CHAPTER 6

DESIGN AND SIMULATION OF TAKAGI–SUGENO FLC BASED DRIVE SYSTEM

In this chapter, modeling and simulation of a Takagi–Sugeno based fuzzy logic control strategy in order to control one of the most important parameters of the IM, viz., speed, is presented. In the control of IMs, FLCs play a very important role. In this context, a novel FLC is developed based on the Takagi–Sugeno principles. This method gives very good response compared to other methods such as the PI method or the Mamdani-based FLC method. Hence, this TS-based FL control design becomes a hybrid method of control approach for the control of IM. Such a hybrid combination yields very good system performance coupled with a high control effect.

The Takagi–Sugeno concept is used in the design of fuzzy controller in closed loop with the drive, the dynamic characteristics of the AC drive increase. The developed strategy does not require the mathematical model of the controller. The sudden fluctuation/change/variation in speed from one value to another and its effect on the various parameters of the dynamic system are also considered, thus exhibiting the robustness behavior. The designed controller not only takes care of the sudden perturbations in speed, but also brings back the parameters to the reference or the set value in a fraction of second. In other words, the designed controller is
robust to parametric variations. From the simulation results depicted at the end of this chapter, it can be observed that the control of speed of an IM has good accuracy and fast dynamic response.

6.1 INTRODUCTION

Induction motors (type of AC motor) play a vital role in the industrial sector, especially in the field of electric drives and control, and have been used in the work undertaken in this chapter. Without proper control of speed, it is virtually impossible to achieve the desired task for a specific application [66]. Many a times, various problems are encountered during the controller design process; if the order of the designed controller is very high, then it may become very difficult to implement it in real time and hence it becomes more expensive. Sometimes, it becomes very difficult or impossible to obtain a mathematical model of the controller.

To get mathematical model of the system, some identification techniques need to be performed such as system identification and obtain the plant model [77]. Since Lotfi Zadeh developed the concept of fuzzy logic. It has been used by many researchers to develop controllers for applications, which yielded good results. Thus, this FLC concept remains a popular control scheme in the control world even today [78]. The research works carried out by various authors [79]-[83] using scalar control, vector or field-oriented control (FOC) [74],[76], direct torque and flux control, PI control, PID control, sliding
mode control, adaptive controls, hybrid control, etc have been reviewed along with their advantages and disadvantages. An attempt is made here to overcome some of the drawbacks and difficulties encountered while designing the controllers using the Takagi–Sugeno-based fuzzy concepts for the speed control of IM with excellent results [84].

6.2. REVIEW OF TAKAGI–SUGENO FUZZY CONTROL

Takagi and Sugeno [40], [85], [86] proposed a new type of fuzzy model, which has been commonly used in several industrial drive applications. The TS model represents a general class of non-linear systems and is based on the fuzzy partition of input space and can be viewed as an 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 [77]. Hence, this class of fuzzy models should be used when only performance is the ultimate goal of predictive modeling. In general, TS models are represented by a series of fuzzy rules of the following form [88].

\[ R_k: \text{IF } \{ x \text{ is } A^k_1 \}, \text{ THEN } \{ y_1 = h^k_1(x) \} \text{ AND } \ldots \ldots \text{ AND } \{ y_m = h^k_m(x) \} \quad (6.1) \]

Rule \( k \), IF \( Z_1 \) is \( A^k_2 \), \ldots, \( Z_m \) is \( A^k_m \)

Then \( y_i = a^i_1 x_1 + a^i_2 x_2 + a^i_q x_q \) \quad (6.2)

\( i=1,2, \ldots, R \) and \( j=1,2, \ldots, T_j \)
Parameter varying systems that possess \( m \) working state 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 above in equation (6.2) [41]. Here, \( x_l \) \((l=1, 2, 3, \ldots, q)\) is the \( l^{th} \) model input and \( y_i \) is the output of the \( i^{th} \) rule. For the \( i^{th} \) rule, \( A^{l,k}_{j} \) is the \( K_j^{th} \) fuzzy sub-set of \( z_j \). Here, \( a_i \) is the coefficient of the consequent terms and \( r_j \) is the fuzzy partition number of \( z_j \).

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 \((z_{10}, z_{20}, \ldots, z_{m0})\) and the model input variables \((x_{10}, x_{20}, \ldots, x_{q0})\) are available, then the output can be calculated by the weighted-average of each \( y_i \) as follows:

\[
y = \frac{\sum_{i=1}^{R} \mu^i y^i}{\sum_{i=1}^{R} R}
\]  

(6.3)

where \( y_i \) is determined by the equation of the \( i^{th} \) rule. The truth-value \( \mu^i \) of the \( i^{th} \) rule can be calculated as follows [41]:

\[
\mu^i = \bigwedge_{j=1}^{m} A^{l,k}_{j}(z_{j0})
\]  

(6.4)

Furthermore, Eq. (6.3) can be rewritten as follows:

\[
y = \frac{\sum_{l=1}^{R} \mu^l a^i_{l} x_l + \sum_{l=1}^{R} \mu^l a^i_{q} x_q}{\sum_{i=1}^{R} \mu_i}
\]  

(6.5)
which is nothing but the final output of the system and is the weighted average of all the rule outputs (from \( i \) to \( R \)). As \( \mu_i \) varies with the working state, the TS fuzzy model becomes a coefficient-varying linear equation for various parameters \([41]\).

In Chapter 5, the design of controllers using Mamdani-based FLC was presented, whereas in this section the design of controller using the Takagi–Sugeno-based FLC is presented. The main differences between the controller presented in Chapters 5 and 6 is that the TS output MFs are constant/linear, whereas in Mamdani it is non-linear in nature. Also, the difference lies in the consequents of their fuzzy rules, and thus, their aggregation and de-fuzzification procedures differ suitably.

### 6.3. TS-BASED CONTROLLER DESIGN

In this section, the design of the TS-FLC is presented. 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 uses the conditional rules of ‘IF-THEN-ELSE’ to decide 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 inputs to the FLC, i.e., the error and the change in error, are modeled using Eqs. (6.6) and (6.7) as follows:

\[ e(k) = \omega_{ref} - \omega_r, \]  
\[ \Delta e(k) = e(k) - e(k-1), \]  

where \( \omega_{ref} \) is the set speed, \( \omega_r \) is the actual speed, \( e(k) \) is the error and \( \Delta e(k) \) is the change in error. The TS-FLC is designed with 2 inputs and 1 output. The error in speed was considered as first input, change in error is treated as second input along with one output. The two input and one output are fuzzified with seven triangular membership function further 49 rule base are written on the basis of knowledge which in turn used for decision making. The centre of gravity (CG) method is used for defuzzification. The output of the defuzzification unit will give the control commands for generating gating signal. The
inverter terminal voltage controlled by these gating signals in turn control the speed of drive.

The same rule base as shown in Table 5.1 in Chapter 5 in Section 5.2, which was used for the Mamdani-based FLC for the decision-making purposes, is used in this chapter for the decision-making purposes to design the TS-based FL controller. Also, the developed TS-based fuzzy rules (7×7=49) included in the fuzzy coordinated controller are shown in the form of an algorithm in Chapter 5 in Section 5.2. The same 49 rules can be used here for control purposes and are not shown here for the sake of convenience.

6.4 DEVELOPMENT OF THE SIMULINK MODEL

The block model of the induction motor system with the controller was developed using the Simulink library in Matlab and is shown in Fig. 6.2. In this section, the various waveforms are observed on the corresponding scopes after running the simulations. The specifications of the SCIM used for simulation purposes were described in Chapter 3 (table 3.1).
Fig. 6.2: Developed Simulink model with TS-FLC
6.5 SIMULATION RESULTS AND DISCUSSIONS

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 TS algorithm is opened in the Matlab command window, after which the fuzzy editor (FIS) dialogue box opens. The .fis file is imported using the command window from the source file and then opened in the fuzzy editor dialog box using the file open command.

Once the .fis file is opened, the TS-fuzzy rules file gets activated. Furthermore, the data are exported to the workspace and the simulations are run for a specific amount of time (say 2 to 3 second). The written 49 TS-fuzzy rules can be viewed from the rule view command. The rule viewer for the 2 inputs and 1 output can also be observed pictorially in the fuzzy editor tool box.

Fig. 6.3: Surface plot for change in error, speed error and output
The surface plot for the error in speed and change in error with the output is shown in Fig. 6.3. Now, after viewing all the preliminary steps, the simulations are run for a period of 3 second in Matlab 7 with a set speed of 100 rads / second \( \left( \frac{100 \times 60}{2\pi} \right) = 955 \text{ rpm} \) and with 2 N-m load torque. Note that in this TS based fuzzy controller with the set of 49 fuzzy rules are called in the form of a file.

After the simulation is run, the performance characteristics like torque, speed, various current, etc are observed on the respective scopes as shown in the Figs. 6.4 to 6.14 respectively.

![Plot of speed vs. time](image)

**Fig. 6.4: Plot of speed vs. time**

It can be observed that, the response characteristics speed curves take less time to settle and reach the final steady-state value compared to that in [76]. The motor speed increases like a linear curve up to the set speed of **955 rpm** in **0.7 second** as shown in Fig. 6.4.
From the variation of flux with time as shown in Fig. 6.5, it can be observed that when the motor speed increases (during the transient period) then 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 – 0.7 second) exponentially. Once, the motor attains the set rated speed, the flux required to develop the torque almost remains constant after ≥ 0.7 second.

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 operate at a constant flux. Torque characteristics for a set reference speed of 100 rad/second (955 rpm) are shown in Fig. 6.6. From this figure, we can conclude that when the motor operates 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 shown in Fig. 6.6.

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

(b) Plot of voltage vs. time b/w t=0.66 s to 0.74 s

Fig. 6.7: Plot of voltage vs. time (normal and zoomed)

The terminal voltage of the IM is shown in Figs. 6.7 (a) and 6.7(b), respectively. The load is set to 2 N-m throughout the simulation and is kept constant. The variation of the 3Φ stator currents ($i_{s-abc}$) with time
is shown in Fig. 6.8. It can be clearly observed from this figure that at lower speeds, the slip is more, and hence the flux required to develop the suitable torque is also more. Moreover, 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 reaches the set value from zero, the 3Φ stator currents decrease exponentially. Once it attains the set speed at **0.7 second**, it requires a nominal stator current to drive the IM system. Fig. 6.9 shows the variation of slip vs. time characteristics for a speed of 100 rad/second (**955 rpm**).

![Fig. 6.8: Plot of 3-Φ stator currents vs. time](image1)

**Fig. 6.8: Plot of 3-Φ stator currents vs. time**

![Fig. 6.9: Plot of slip vs. time](image2)

**Fig. 6.9: Plot of slip vs. time**
From this simulation result, we infer that the IM attains the set reference speed of 955 rpm in **0.7 second** using the TS-based fuzzy controller. At that instant, the slip is \( \frac{N_s - N}{N_s} = \frac{1800 - 955}{1800} = 0.46 \), which 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 second**.

![Slip-speed characteristics](image)

**Fig. 6.10: Slip-speed characteristics**

The slip-speed characteristics are shown in Fig. 6.10. 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 a characteristic of IM. When the speed is zero, the slip is 100%, while the IM operates close to the rated speed (180 rad/second), the slip is very low (0.46).

The plots of the direct axes \( (i_d) \) and quadrature axes currents \( (i_q) \) versus time are shown in Figs. 6.11 and 6.12, respectively. From these figures, it can be inferred that the machine reaches the set reference speed of **955 rpm** at a time interval of **0.7 second**.
Fig. 6.11: Plot of $i_d$ vs. time

Fig. 6.12: Plot of $i_q$ vs. time

Fig. 6.13: Plot of $i_{rabc}$ vs. time
The variation of the 3Φ rotor currents \((i_{r-abc})\) with time is shown in Fig. 6.13. It can be inferred that at lower speeds, the slip is more, and hence 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 reaches the set value from zero, the 3Φ rotor currents decrease exponentially.

The 3Φ rotor currents \((i_{r-abc})\) are transformed to direct axes and quadrature axes currents using the \(d–q\) transformation techniques and the variation of the transformed currents with time is shown in Fig. 6.14. Here, only two phases \((d\) and \(q\) axes) of the currents can be observed in the characteristic curve. In this case, also, once the motor achieves the set speed at 0.7 second, it requires a nominal current to drive the IM system.

![2-Phase rotor current characteristics](image)

**Fig. 6.14: Plot of \(i_{rdq}\) vs. time**
6.6 JUSTIFICATION OF ROBUSTNESS ISSUES

Another important significant contribution of proposed controller is that the designed controller can also be used for variable speed. 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 120 or anything else and then suddenly decreases 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 millisecond (ms), which can be observed from the simulation results.

The simulation results due to the parametric variations of speed from 100 to 120 rad/second and then back to normal are shown in Figs. 6.15–6.20, respectively. It can be clearly observed from these simulation results that with the developed robust controller, the dynamic performance of the system is quite improved and is insensitive to parametric variations with the incorporation of the TS-based fuzzy coordination scheme. Furthermore, it can be also concluded that even though some of the motor parameters are non-linear, it appears linear in nature.

From the simulation result shown in Fig. 6.15, it can be observed that when the speed is varied from 100 to 120 rad/second at say \( t=1 \) s, the motor takes very less time to reach the new set speed point (120 rad/second) to become stable. Again when the IM runs at 120
rad/second, the speed suddenly varies from 120 to 100 rad/second at say $t=1.7$ s, the motor takes very less time to reach the new set speed point (100 rad/second) to become stable as shown in Fig. 6.15. From this, it can be observed that the speed of the IM is robust (insensitive) to sudden changes in speed, which is because of the TS-based fuzzy controller.

\[ \text{Fig. 6.15: Variation of speed curve from 100 to 120 rad/second and back to 100 rad/second} \]

The torque vs. time for variation in speed from 100 to 120 rad/second and back to 100 rad/second is shown in Fig. 6.16. It can be seen that when the speed of IM increases from 0 to the set value (100 rad/second), the torque required to reach the set speed is high. After the motor reaches the set speed of 100 rad/second, the average torque required to run the motor at the set speed of 100 rad/second will be zero between the period from $t=0.7$ second to 1.0 second.
Now, if the speed is suddenly increased from 100 to 120 rad/second, again the torque requirement is also high between the period from $t=1.0$ second to 1.2 second. After the motor reaches the new set speed of 120 rad/second, the average torque required to run the motor at the new set speed of 120 rad/second will be zero between the period from $t=1.2$ second to 1.7 second.

![Torque chs. for variation in speed](image)

**Fig. 6.16: Torque char. for variation in speed from 100 to 120 rad/second and back**

Now, if the speed is suddenly decreased from 120 to 100 rad/second, the torque requirement is less between the period from $t=1.7$ second to 2.2 second. After the motor reaches the original set speed of 100 rad/second, the average torque required to run the motor at the original set speed of 100 rad/second will be zero from $t=2.2$ second onwards.

The plot of the 3Φ stator currents ($i_{s-abc}$) with time for the variation in speed from 100 to 120 rad/second and back to normal is shown in Fig. 6.17. 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 in the flux characteristics during the change in speed is that, during speed variation, the flux varies slightly, as shown in Fig. 6.18.

**Fig. 6.17:** Stator current char. for speed variation from 100 to 120 r/s and back

**Fig. 6.18:** Flux char. for variation of speed from 100 to 120 rad/second and back
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 is shown in Fig. 6.19.

![Load characteristics for variation in speed](image1)

**Fig. 6.19:** Load char. for variation of speed from 100 to 120 and back

![Plot of variation of speed with time](image2)

**Fig. 6.20:** Plot of variation of speed with time for clockwise and anticlockwise rotation of IM

The performance of the developed method in this chapter also demonstrates the effectiveness of the sudden variation of speed from
clockwise to anticlockwise rotation (-50 rad/second to +50 rad/second with specific amount of time) to obtain stability (which is shown in Fig. 6.20). The simulation results demonstrate the good damping performance of the designed robust controller despite speed fluctuations.

**Fig. 6.21: Slip char. for varying speeds (50, 100, 140, 180 rad/second)**

Another significant contribution of this chapter is the slip characteristic curves for variable speed of IM. The speed is varied from 50 rads/second (477 rpm) to near the rated speed of 180 rads/second (1717 rpm). For the sake of convenience, 4 cases of variation in speed are considered, viz., 50 rad/second (477 rpm), 100 rad/second (955 rpm), 140 rad/second (1335 rpm) and 188.5 rad/second (1717 rpm). The simulation is run for a period of 3 second and the quantitative results of the slip vs. time for various speeds are shown in Table 6.1 along with the simulation results in Fig. 6.21.
From these results, we infer that the slip is more for low speed operation of the induction motor and it is very less when the IM operates close to the rated speeds. Moreover, the slip characteristics look linear in nature due to the incorporation of the TS-based fuzzy controller, which is the highlight of this simulation result.

**Table 6.1: Quantitative results of slip characteristics for various speeds**

<table>
<thead>
<tr>
<th>No.</th>
<th>Speed (r/s)</th>
<th>Slip (%)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.75</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.46</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>0.28</td>
<td>1.05</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>0.04</td>
<td>1.4</td>
</tr>
</tbody>
</table>

**6.7 SUMMARY**

The TS-based FLC drive system was developed in this chapter by using Matlab simulink environment. The simulation was run for a period of 3 second and performance characteristics are observed. The TS-based FLC provides control commands for generating gating signal. The inverter terminal voltage controlled by these gating signals, in turn control the speed of drive. It was observed that the motor reaches the set speed very quickly in a lesser time, i.e., only **0.7 second** to reach the set speed (**100 rad/second**). The performance of
the developed method in this chapter also demonstrates the effectiveness of the sudden variation of speed (because of parametric variation) from the normal value and its effects on various parameters (such as slip, current, torque, etc.) to obtain stability. The simulation results demonstrate the good damping performance of the designed robust controller despite speed fluctuations.

The simulation results show that the TS-fuzzy controller provides faster settling times, and has very good dynamic response and good stabilization. The main advantages of the designed TS-based fuzzy scheme is it is computationally efficient, works well with linear techniques, works well with optimization, works well for clockwise and anticlockwise rotation of the IM and the adaptive techniques and has guaranteed continuity of the output surface. To achieve still better performance of the controller, a new type of controller, called the adaptive neuro fuzzy-based controller, can be used to control the speed of the IM, which is depicted in a further chapter.