V_{rq}	Quadrature axis rotor voltage	IM	Induction Motor
i_{sd}	Direct axis stator current	PI	Proportional Integrator
i_{sq}	Quadrature axis stator current	PID	Proportional Integral Derivative
i_{rd}	Direct axis rotor current	PWM	Pulse Width Modulation

[1] Research Scholar, EEE Dept., JNTU, Hyderabad-85, Andhra Pradesh, India,
Professor & Head of the Department, HMSIT, Tumkur, Karnataka, India., ashok.kusagur@gmail.com
[2] Director, Krishnamurthy Inst. of Tech. & Engg., Hyderabad, Andhra Pradesh, India.,
[3] Professor, Dept. of EEE, JNTUCE, Kukatpally, Hydarabad-85, Andhra Pradesh, India.

i_{rq}	Quadrature axis rotor current
λ_{sd}	Direct axis stator flux linkages
λ_{sq}	Quadrature axis stator flux linkages
λ_{rd}	Direct axis rotor flux linkages
λ_{rq}	Quadrature axis rotor flux linkages
t	Time
L_r	Rotor inductance
L_s	Stator inductance
L_m	Mutual inductance
ω	Angular frequency
T_{em}	Electromagnetic torque
P	Power
T_L	Load torque
J_{eq}	Equivalent Moment of Inertia
V_m	Maximum value of AC voltage
V_{An}	Voltage of phase-A to neutral
V_{Bn}	Voltage of phase-B to neutral
V_{Cn}	Voltage of phase-C to neutral
V_{DC}	DC voltage
R	Number of rules in the TS fuzzy model
y	Final output of the system
A^k	Antecedent
m	Working state characteristic variables
i, j, k, l	Variables
Σ	Summation
h	Polynomial functions
SCIM	Squirrel Cage Induction Motor
SMC	Sliding Mode Control
TS	Takagi Sugeno

2. Introduction

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.

Induction motors play a vital role in the industrial sector especially in the field of electric drives & control. Without proper controlling of the speed, it is virtually impossible to achieve the desired task for a specific application. AC motors, particularly the squirrel-cage induction motors (SCIM), enjoy several inherent advantages like simplicity, reliability, low cost and virtually maintenance-free electrical drives. However, for high dynamic performance industrial applications, 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 [5]. Field orientation control (FOC) or vector control [6] of an induction machine achieves decoupled torque and flux dynamics leading to independent control of the torque and flux as for a separately excited DC motor. FOC methods are attractive, but suffer from one major disadvantage, viz., they are sensitive to motor parametric variations such as the rotor time constant and an incorrect flux measurement or estimation at low speeds [7]. Consequently, performance deteriorates and a conventional controller such as a PID is unable to maintain satisfactory performance under these conditions.

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].

Induction motors are widely used in various industries as prime work-horses to produce rotational motions and forces. Generally, variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations. Usually, the classical control is used in majority of the electrical motor drives. Conventional control makes use of the mathematical model for the controlling of the system. When there are system parametric variations or environmental disturbance (say noise), behavior of system is not satisfactory & deviates from the desired performance [11]. In addition, usual computation of system mathematical model is difficult or impossible. To obtain the exact mathematic model of the system, then one has to do some identification techniques such as the system identification & obtain the plant model.

Moreover, the design and tuning of conventional controller increases the implementation cost and adds additional complexity in the control system & thus, may reduce the reliability of the control system. Hence, the fuzzy based techniques are used to overcome this kind of problems. Efficient torque control of induction motor drives in combination with resonant DC-link input filters can lead to a type of stability problem that is known as negative impedance instability. To overcome this, Henry *et.al.*, proposed a solution to the above problem by using the concept of non-linear system stabilizing controller in [39] with the plant.

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. A fuzzy controller of the type of the Takagi-Sugeno model was investigated in [37] by Chen & Wong.

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. T-S fuzzy model-based impulsive control of chaotic systems with exponential decay rate was discussed by X. Liu, and S. Zhong in [41]. In their paper, they presented a new approach for stability analysis of the fuzzy impulsive controllers in which the fuzzy system was presented by Takagi-Sugeno model.

Zhang & Jiang proposed an efficient approach for indirect field-oriented control of induction machines based on the synergetic control method, taking speed control of an induction motor by using an example in [17]. Space Vector Pulse Width Modulation (SVPWM) method is one of the advanced, computation-intensive PWM method and possibly the best among all the PWM techniques for variable frequency drive applications. Because of its superior performance characteristics, it has been finding widespread applications in recent years. Satean, *et.al.*, presented a novel control technique of control of the induction motors using space vector pulse width modulation method in [20]. They even developed an excellent 3-ϕ bridge inverter which was used to apply a balanced 3ϕ voltages to the SCIM.

In due course, fuzzy logic concept was introduced by Lotfi Zadeh in 1965. Many researchers used this FLC concept developed by Zadeh to develop controllers for their applications, which had yielded good results. Thus, this FLC concept remained as a popular control scheme in the control world even today. Arulmozhiyal & Baskaran described in brief a number of fuzzy control logic applications on various plants in his paper in [21]. They even devised a new control strategy to control the speed of IMs using FLC technique.

Fuzzy Logic control (FLC) has proven effective for complex, non-linear and imprecisely defined processes for which standard model based control techniques are impractical or impossible [22]. Fuzzy Logic, deals with problems that have vagueness, uncertainty and use membership functions with values varying between 0 and 1 [23]. This means that if the reliable expert knowledge is not available or if the controlled system is too complex to derive the required decision rules, development of a fuzzy logic controller become time consuming and tedious or sometimes impossible.

In the case that the expert knowledge is available, fine-tuning of the controller might be time consuming as well [24]. Furthermore, an optimal fuzzy logic controller cannot be achieved by trial-and-error. These drawbacks have limited the application of fuzzy logic control [25]. Some efforts have been made to solve these problems and simplify the task of tuning parameters and developing rules for the controller [26]. These approaches mainly use adaptation or learning techniques drawn from artificial intelligence or neural network theories. Application of fuzzy logic control for the control a speed induction motor using space vector pulse width modulation is not quite new [27]. However, there is no systematic method for designing and tuning the fuzzy logic controller & one has to design using some trail & error using the IF, ELSE, THEN rules.

Haider *et.al.* [28] presented the design and implementation of Fuzzy-SMC-PI methodology to control the flux and speed of an induction motor. The Fuzzy-SMC-PI was basically a combination of Sliding Mode Control (SMC) and PI control methodologies through fuzzy logic, but the drawback being the chattering during the time of switching. In [29] & [30], the researchers implemented a fuzzy logic controller to adjust the boundary layer width according to the speed error. The drawback of their controller is that it depends on the equivalent control & on the system parameters.

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 sincere attempt is made to overcome some of the drawbacks & difficulties which was encountered while designing the controller in this paper. Here, we have formulated a control strategy using the Takagi-Sugeno fuzzy scheme for the speed control of IM, which has yielded excellent results. 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 simulation results & the discussion on it are presented in the section 6. This is followed by the conclusions in the concluding section, the nomenclatures, abbreviations, references & the author biographies.

3. Modelling of the 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 mathematical model can be obtained by various methods, viz., from first principles, system identification methods, etc. This mathematical model may be a linear / non-linear differential equation or a transfer function (in s or z-domain) or in state space form. In this section, we present the mathematical model of the induction motor. The mathematical model of the SCIM system used in our work consists of space vector PWM voltage source inverter, induction motor, direct flux and the torque control [17].

The drawback of the coupling effect in the control of SCIMs is that, it gives sluggish response and the system is easily prone to instability because of a high-order system effect.

This problem can be solved by making use of either vector control or field-oriented control. When this type of control strategy is adopted, it can make an induction motor to be controlled like a separately excited DC motor. Of course, the control of AC drives can exhibit better performance. Thus, due to the above mentioned reasons, an induction motor model was 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.

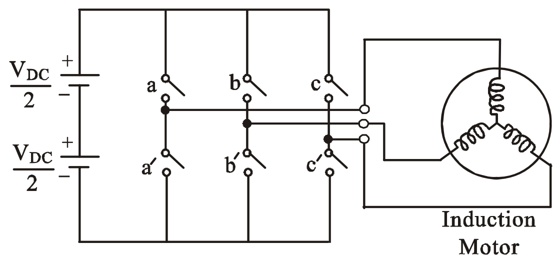


Fig. 1: Power circuit connection diagram for the IM

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. This calculated voltage is then synthesized using the space vector modulation. The stator & rotor voltage equations are given by [17]

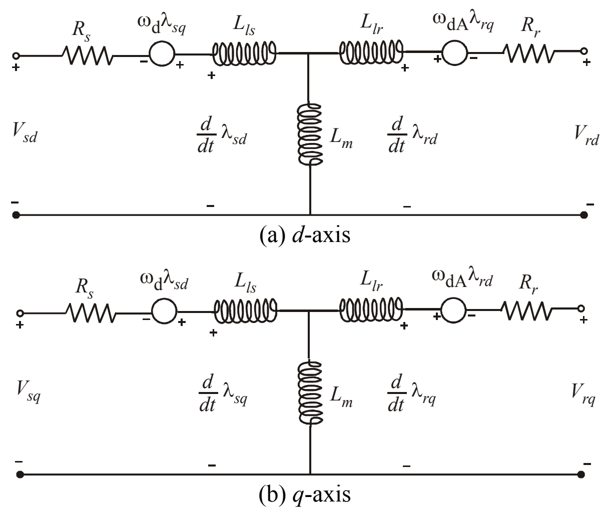


Fig. 2 : Power circuit connection diagram for the IM

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

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

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

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

where V_{sd} and V_{sq}, V_{rd} and V_{rq} are the direct axes & quadrature axes stator and rotor voltages [17].

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

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

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 [17]

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

where, A is given by

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

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

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

The electromagnetic torque expressed in terms of inductances is given by

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

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

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

where,

J_{eq} = Equivalent Moment of Inertia,

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

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

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

This IMs mathematical model is further used to design a controller using TS-fuzzy control strategy in the next but next section. The induction motor can be observed as a system of electric and magnetic circuits, which are coupled magnetically and electrically. A 3-ϕ balanced sinusoidal voltages given by [20]

$$V_{An} = V_m \cos \omega t \,, \tag{11}$$

$$V_{Bn} = V_m \cos\left(\omega t - \frac{2\pi}{3}\right), \tag{12}$$

$$V_{Cn} = V_m \cos\left(\omega t + \frac{2\pi}{3}\right) \tag{13}$$

are applied to the IM using the equation

$$\mathbf{V} = \frac{2}{3}\left[v_{An} + a v_{Bn} + a^2 v_{Cn}\right] \tag{14}$$

through the 3-ϕ bridge inverter shown in the Fig. 1 which has got 8 permissible switching states. This 8 permissible switching states can be graphically represented as shown in the Fig. 3. The table I gives the summary of the switching states and the corresponding phase-to-neutral voltages of the isolated neutral induction machine [20].

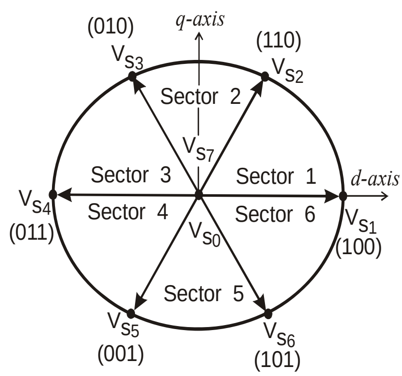


Fig. 3 : Diagrammatic representation of the sequence of the space vectors

V_i	a	b	c	V_{An}	V_{Bn}	V_{Cn}
V_0	0	0	0	0	0	0
V_1	1	0	0	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$
V_2	1	1	0	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$
V_3	0	1	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$
V_4	0	1	1	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$
V_5	0	0	1	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$
V_6	1	0	1	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$
V_7	1	1	1	0	0	0

Table I : The inverter switching states

4. Review of Takagi-Sugeno fuzzy control scheme

In this section, a brief review of the Takagi and Sugeno control strategy to control various system parameters of the plant 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 AC motors, DC motors, etc [38], [42]. 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 short to say, the TS model represents a general class of non-linear systems & is based on the fuzzy partition of input space and can be viewed as a expansion of piecewise linear partitions. The whole input space is decomposed into several partial fuzzy spaces and each output space is represented with a linear equation [12]. This type of knowledge representation does not allow the output variables to be described in linguistic terms, which is one of the drawbacks of this approach. Hence, this class of fuzzy models should be used when only performance is the ultimate goal of predictive modeling.

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]

$$R_k : \mathrm{IF}\left\{\mathrm{x\ is\ A}^k\right\}, \mathrm{THEN}\left\{y_1 = h_1^k(x)\right\}\ \mathrm{AND}\ .....\ \mathrm{AND}\left\{y_m = h_m^k(x)\right\}, \tag{15}$$

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]

$$\begin{aligned} &\text{Rule } i: \text{if } z_1 \text{ is } A_1^{i,k_1}, z_2 \text{ is } A_2^{i,k_2}, \wedge, \text{and } z_m \text{ is } A_m^{i,k_m}, \\ &\quad \text{then, } y^i = a_1^i x_1 + a_2^i x_2 + \wedge + a_q^i x_q, \\ &\quad i = 1, 2, \wedge, ...R.\ \ k_j = 1, 2, \wedge, ...r_j, \end{aligned} \tag{16}$$

where, *R* is the number of rules in the TS fuzzy model, z_j (j = 1, 2, 3, Λ,…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, Λ,…, 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}, Λ, z_{m0}) and the model input variables (x_{10}, x_{20}, Λ, 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]

$$y = \sum_{i=1}^{R} \frac{\mu^i y^i}{\sum_{i=1}^{R} R}, \tag{17}$$

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]

$$\mu^i = \bigwedge_{j=1}^{m} A_j^{i,k_j}\left(z_{j0}\right). \tag{18}$$

Furthermore, Eq. (17) can be rewritten as [15]

$$y = \frac{\left(\sum_{i=1}^{R} \mu^i a_1^i x_1 + \Lambda + \sum_{i=1}^{R} \mu^i a_q^i x_q\right)}{\sum_{i=1}^{R} \mu^i}, \tag{19}$$

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 using the TS fuzzy approach [15].

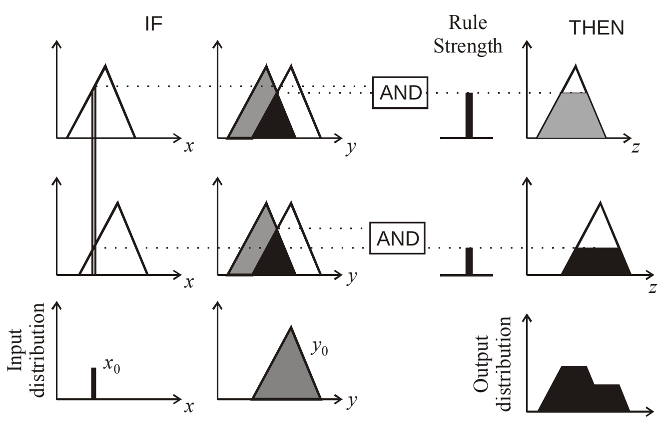


Fig. 4 : A 2-input, 2-rule Mamdani model with a fuzzy input

In [1], speed control of induction motor using the Mamdani control strategy with the fuzzy approach was presented by the authors, whereas in this paper, we present the speed control of induction motor using the TS control strategy based fuzzy approach, apart from which we also present the robustness due to sudden variations of speed from one value to another value. The Fig. 4 shows a 2-input Mamadani FIS with 2 rules. It fuzzifies the 2 inputs by finding the intersection of the crisp input value with the input membership function & uses the minimum operator to compute the fuzzy AND for combining the 2 fuzzified inputs to obtain the rule strength. Finally, it uses the maximum operator to compute the fuzzy OR for combining the outputs of the 2 rules [16].

Mamdani's fuzzy inference method is one of the most commonly used fuzzy methodologies for control applications. His method was among the first control systems built using fuzzy set theory. It was proposed by him as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Mamdani's effort was based on Zadeh's paper on fuzzy algorithms for complex systems and decision processes. Mamdani type inference expects the output membership functions to be fuzzy sets. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output membership functions rather than a distributed fuzzy set. This is sometimes known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set.

This concept enhances the efficiency of the defuzzification process, because it greatly simplifies the computation required by the more general Mamdani method & finds the centroid of a two-dimensional function rather than integrating across the two-dimensional function to find the centroid. Sugeno type systems support this type of model. Note that in his control strategy, to compute the output of this FIS, given the inputs, 6 steps has to be followed :

- Fuzzifying the inputs using the input membership functions,
- Combining the fuzzified inputs according to the fuzzy rules to establish a rule strength,
- Determining a set of fuzzy rules,
- Finding the consequence of the rule by combining the rule strength & the output membership functions,
- Combining the consequences to get an output distribution,
- Defuzzifying the output distribution {this step is only if a crisp output (class) is needed}.

The main differences between Mamdani & TS models are that the TS output membership functions are either linear or constant. Also, the difference lies in the consequents of their fuzzy rules, and thus, their aggregation & defuzzification procedures differ suitably. The number of the input fuzzy sets and fuzzy rules needed by the TS fuzzy systems depend on the number & locations of the extrema of the function to be approximated. In TS method, a large number of fuzzy rules must be employed to approximate periodic or highly oscillatory functions. The minimal configuration of the TS fuzzy systems can be reduced & becomes smaller than that of the Mamdani fuzzy systems. TS controllers usually have far more adjustable parameters in the rule consequent & the number of parameters grows exponentially with the increase of number of input variables.

Far fewer mathematical results exist for TS fuzzy controllers than do for Mamdani fuzzy controllers, notably those on TS fuzzy control system stability. Mamdani's approach of designing controller for the plant is easy compared to the TS method. For Mamdani fuzzy models the de-fuzzification process may be time-consuming and systematic fine tuning of the parameters is not easy [14]. For TS fuzzy models, it is hard to assign appropriate linguistic terms to the rule consequence part, which does not use fuzzy values. Readability and performance thus appear as antagonist objectives in fuzzy rule-based systems. Because the TS model is more compact and computationally efficient representation than a Mamdani system, it lends itself to the use of adaptive techniques for constructing more complicated fuzzy models. These adaptive techniques can be used to customize the membership functions so that the fuzzy system best models the data.

5. 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, current is presented using the concepts of Takagi-Sugeno based fuzzy control scheme, the block diagram of which is shown in the Fig. 5.

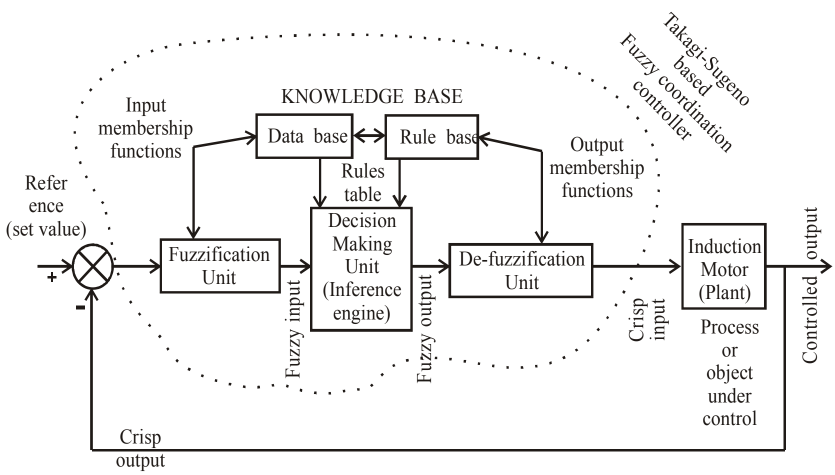


Fig. 5 : Block diagram of the TS-fuzzy logic control scheme of the IM

To start with, we design the controller using the TS scheme based FL controller. Fuzzy logic is one of the successful applications of fuzzy set in which the variables are linguistic rather than the numeric variables. 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 $\mu : X \to [\,0 \quad 1]$, which associates a number $\mu_A(x) : X \to [\,0 \quad 1]$, 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 control the speed of the IM 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.

The inputs to the FLC, i.e., the error & the change in error is modeled using the Eq. (20) as

$$\begin{aligned} e(k) &= \omega_{ref} - \omega_r, \\ \Delta e(k) &= e(k) - e(k-1), \end{aligned} \tag{20}$$

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. 5. 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 membership function of triangular type is used in our work & is shown in the Fig. 9. 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 II.

ΔE \ E	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 II : Rule base for controlling the speed

The developed Takagi-Sugeno fuzzy rules (7 × 7 = 49) included in the fuzzy coordinated controller is given below in the form of an algorithm as follows :

1. If (speederror is NB) and (changeinerror is NB) then (output1 is NS) (1)
2. If (speederror is NB) and (changeinerror is NM) then (output1 is NS) (1)
3. If (speederror is NB) and (changeinerror is NS) then (output1 is NS) (1)
4. If (speederror is NB) and (changeinerror is NS) then (output1 is NS) (1)
5. If (speederror is NB) and (changeinerror is PS) then (output1 is NM) (1)
6. If (speederror is NB) and (changeinerror is PM) then (output1 is NS) (1)

7. If (speederror is NB) and (changeinerror is PB) then (output1 is Z) (1)
8. If (speederror is NM) and (changeinerror is NB) then (output1 is NS) (1)
9. If (speederror is NM) and (changeinerror is NM) then (output1 is NS) (1)
10. If (speederror is NM) and (changeinerror is NS) then (output1 is NB) (1)
11. If (speederror is NM) and (changeinerror is Z) then (output1 is NM) (1)
12. If (speederror is NM) and (changeinerror is PS) then (output1 is NS) (1)
13. If (speederror is NM) and (changeinerror is PM) then (output1 is Z) (1)
14. If (speederror is NM) and (changeinerror is PB) then (output1 is PS) (1)
15. If (speederror is NS) and (changeinerror is NB) then (output1 is NS) (1)
16. If (speederror is NS) and (changeinerror is NM) then (output1 is NB) (1)
17. If (speederror is NS) and (changeinerror is NS) then (output1 is NM) (1)
18. If (speederror is NS) and (changeinerror is Z) then (output1 is NS) (1)
19. If (speederror is NS) and (changeinerror is PS) then (output1 is Z) (1)
20. If (speederror is NS) and (changeinerror is PM) then (output1 is PS) (1)
21. If (speederror is NS) and (changeinerror is PB) then (output1 is PM) (1)
22. If (speederror is Z) and (changeinerror is NB) then (output1 is NB) (1)
23. If (speederror is Z) and (changeinerror is NM) then (output1 is NM) (1)
24. If (speederror is Z) and (changeinerror is NS) then (output1 is NS) (1)
25. If (speederror is Z) and (changeinerror is PB) then (output1 is PB) (1)
26. If (speederror is Z) and (changeinerror is Z) then (output1 is Z) (1)
27. If (speederror is Z) and (changeinerror is PS) then (output1 is PS) (1)
28. If (speederror is Z) and (changeinerror is PM) then (output1 is PM) (1)
29. If (speederror is PS) and (changeinerror is NB) then (output1 is NM) (1)
30. If (speederror is PS) and (changeinerror is NM) then (output1 is NS) (1)
31. If (speederror is PS) and (changeinerror is NS) then (output1 is Z) (1)
32. If (speederror is PS) and (changeinerror is Z) then (output1 is PS) (1)
33. If (speederror is PS) and (changeinerror is PS) then (output1 is PM) (1)
34. If (speederror is PS) and (changeinerror is PM) then (output1 is PB) (1)
35. If (speederror is PS) and (changeinerror is PB) then (output1 is PS) (1)
36. If (speederror is PM) and (changeinerror is NB) then (output1 is NS) (1)
37. If (speederror is PM) and (changeinerror is NM) then (output1 is Z) (1)
38. If (speederror is PM) and (changeinerror is NS) then (output1 is PS) (1)
39. If (speederror is PM) and (changeinerror is Z) then (output1 is PM) (1)
40. If (speederror is PM) and (changeinerror is PS) then (output1 is PB) (1)
41. If (speederror is PM) and (changeinerror is PM) then (output1 is PS) (1)
42. If (speederror is PM) and (changeinerror is PB) then (output1 is PB) (1)
43. If (speederror is PB) and (changeinerror is NB) then (output1 is Z) (1)
44. If (speederror is PB) and (changeinerror is NM) then (output1 is PS) (1)
45. If (speederror is PB) and (changeinerror is NS) then (output1 is PM) (1)
46. If (speederror is PB) and (changeinerror is Z) then (output1 is PB) (1)
47. If (speederror is PB) and (changeinerror is PS) then (output1 is PB) (1)
48. If (speederror is PB) and (changeinerror is PM) then (output1 is PB) (1)
49. If (speederror is PB) and (changeinerror is PB) then (output1 is PB) (1)

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. The simulated rules in simulink are shown in the Fig. 10. 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 defuzzifcation, 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. (21) as

$$y = \left(\sum_{i=1}^{R} \mu^i a_1^i x_1 + \Lambda + \sum_{i=1}^{R} \mu^i a_q^i x_q \right) \Bigg/ \sum_{i=1}^{R} \mu^i , \tag{21}$$

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. (21), 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 in this paper is to control the speed of the IM to increase the dynamic performance & to provide good stabilization.

6. Development of simulink model

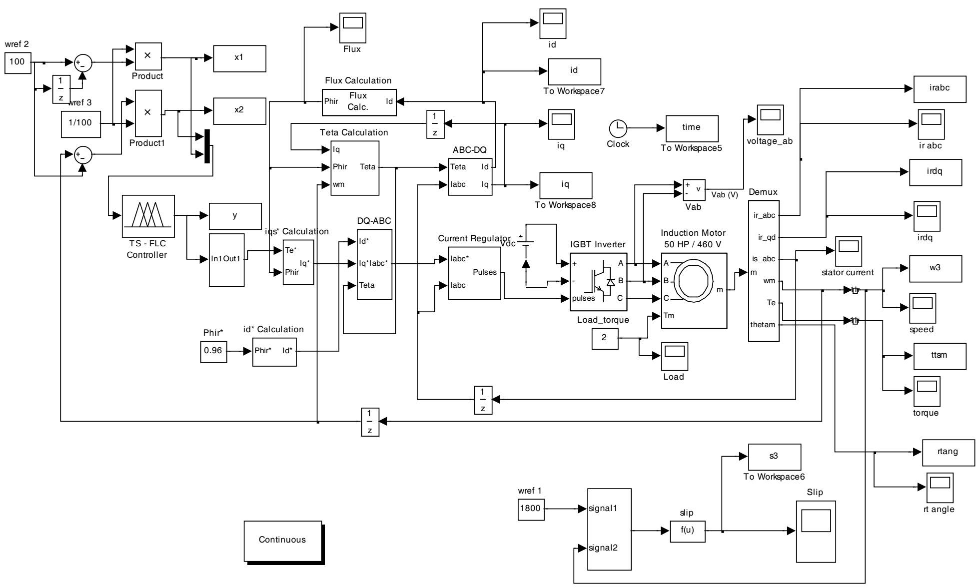


Fig. 6 : The developed simulink model with the TS based Fuzzy logic controller

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, slip, current, 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, constants, the mux, de-mux, summers, adders, gain blocks, multipliers, clocks, sub-systems, integrators, state-space models, 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. 6. The specifications of the SCIM used for simulation purposes are given in the appendix.

7. Simulation results & discussions

Simulink model with the controller for the speed control of IM was developed in Matlab 7 as shown in the Fig. 6 above. In order to start the simulations, the fuzzy rule set has to be invoked first from the command window. Initially, the fuzzy file where the rules are written with the incorporation of the T-S control strategy is opened in the Matlab command window, after which the fuzzy editor (FIS) dialogue box opens as shown in the Fig. 7. The .fis file is imported using the command window from the source file & then opened in the fuzzy editor dialog box using the file open command. Once the file is opened, the TS-fuzzy rules file gets activated as shown in the Fig. 8.

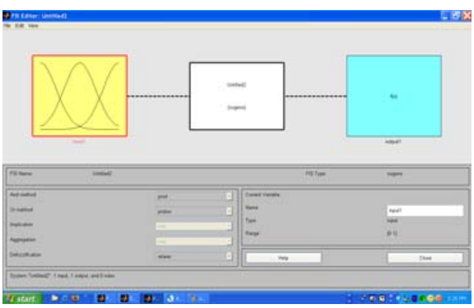


Fig. 7 : FIS editor dialog box

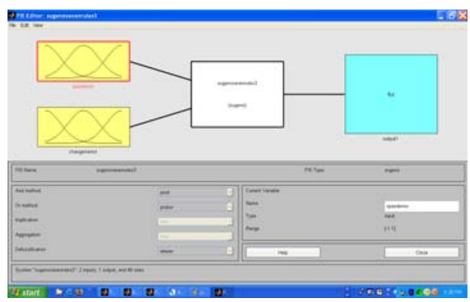


Fig. 8 : Fuzzy editor with 2 inputs & 1 output ; Importing of the .fis file from the source

Further, the data is exported to the workspace & the simulations are run for a specific amount of time (say 2 to 3 secs). The fuzzy membership function editor is then obtained using the view membership command from the menu bar and this is shown in the Fig. 9. The written TS-fuzzy rules also can be viewed from the rule view command, which is presented in the Fig. 10. The rule viewer for the 2 inputs and 1 output can be observed pictorially in the Fig. 11. The surface plot for the error speed & change in error with the output is shown in the Fig. 12.

Now, after viewing all the preliminary results, the simulations are run for a period of 3 seconds in Matlab 7 with a reference speed of 100 rads / sec $\left\{ \text{i.e.,} \left(100\times 60\right) / 2\pi \right\} = 955$ rpm & with a load torque of 2 N-m.

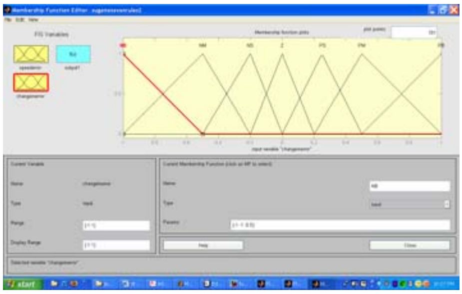


Fig. 9 : Membership function editor

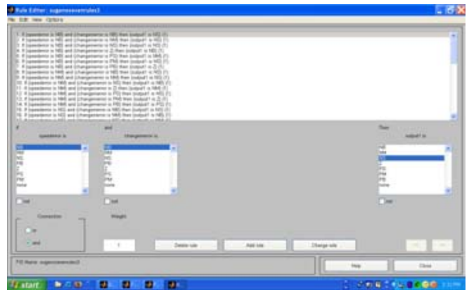


Fig. 10 : The written set of 49 TS-Fuzzy rules

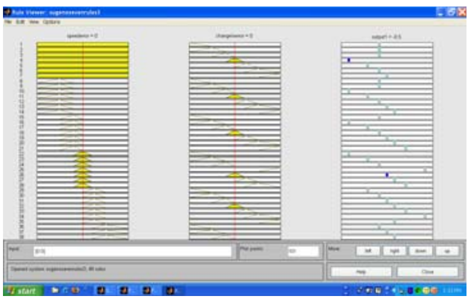


Fig. 11 : Rule viewer for 2 inputs & 1 output

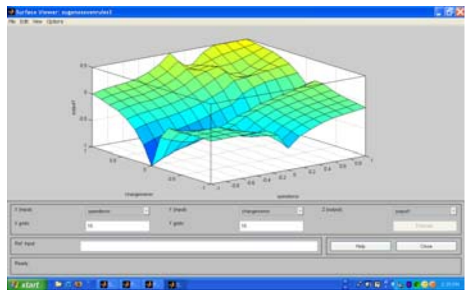


Fig. 12 : Surface plot for change in error, speed error & output

While the simulation is run, the 2 fuzzy inputs are then given to the controller (Takagi-Sugeno-fuzzy) as shown in the Fig. 8, where the controller output is obtained thereafter. Note that in this TS based fuzzy controller (which consists of 3 basic blocks viz., fuzzification, inference, and the de-fuzzification blocks) the set of 49 fuzzy rules are called in the form of a file. After the simulation is run, the performance characteristics are observed on the respective scopes. The response curves of flux, load, torque, terminal voltage, speed, stator currents, slip, i_d, i_q, rotor currents (3ϕ & d-q) v/s time, slip vs. speed, torque vs. slip are observed on the respective scopes & are shown in the Figs. 13 - 24 respectively.

From the simulation results shown in the Figs. 13 to 24, it is observed that the stator current does not exhibit any overshoots nor undershoots. The response of the flux, slip, torque, terminal voltage, speed, 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 fuzzy 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 of 100 r / s & 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]. The motor speed increases like a linear curve upto the set speed of 955 rpm in 0.7 secs.

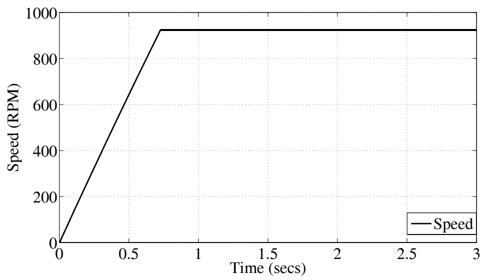


Fig. 13 : Plot of speed vs. time

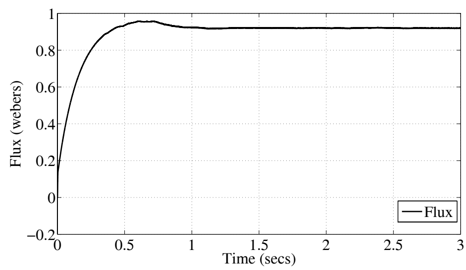


Fig. 14 : Plot of flux vs. time

From the variation of flux with time as shown in the Fig. 14, it can be observed that when the motor speed is increasing (during the transient period), more stator current is required to develop the requisite flux in the air gap. Hence, the flux also starts increasing during the transient period (0 to 0.7 sec) exponentially. Once, the motor attains the set rated speed, the flux required to develop the torque almost remains constant after ≥ 0.7 secs. Once, the saturation of the flux takes place in the air gap, the variation of the load torque and speed will not disturb the flux curve. Hence, the IM will be operating at a constant flux.

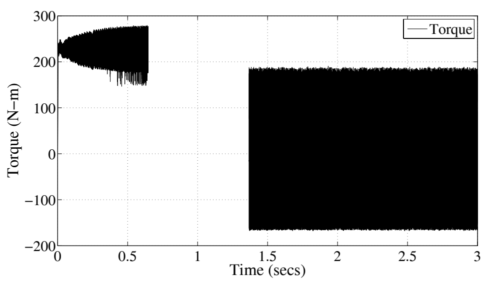


Fig. 15 : Plot of Torque vs. time

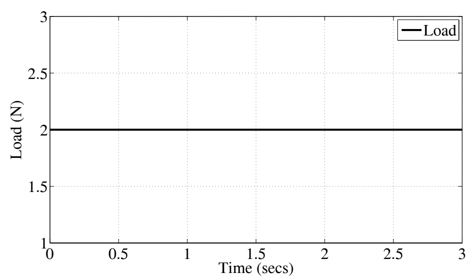
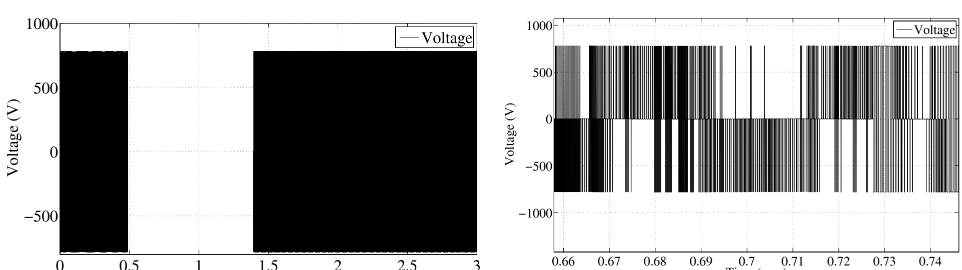


Fig. 16 : Plot of load vs. time

Torque characteristics for a set reference speed of 100 r/s (955 rpm) are shown in the Fig. 15. From this figure, we arrive at a conclusion that when the motor is operating at lower speeds, the slip is more. Hence, the machine requires more torque to attain the set speed. Once the machine reaches the set speed of 955 rpm the average torque of the machine becomes nearly zero, which is justified from the simulation result in Fig. 15.



(a) Plot of voltage vs. time (normal)

(b) Plot of voltage vs. time (zoomed) between t = 0.66 s to 0.74 s

Fig. 17 : Plot of voltage vs. time

The load torque is set to 2 N-m throughout the simulation & is kept constant, which can be observed from the simulation result shown in the Fig. 16. The terminal voltage of the IM is shown in Figs. 17 (a) & (b) respectively.

The variation of the 3-ϕ stator currents (i_s - abc) with time is shown in the Fig. 18. It can be clearly observed from this figure, that at lower speeds, the slip is more, the flux required to develop the suitable torque is also more. Also, the torque required to reach the set speed is also more. Hence, the magnitude of the stator currents will also be more during the transient periods (starting periods) of the induction motor. When the speed is reaching the set value from zero, the 3-ϕ stator currents decreases exponentially. Once, it attains the set speed at 0.7 secs, it requires a nominal stator current to drive the IM system.

The Fig. 19 shows the variation of slip vs. time characteristics for a speed of 100 r/s (955 rpm). From this simulation result, we infer that the IM attains the set reference speed of 955 rpm in 0.7 secs using the TS based fuzzy controller. At that instant, the slip being $\frac{N_s - N}{N_s} = \frac{1800-955}{1800} = 0.46$, can be verified from the result shown. Note that the slip decreases from 1.0 to 0.46 linearly in a time span of just. 0.7 secs.

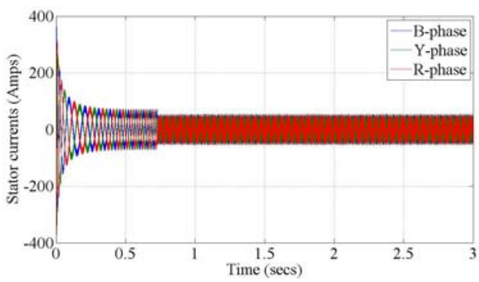


Fig. 18 : Plot of 3-ϕ stator currents vs. time

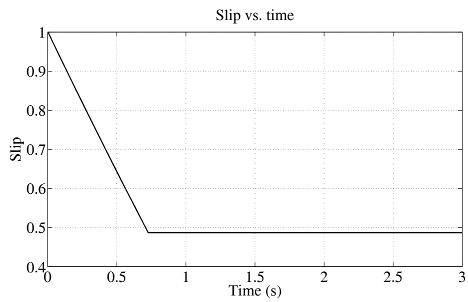


Fig. 19 : Plot of slip vs. time

The slip-speed characteristics is shown in the Fig. 20. It can be noted that when the speed is varied from 0 to the rated speed, the slip decreases, i.e., the slip is inversely proportional to the speed, which is the property of the IM. When the speed is zero, the slip is 100 %, while the IM is operating at near the rated speed (180 r/s), the slip is very very low (0.46).

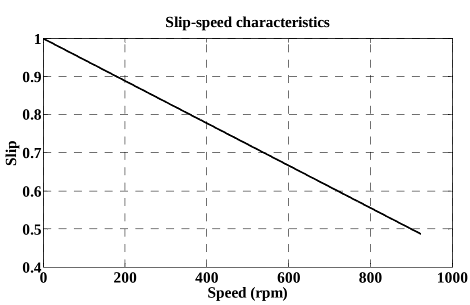


Fig. 20 : Slip - speed characteristics

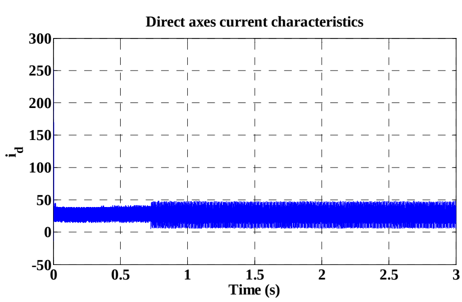


Fig. 21 : Plot of i_d vs. time

The plots of the direct axes (i_d) & quadrature axes currents (i_q) versus time is shown in the Figs. 21 & 22 respectively. From these figures, it can be inferred that the machine reaches the set reference speed of 955 rpm in a time interval of 0.7 secs.

The variation of the 3-ϕ rotor currents (i_r - abc) with time is shown in the Fig. 23. It can be inferred that at lower speeds, the slip is more, the flux required to develop the suitable torque is also more. Also, the torque required to reach the set speed is also more. Hence, the magnitude of the rotor currents will also be more during the transient periods (starting periods) of the induction motor. When the speed is reaching the set value from zero, the 3-ϕ rotor currents decreases exponentially.

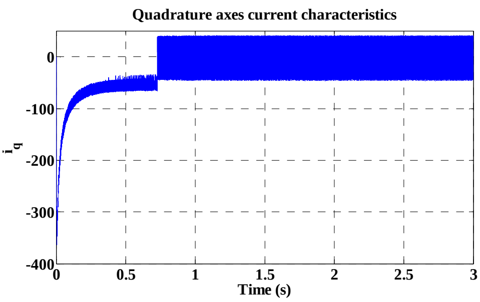


Fig. 22 : Plot of i_q vs. time

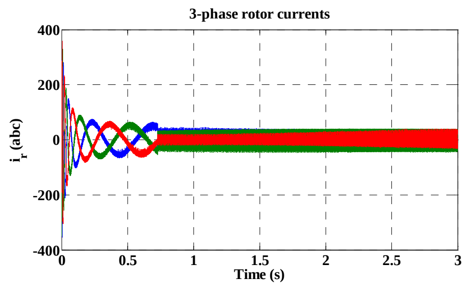


Fig. 23 : Plot of i_r abc vs. time

The 3-ϕ rotor currents (i_r - abc) is transformed to direct axes & quadrature axes currents using the d - q transformation techniques and the variation of the transformed currents with time is shown in the Fig. 24. Here, only two phases (d & q axes) of the currents can be observed in the characteristic curve. In this case, also, once the motor achieves the the set speed at 0.7 secs, it requires a nominal current to drive the IM system.

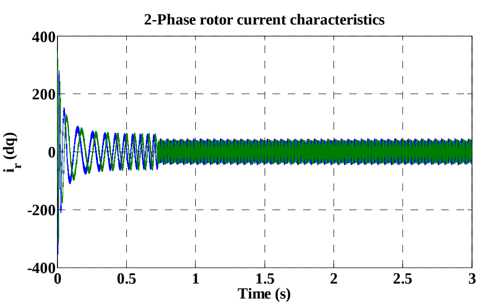


Fig. 24 : Plot of rotor current i_r (d - q) vs. time

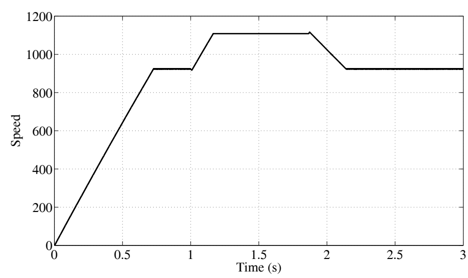


Fig. 25 : Variation of speed curve from 100 to 140 r/s & back to 100 r/s

Another important significant contribution of this controller is that, the designed controller can also be used for variable speed also. When the system is in operation (when the simulations are going on), due to sudden changes in set speed (say, the set speed immediately changed from 100 to 140 or anything else & then suddenly decreasing the speed back to normal), with the incorporation of the designed controller in loop with the plant, the system comes back to stability within a few milli-seconds (ms), which can be observed from the simulation results. The simulation results due to the parametric variations of speed from 100 to 140 and then back to normal are shown in the Figs. 25 to 29 respectively. It is clearly observed from these simulation results that with the developed robust controller, the dynamic performance of the system is quite improved, insensitive to parametric variations with the incorporation of the TS based fuzzy coordination scheme. Further, it can be also concluded that even though that some of the motor parameters are non-linear, it looks like linear in nature.

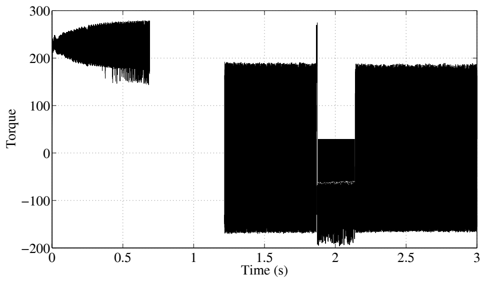


Fig. 26 : Plot of torque vs. time for variation in speed from 100 to 140 r/s & back to 100 r/s

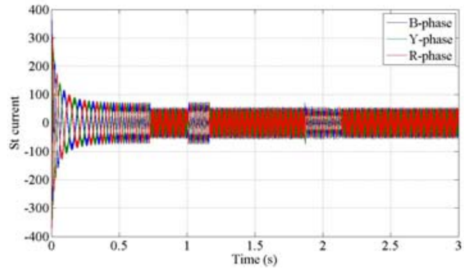


Fig. 27 : Plot of stator current vs. time for variation of speed from 100 to 140 r/s & back to 100 r/s

Note that when the speed is varied from 100 to 140 r/s at say t = 1 s, the motor takes very less time to reach the new set speed point (140 r/s) to become stable. Again when the IM is running at 140 r/s, the speed is suddenly varied from 140 to 100 r/s at say t = 1.7 s, the motor takes very less time to reach the new set speed point (100 r/s) to become stable as shown in the Fig. 25. From this, it can be observed that the speed of the IM is robust (insensitive) to sudden changes in the speed, which is because of the TS based fuzzy controller.

The torque vs. time for variation in speed from 100 to 140 r/s & back to 100 r/s is shown in the Fig. 26. It can be seen that when the speed of the IM is increasing from 0 to the set value (100 r/s), the torque required to reach the set speed in high. After the motor reaches the set speed of 100 r/s, the average torque required to run the motor at the set speed of 100 r/s will be zero between the period from t = 0.7 s to 1.0 s. Now, if the speed is suddenly increased from 100 to 140 r/s, again the torque requirement is also high between the period from t = 1.0 s to 1.2 s. After the motor reaches the new set speed of 140 r/s, the average torque required to run the motor at the new set speed of 140 r/s will be zero between the period from t = 1.2 s to 1.7 s. Now, if the speed is suddenly decreased from 140 to 100 r/s, the torque requirement is less between the period from t = 1.7 s to 2.2 s. After the motor reaches the original set speed of 100 r/s, the average torque required to run the motor at the original set speed of 100 r/s will be zero from t = 2.2 s onwards.

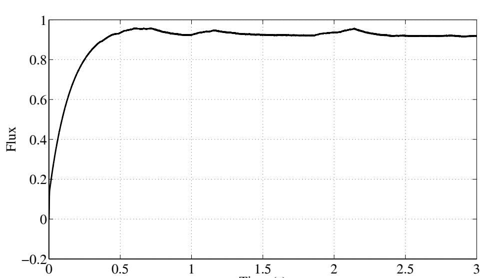


Fig. 28 : Plot of variation in flux vs. time for variation of speed from 100 to 140 r/s & back to 100 r/s

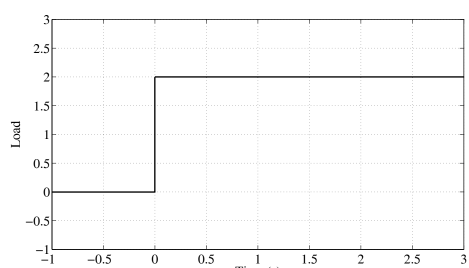


Fig. 29 : Plot of variation in load vs. time for variation of speed from 100 to 140 & back to 100 rotations

The plot of the 3-ϕ stator currents (i_s - abc) with time for the variation in speed from 100 to 140 r/s & back to normal is shown in the Fig. 27. There is a change in the stator current variation during the change in speed from one value to another. Once the stable point is reached, the stator current becomes normal.

One observation that can be made in the flux characteristics during the change in speed is that, during the speed variation, the flux varies slightly which is shown in the Fig. 28.

The load torque is set at a constant value of 2 N-m throughout the process of simulation at the time of change in speed, which can be seen in the Fig. 29.

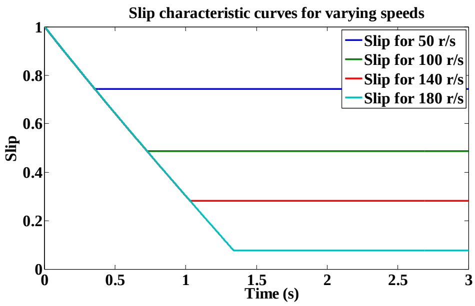


Fig. 30 : Plot of slip vs. time for varying speeds (50, 100, 140, 180 rads/sec)

No.	Speed (rads / sec)	Slip %	Time (secs)
1.	50	0.75	0.4
2.	100	0.46	0.7
3.	140	0.28	1.05
4.	180	0.04	1.4

Table III : Quantitative results of slip characteristics for various speeds

Another significant contribution presented in this research paper is the slip characteristic curves for variable speed of the IM. The speed is varied from 50 rads / sec (477 rpm) to near the rated speed of 180 rads / sec (1717 rpm). For the sake of convenience, 4 cases of variation in speed are considered, viz., 50 r/s (477 rpm), 100 r/s (955 rpm), 140 r/s (1335 rpm), 188.5 r/s (1717 rpm). The simulation is run for a period of 3 secs & the quantitative results of the slip vs. time for various speeds is shown in the table III along with the simulation results in Fig. 30. From these results, we infer that the slip is more for low speed operation of the induction motor & it is very less when the IM is operating at near the rated speeds. Also, the slip characteristics looks like linear in nature due to the incorporation of the TS based fuzzy controller, which is the highlight of this simulation result.

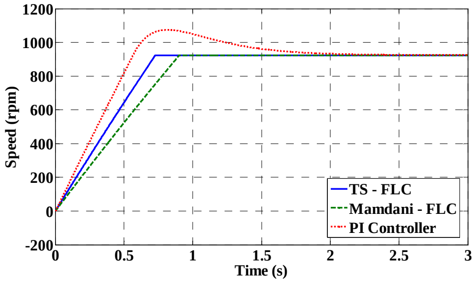


Fig. 31 : Comparison of speed curves for Mamdani method [1], PI & TS-fuzzy scheme

Type of controller	Set Speed r/s	Settling Time sec
TS-Fuzzy controller	100	0.7
Mamdani Controller	100	0.9
PI Controller	100	2.0

Table IV : Quantitative results of comparison of settling times with different types of controllers

The comparison of speed curves for Mamdani method [1], PI & TS-fuzzy scheme is shown in the Fig. 31. From this result, it can be observed that using the TS-based fuzzy control, the system stabilizes in a very less time ($t = 0.7$ s) compared to the other methods.

8. 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 model was developed in Matlab 7 with the TS-based fuzzy controller for the speed control of IM. Simulink model using PI control was developed for the IM speed control. 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 was to increase the dynamic performance & provide good stabilization. Simulations were run in Matlab 7 & the results were observed on the corresponding scopes. The characteristic curves of speed, torque, current, flux, slip, load, etc. vs. time were observed. The outputs take less time to stabilize, which can be observed from the simulation results. Due to the incorporation of the TS based fuzzy coordination system in loop with the plant, it was observed that the motor reaches the rated speed very quickly in a lesser time compared to the mamdani method [1] or the PI method.

The developed control strategy is not only simple, but also reliable and may be easy to implement in real time applications. The performance of the developed method in this paper also demonstrates the effectiveness of the sudden variation of speed (because of parametric variation) from the normal value & its effects on the various parameters (such as slip, current, torque, etc.) to obtain the stability. Simulation results demonstrate the good damping performance of the designed robust controller even in spite of speed fluctuations. Collectively, these results show that the TS-fuzzy controller provides faster settling times, has very good dynamic response & good stabilization compared to the Mamdani-fuzzy control scheme [1] or the PI method. The performance and robustness of the proposed TS-fuzzy controller have been evaluated under a variety of conditions of the drive system and the results demonstrate the effectiveness of these control measures.

The main advantages of the TS based fuzzy scheme being, it is computationally efficient, works well with linear techniques, works well with optimization & adaptive techniques & has guaranteed continuity of the output surface. The method developed in this paper, being efficient, reliable & robust, can be used in real time applications using some interfacing cards like the dSPACE, data acquisition cards, TMSDSP cards, NI cards, etc. for control of various parameters & also be combined with ANNs & rough sets for other applications.

Appendix

A1. SCIM specs :

50 HP, 1800 rpm, 460 V, 60 Hz., 2 pair of poles, Squirrel Cage type IM

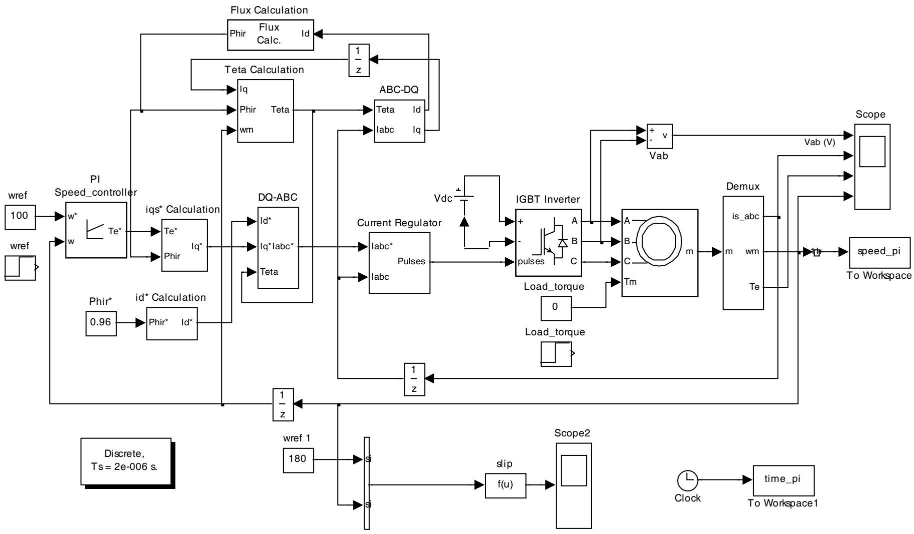
$R_s = 0.087\,\Omega,\ L_s = 0.8 \times 10^{-3}\,\mathrm{H}$

$R_r = 0.228\ \Omega,\ L_r = 0.8\,\mathrm{mH}$,

$L_m = 34.7\ \mathrm{mH}$

$J = 1.662\ kg.m^2$

A2. Simulink model for the speed control of IM using PI method :



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