CHAPTER 4

WAVELET FUZZY BASED SELF-TUNING CONTROLLER
FOR INDUCTION MOTOR DRIVES

4.1 INTRODUCTION

The wavelet based speed controller for induction motor drive which is presented in the previous chapter, has fixed scaling gain values. The choice of appropriate gain values plays an important role in the performance of the wavelet based controller (Parvez and Gao 2005). Therefore a self-tuning mechanism is proposed for online tuning of the scaling gains of the wavelet based controller. The self-tuning mechanism uses fuzzy logic for tuning the scaling gains. Thus, the controller combines the advantage of wavelet transform and fuzzy logic.

The proposed wavelet fuzzy based self-tuning (WFST) controller is simulated for IFOC of induction motor drive and the results are presented. The stability of the proposed controller is discussed in this chapter. The simulation results are compared with conventional controller, fuzzy based controller and wavelet based controller.

Part of the thesis work reported in this chapter has been published as detailed below:

4.1.1 Fuzzy Logic Control

Fuzzy logic is a technique to incorporate human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, the process people use to infer conclusions from what they know. Fuzzy logic control is primarily applied to the control of processes through fuzzy linguistic descriptions. Fuzzy logic control essentially embeds the experience of the designer of a system (Ian Shaw 1998).

Fuzzy logic control is basically an adaptive and nonlinear control, which gives better performance for a linear or nonlinear system which is ill defined with parameter variations. Fuzzy logic control is the best among all the adaptive control techniques (Bose 2006). The main advantages of this control are its simplicity, adaptability and good performance. Complex nonlinear mapping of system's dynamics through terminal characteristics can be obtained without the need for structured models. These controllers can satisfy design objectives that are difficult to express mathematically in linguistic or descriptive rules. The superior noise rejection capability and the tolerance to the system fluctuations are some of the key advantages over the classical control. They tend to be fast, simple and straightforward. The structure of a fuzzy logic controller is shown in Figure 2.6 (Ian Shaw 1998).

Controllers that combine the advantage of intelligent techniques such as fuzzy logic control and conventional controllers are commonly used in the intelligent control of complex dynamic systems. In these types of control systems, the fuzzy logic control will be a portion of the total control system. Fuzzy logic control is also combined with other intelligent techniques such as neural network to produce interesting results (Moallem et al 2001). In the proposed work, the advantages of wavelet transform and fuzzy logic are combined together to produce a novel speed controller for IFOC of induction motor drive. Wavelet transform is used to decompose the speed error into
different frequency components and fuzzy logic control is used to generate the scaling gains of the different frequency components.

### 4.2 RELATIONSHIP BETWEEN WAVELET TRANSFORM AND FUZZY LOGIC

A major challenge to fuzzy logic is the translation of the information contained implicitly in a collection of data points into linguistically interpretable fuzzy rules. Neuro-fuzzy methods have been developed for this purpose (Bose 1994). A serious drawback with most neuro-fuzzy methods is that they do often furnish rules without a transparent interpretation. Because of this difficulty they have not yet reached a widespread acceptance in industrial applications, despite the good performance they offer with a reduced design effort (Chao and Liaw 2008).

A solution to this problem is furnished by multiresolution techniques (Mallat 1987). The basic idea is to use a dictionary of membership functions forming a multiresolution and to determine which membership functions are the most appropriate to describe the system. In order to associate a linguistic interpretation to each membership function, the membership functions are chosen among the family of scaling functions that have the property to be symmetric, everywhere positive and with single maxima. The main advantage of using a dictionary of membership functions is that each term, such as negative large (NL), negative small (NS), zero (ZE), positive large (PL) and positive small (PS) are well defined beforehand and is not modified during learning (Thuillard 2000).

The multiresolution properties of the membership functions in the dictionary permits to fuse or split membership functions quite easily so as to put the control surface under a linguistically understandable and intuitive
form for the human expert. Different techniques, generally referred by the term fuzzy-wavelet, have been recently published.

In the Takagi-Sugeno model, the fuzzy rules are expressed under the form (Thuillard 2000)

$$R_i: \text{If } x \text{ is } A_i \text{ then } y = f_i(x)$$

(4.1)

where \( A_i \) are linguistic terms, \( x \) is the input linguistic variable, while \( y = (y_1, \ldots, y_j, \ldots y_{max}) \) is the output variable. The value of the input linguistic variable may be crisp or fuzzy. If the value of the input variable is a crisp number then the variable \( x \) is called a singleton.

For a crisp input, the output of the fuzzy system is given by

$$\hat{y}_j = \sum_i \hat{a}_i \cdot f_j(\hat{x})/\sum_i \hat{a}_i$$

(4.2)

In the equation (4.2) \( \hat{a}_i \) is the degree of fulfilment and is given by \( \hat{a}_i = \mu_{A_i}(\hat{x}) \), where \( \mu_{A_i}(\hat{x}) \) is the membership function to the linguistic term \( A_i \). In many applications, a linear function is taken of the form \( f(\hat{x}) = a^T \cdot \hat{x} + b \). If a constant \( b \) is chosen to describe the crisp output \( y_i \), the system becomes

$$R_i: \text{If } x \text{ is } A_i \text{ then } y = b$$

(4.3)

If spline functions \( N^k \) are taken, as membership function \( \mu_{A_i}(\hat{x}) = N^k(2^m(\hat{x} - n)) \) then the system is equivalent to:

$$\hat{y}(x) = \sum b_i \cdot N^k(2^m(\hat{x} - n))$$

(4.4)
In this case, the output $y$ is a linear sum of translated and dilated splines. This means that under this last form the Takagi-Sugeno model is equivalent to a multiresolution spline model. It follows that wavelet-based techniques can be combined with fuzzy logic (Thuillard 2000).

**4.2.1 Initialization of Wavelet Parameters**

Due to the fact that wavelets are rapidly vanishing functions, a wavelet may be too local if its dilation parameter is too small. If the translation parameter is not chosen appropriately, it may go out of the domain of control. Therefore, it is very much essential to initialize the dilation and translation parameters. Different initialization procedures are available, but the simple and the most commonly used heuristic initialization procedure (Thuillard 2000) is used to initialize the wavelet parameters in the proposed wavelet fuzzy based induction motor control. Heuristic procedure takes into account the domain of input space where the wavelets are not zero.

Let the mother wavelet be (Stang and Nguyen 1997):

$$
\Psi(x) = -x e^{-\frac{1}{2}x^2} \tag{4.5}
$$

Let $[a_k, b_k]$ denote the domain containing the values of the $k$-th component of the input vectors. The centre of wavelet $m$ is initialized at the centre of the vector defined by the intervals $[[a_k, b_k]]$. For the $k^{th}$ input, the translation parameters are initialized to:

$$
c_{m,k} = \frac{1}{2} (a_k + b_k) \tag{4.6}
$$

The dilations parameters of wavelet are initialized to:

$$
d_{m,k} = \frac{1}{5} (b_k - a_k) \tag{4.7}
$$

These initializations guarantee that the wavelets extend initially over the whole input domain (Stang and Nguyen 1997).
4.3 WAVELET FUZZY BASED CONTROLLER

The schematic of the wavelet fuzzy based speed controller is shown in Figure 4.1. The error speed which is the difference between the command speed and actual speed is applied as input to both the wavelet transform block and fuzzy logic control block. The wavelet transform decomposes the speed error into approximate and details components up to level two using DWT. The fuzzy logic control operates on the speed error and the derivative of the speed error to generate the scaling gains $k_{d^1}$, $k_{d^2}$ and $k_{a^2}$ for the respective frequency components $e_{d^1}$, $e_{d^2}$ and $e_{a^2}$.

![Figure 4.1 Schematic of the proposed wavelet fuzzy based speed controller for IFOC of Induction motor drive](image)

The scaling gains are multiplied with their frequency components and summed up together to generate the control signal for the IFOC of induction motor drive. The performance of the speed controller is further improved introducing an online self-tuning algorithm for generating the scaling gains of the wavelet based speed controller. A self-tuning algorithm is
proposed for updating the scaling gains which are generated by the fuzzy logic control.

4.4 WAVELET FUZZY BASED SELF-TUNING CONTROLLER

The self-tuning of fuzzy logic can be obtained by using a tuning algorithm to directly adjust any one of the following: i) the fuzzy rules ii) the membership function iii) the scaling factors.

Figure 4.2 Schematic of the proposed wavelet fuzzy based self-tuning controller for IFOC of Induction motor drive

In the recent literatures, the highest priority is given to tuning the scaling factors. In the proposed, the real time tuning of the scaling factors is performed to get the desired performance using the wavelet fuzzy based self-tuning controller. The schematic of the controller is shown in Figure 4.2.
The self-tuning mechanism consists of a performance model, evaluation block and fuzzy logic control (FLC) block (Masiala et al 2008). The reference model describes the dynamic performance of the drive. For an induction motor, the reference model can be approximated by a second order system.

Figure 4.3  Control system block diagram of the Induction Drive

The dynamic behavior of the IFOC of induction motor drive can be represented by the control system block diagram shown in Figure 4.3.

\[ T_e = k_t i_{qs}^* \quad (4.8) \]

\[ k_t = \left( \frac{3P}{4} \right) \left( \frac{l_m}{l_r} \right) i_{ds}^* \quad (4.9) \]

\[ H_P(s) = \frac{1}{Js+B} \quad (4.10) \]

where \( L_m \) is the magnetizing inductance per phase, \( L_r \) is the rotor inductance per phase referred to stator, \( P \) is the number of poles, \( i_{qs}^* \) is the torque current command, \( i_{ds}^* \) is the flux current command, \( J \) is the mechanical inertia and \( B \) is the friction coefficient. The approximated second order model is obtained from the control system model as (Masiala et al 2008):
The constants $a$ and $b$ are obtained by substituting the values of motor parameters in eq 4.8 - 4.10 and they are adjusted to meet the specific requirements of induction motor investigated in the proposed work. In this case $a = 47,000$ and $b = 180$.

The actual speed of the motor $\omega_r$ is compared with the output from the reference model $\omega_r'$, to generate the speed signal $e_r'$, which is the difference between $\omega_r$ and $\omega_r'$. This error signal is given as input to the evaluation block. The evaluation block is designed in such a way that, if the error signal is within $\pm 1$ rad/sec, the self-tuning mechanism will not operate. If the error $e_r'$ exceeds the specific range of $\pm 1$ rad/sec, the evaluation block generates the tuning error $e_{\omega}$ to be given as input to Takagi Sugeno-fuzzy logic control (TS-FLC) block. The TS-FLC operates on this error signal to generate the online weight values $w_e$ and $w_{de}$. These weight values are used to generate the scaling factors $n_e(k)$ and $n_{de}(k)$ of the self-tuning FLC. The scaling factors are generated at each step as

\[
n_e(k) = n_e(k - 1)[\alpha w_e(k)] \tag{4.12}
\]

\[
n_{de}(k) = n_{de}(k - 1)[\beta w_{de}(k)] \tag{4.13}
\]

where $\alpha$ and $\beta$ are weight constants. They are taken as arbitrary values. The value of $\alpha$ is taken as 0.7 and $\beta$ as 0.4. The self-tuning FLC operates on the actual speed error $e$ and the scaling factors to generate the scaling gains $k_{d^1}$, $k_{d^2}$ and $k_{a^2}$, which are used to tune the high, medium and low frequency components of the error signal $e_{d^1}$, $e_{d^2}$ and $e_{a^2}$ respectively.
4.4.1 Self-tuning Fuzzy Logic

The structure of the self-tuning FLC block is shown in Figure 4.4 (Masiala et al 2008). The inputs are speed error \( e(k) \), which is the difference between command speed and actual speed and change in error \( de(k) \). \( w_e \) and \( w_{de} \) are the weight values obtained from the TS-FLC block. These weight values are varied online to tune the FLC block. The basic FLC block consists of fuzzy interface (Fuzzification), fuzzy rules (Rule Base), fuzzy inference (Inference Machine) and defuzzification interface (Defuzzification). The basic FLC block is shown in Figure 2.6.

![Figure 4.4 Structure of Self-Tuning FLC Block](image)

The input and output variables are fuzzified using five membership functions normalized between +1 and -1. The range of input and output variables can be changed by altering the scaling factors of \( n_e(k) \) and \( n_{de}(k) \) of the self-tuning fuzzy logic controller. Centroid method of defuzzification is used to convert the fuzzy values into crisp values. The weight values of the self-tuning fuzzy logic are generated with five membership functions and 25
rules, using the TS-FLC block. In the design of the rule base, the look up table is created offline, using data obtained during simulation under different operating conditions such as sudden changes in the command speed, load torque disturbances and change in stator resistance. The fuzzy look up table is given in Table 2.1.

The scaling factors are updated only when the error $e'_r$ is greater than $\pm 1 \text{ rad / sec}$. The tuning of the FLC is performed according to a simple predefined performance index. The integral time absolute error (ITAE) criterion is used as the performance index. The ITAE criterion is used to locally optimize the controller and evaluate the degree in which the current set parameters satisfy the formulated objective. The ITAE criterion is represented as (Martins 2005)

\[
\text{ITAE} = \int_0^{t_{max}} t \cdot |e_\omega(t)| \, dt 
\]

(4.14)

where $t_{max}$ is the maximum time. The ITAE performance index has the advantages of producing better optimization than the other performance indices such as the integral of the absolute error (IAE) and the ISE (integral square error) criterion. In addition, the ITAE criterion is more sensitive and it has the best selectivity (Martins 2005).

If the speed error $e_\omega$ is not within the specified limit, the TS-FLC block operates as follows (Nasir Uddin et al 2002)

If \{ $e_r$ is ZERO and $de_r$ is ZERO \}

THEN \{ $w_e$ is ZERO and $w_{de}$ is ZERO \}

(4.15)
The \( n_e \) and \( n_{de} \) values are calculated from \( \omega_e \) and \( \omega_{de} \) using (4.12) and (4.13). This self-tuning mechanism optimizes the proposed controller to ensure better speed control.

### 4.4.2 Control Algorithm

The flowchart for implementing the proposed WFST controller for IFOC of induction motor drive is shown in Figure 4.5. The speed error which is the difference between the command speed and the actual speed is computed and is given as input to the proposed wavelet fuzzy based self-tuning controller.

The speed error is decomposed into different frequency components using wavelet transform. The optimum level of decomposition is selected as two and the db4 wavelet of Daubechies wavelet family is selected as the optimum wavelet function. The wavelet coefficients of different frequency bands are generated using DWT.

The initial values of the scaling gains are fixed by trial and error method and the speed controller is simulated under different conditions. The lookup table for the fuzzy logic is constructed offline during simulations using PI controller under different conditions such as load torque disturbances, sudden changes in command speed, change in moment of inertia and change in stator resistance. The speed error and the change in speed error data are collected and are used for generating the look up table.
Figure 4.5 Flowchart for implementing the proposed WFST controller
The speed error is also given as input to the self-tuning fuzzy logic control. The TS-FLC along with the reference model generates the weight values required for updating the scaling factors of the self-tuning fuzzy logic control. The self-tuning fuzzy logic control generates scaling gains of the controller. The self-tuning fuzzy logic generates the scaling gains for the proposed wavelet fuzzy based controller. However, the self-tuning algorithm works only if the speed error between the actual speed and the reference model speed is ±1 rad/sec. The scaling gains were updated online according to the self-tuning algorithm. The scaling gains are combined with the corresponding wavelet coefficients to generate the electromagnetic torque component command for the induction motor drive. The torque component command generated by the WFST controller is used to perform the indirect field oriented control of induction motor drive.

4.4.3 Stability Analysis

The Scaling gains of the proposed controller have been determined by the self-tuning fuzzy logic control. The scaling gains are updated according to the self-tuning control algorithm. The stability of the proposed controller depends on the performance of the self-tuning fuzzy logic control algorithm. A promising approach to stability analysis of such fuzzy based control systems is the passivity approach, since it can lead to general conclusions on the absolute stability of broad classes of nonlinear control systems, using only some general characteristics of the input-output dynamics of the controlled system and on the input-output mapping of the controller (Calcev et al 1998). Hence, the stability of the self-tuning fuzzy logic in the speed control loop can be analyzed using the passivity approach.
The mapping between the input and output of the self-tuning fuzzy logic can be in general described by the mamdani fuzzy function as

\[ u_k = \frac{\sum_{i,j} \left( \mu_{E_i(e_1)} \cap \mu_{E_j(e_2)} \right) u_{n(i,j)}}{\sum_{i,j} \left( \mu_{E_i(e_1)} \cap \mu_{E_j(e_2)} \right)} \]  

(4.16)

where \( e_1 \) is the error \( e(k) \) at time instant \( k \), \( e_2 \) is the change in error \( de(k) \), \( u_k \) represents the output of the fuzzy logic control, \( E_i, E_j \) and \( u_{n(i,j)} \) are the linguistic variables of \( e_1, e_2 \) and \( u_k \) respectively, and \( \cap \) denotes the intersection operator of the fuzzy sets. The fuzzy logic control considered in this work share the same distinguished characteristics such as

1) The fuzzy control rules are symmetric about the off-diagonal of the fuzzy rule matrix.

2) The numeric value in the fuzzy table gradually increases / decreases from left to right within a row, while within a column it gradually increases / decrease from top to bottom.

3) The control decision corresponding to the central element of the rule table is usually zero and the value around the central area is small.

The self-tuning fuzzy logic, which has the specific sectorial properties of the mapping are classified as sectorial fuzzy control (SFC). The properties of SFC are as follows (Calcev 1998)

1) The summation of membership function values is one.

\[ \sum_{i=-N}^{N} \mu_{E_i}(e) = 1 \]  

(4.17)
2) For the input value outside of the range of \([-L, L]\)
\[ e > L \quad \Rightarrow \quad \mu_{E_N}(e) = 1 \quad \text{and} \quad e < -L \quad \Rightarrow \quad \mu_{E_{-N}}(e) = 1 \] (4.18)

3) \(E_i\) and \(E_{-i}\) cover intervals which are symmetric with respect to zero.
\[ 0 \leq \mu_{E_i}(e) = \mu_{E_{-i}}(-e) \leq 1 \] (4.19)

4) At one time, each input value fires at most two adjacent fuzzy sets, with complementary membership grades.
\[ |i - j| > 1 \quad \Rightarrow \quad \mu_{E_i}(e)\mu_{E_j}(e) = 0 \] (4.20)

5) The fuzzy sets for the input membership functions must be convex.
\[ \mu_{E_i}(e) \geq \min[\mu_{E_j}(e), \mu_{E_j}(e')] \] (4.21)

The self-tuning fuzzy logic control satisfies all the properties mentioned above and it come under the category of SFC. Using passivity approach the stability of the SFC is derived as below. The mathematical formulations of the following stability theorem have been adapted from the reference (Calcev 1998)

According to the definition of passivity, a continuous time system with input \(y(.) : R \rightarrow R\), output \(u(.) : R \rightarrow R\) and the state vector \(x \in R^n\) is said to be passive if there exist a continuous nonnegative real-valued storage function \(V(x)\), with \(V(0) = 0\) and a supply rate \(W(y(\tau), u(\tau)) = y(\tau)u(\tau)\), such that the following dissipation inequality holds \(\forall t > 0, u \in U, x(0) \in X:\)
\[ V(x(t)) - V(x(0)) \leq \int_0^t W(y(\tau), u(\tau))d\tau \] (4.22)
where \(U\) is the control decision.
If the supply rate is:

- \( W(y(\tau), u(\tau)) = y(\tau), u(\tau) - \varepsilon y(\tau)^2, \varepsilon > 0 \), then the system is said to be input strictly passive.

- \( W(y(\tau), u(\tau)) = y(\tau), u(\tau) - \varepsilon u(\tau)^2, \varepsilon > 0 \), then the system is said to be output strictly passive.

- \( W(y(\tau), u(\tau)) = y(\tau), u(\tau) - \varepsilon_1 y(\tau)^2 - \varepsilon_2 u(\tau)^2; \varepsilon_1, \varepsilon_2 > 0 \), then the system is said to be input and output strictly passive.

One of the main advantages of passivity theory is that the stability of the feedback systems can be concluded from the passivity properties of connected systems. So, if proved that a subsystem in a feedback loop is passive, a sufficient condition for the stability of zero solution is the passivity of the other subsystem of feedback loop. In general, the SFC satisfies the passivity conditions and can be proved to be stable for all times.

Proof:

Consider the following single input single output system driven by an SFC with state access

\[
\dot{x} = f(x) + G(x)u \\
\zeta = h(x) \\
\dot{\zeta} = \zeta \\
u = \Phi(e, \dot{e}) \\
e(t) = y_d - y(t)
\]
where \( x \in X \subset R^n, \zeta \in R, u \in R \) and \( f(x):X \to R^n, f(0) = 0, G(x):X \to R^n, h(x):X \to R, h(0) = 0 \) are smooth functions, \( e \) denotes the error between \( y_d \) and \( y \), the desired and measured outputs, and \( \Phi: R X R \to R \in C^1 \) is a control function (nonlinear mapping implemented by a SFC). We impose the restriction that the system is completely reachable and zero-state detectable (that is, \( u(t) = 0 \) and \( \zeta(t) = 0 \) implies \( \lim_{t \to x} x(t) = 0 \)). It is imposed as well that the system is well defined (Calcev 1998).

It is obvious that the origin is an equilibrium point. The main goal is to give sufficient conditions for stability of zero solution of fuzzy control system where the controller is an SFC. The stability of a fuzzy control system driven by an SFC can be formulated as a simple consequence of the passivity property of SFC.

A sufficient condition for asymptotic stability of zero solution of the fuzzy control system is that the input and output is strictly passivity of the subsystem \((f, G, h)\). If the subsystem is only passive, then the zero solution of the feedback control system is Lyapunov stable (Calcev 1998).

Indeed, from the odd symmetry of nonlinear mapping \( \Phi(., .) \) it results that for null set point \( y_d = 0 \), \( \Phi(e, \dot{e}) = \Phi(-y, -\dot{y}) = -\Phi(y, \dot{y}) \). Then, by applying passivity theorems, it results the sufficient condition for asymptotic stability of \( \zeta \) is input and output strictly passivity of \((f, G, h)\) (Calcev 1998).

The proposed WFST controller, which consists of two fuzzy blocks, satisfies the properties of the SFC and hence can be considered as a SFC. Hence, the proposed wavelet fuzzy based self-tuning controller is stable at all times. Since the controller is stable, the overall closed loop speed control system is also stable.
4.5 SIMULATION OF THE WAVELET FUZZY BASED SELF-TUNING SPEED CONTROLLER

The of the proposed WFST controller for induction motor drive is simulated using Matlab/Simulink for different operating conditions. A 1.47 kW squirrel cage induction motor is used for investigation of the proposed controller. The switching frequency of the PWM signal is 2 MHz and hence the sampling time of simulation is fixed as 2 μsec. The performance of the induction motor drive is investigated for step change in command speed, step change in load and variation of motor parameters. The rise time, the peak over shoot and undershoot, the steady state error and root mean square error (RMSE) are selected as performance indices for the proposed wavelet fuzzy based self-tuning controller.

4.5.1 Results and Discussion

The starting performance of the induction motor drive is investigated using the proposed wavelet fuzzy based self-tuning controller for the rated speed of 183.3 rad/sec. at no load and with load. The starting performance is shown in Figure 4.6 is for no load condition and in Figure 4.7 when the motor is started with a load of 2.5 Nm. The induction motor drive has followed the command speed with negligible steady state error and without any overshoot under both the conditions. The proposed controller takes less than 0.1 sec to settle under both no load and with load conditions. The command torque component current \( i_{qs} \) and the motor line current \( i_a \) are shown in the figure for both the cases. The \( i_{qs} \) current has settled down to constant value during steady state region at the rated load condition of the
induction motor drive. The starting performance of the induction motor drive is simulated with the command speed of 91.7 rad/sec which is half of the rated speed is shown in Figure 4.8. The induction motor drive followed the command speed with less steady state error and almost without any overshoot. The controller takes less than 0.07 sec to settle to the steady state value.

The performance of the induction motor drive with the proposed controlled is analyzed for above rated speed condition. The motor is simulated with a command speed of 229.1 rad/sec which is 125 % of the rated speed. The responses are shown in Figure 4.9. The proposed WFST controller based induction motor drive is able to settle to the command speed in 0.15 sec. The motor line current ($i_a$) and the command torque component current ($i_{qs}$) and shown in Figure 4.8 (a) and (b) respectively.

The speed and current response of the induction motor drive with step increase in command speed from 120 rad/sec to 180 rad/sec at $t = 0.5$ sec is shown in Figure 4.10. The proposed WFST controller has successfully tracked the step increase in command speed in less than 0.07 sec. The performance of the WFST controller for step decrease in speed is investigated in Figure 4.11. The command speed is decreased from 150 rad/sec to 90 rad/sec. The controller followed the command speed with less overshoot and less steady state error.

The performance of the WFST controller in the IFOC of the induction motor drive is investigated for step change in load. Figure 4.12 shows the performance when the motor is started at no load with a command speed of 180 rad/sec and 25 % of rated load is applied at $t = 0.5$ sec. The drive
system handled the sudden impact of load with almost zero steady state error. The command torque component current $i_{qs}^*$ has changed to a new level in order to handle the sudden change in load torque of the induction motor drive.

The performance of the induction motor drive using the WFST controller is investigated for sudden decrease in load. The induction motor drive is started with 25% of rated load at a command speed of 180 rad/sec. The load is then fully removed at $t = 0.5$ sec and the performance is shown in Figure 4.13. The induction drive has settled to the steady state even after the removal of load with a small overshoot. The command torque component current provided sufficient torque to drive the induction motor when started with load.

The performance of the proposed controller is studied for change in motor inertia considering the effect of a high inertia machine connected to the induction motor drive. Figure 4.14 shows the speed and the current responses when then the rotor inertia of is doubled at no load, with a command speed of 180 rad/sec. The drive system has followed the command speed. The motor line current $i_a$ and the command torque component current $i_{qs}^*$ and are shown in the Figure.

The performance of the induction motor drive using the WFST controller is investigated for change in stator resistance. The responses of the proposed controller based induction motor drive for doubled stator resistance at no load with a command speed of 180 rad/sec is shown in Figure 4.15. The drive system has followed the command speed quickly. However, the settling time of the response is higher when compared to the normal operation.
Figure 4.6 Simulated starting responses of the proposed WFST controller based induction motor drive at no load with a command speed of 183.3 rad/sec (Rated speed) (a) Speed (b) Line current (c) q-axis command current
Figure 4.7 Simulated starting responses of the proposed WFST controller based induction motor drive with 2.5 Nm load and a command speed of 183.3 rad/sec (Rated speed)
(a) Speed (b) Line current (c) q-axis Command current
Figure 4.8 Simulated starting responses of the proposed WFST controller based induction motor drive at no load with a command speed of 91.7 rad/sec (50% of Rated Speed)  
(a) Speed (b) Line current (c) q-axis Command current
Figure 4.9  Simulated starting responses of the proposed WFST controller based induction motor drive at no load with a command speed of 229.1 rad/sec (125% of Rated Speed)  
(a) Speed (b) Line current (c) q-axis Command current
Figure 4.10  Simulated responses of the proposed WFST controller based induction motor drive at no load for step increased in command speed from 120 rad/sec to 180 rad/sec at t = 0.5 sec (a) Speed (b) Line current (c) q-axis Command current
Figure 4.11  Simulated responses of the proposed WFST controller based induction motor drive at no load for step decrease in command speed from 150 rad/sec to 90 rad/sec at $t = 0.5$ sec
(a) Speed (b) Line current  (c) q-axis Command current
Figure 4.12  Simulated responses of the proposed WFST controller based induction motor drive stated at no load and 25% of rated load is applied at $t = 0.5$ sec (a) Speed  (b) Line current  (c) q-axis Command current
Figure 4.13 Simulated responses of the proposed WFST controller based induction motor drive started with 25% of rated load and the load is removed at $t = 0.5$ sec (a) Speed (b) Line current (c) $i_{qs}^*$ (pu)
Figure 4.14 Simulated starting responses of the proposed WFST controller based induction motor drive for doubled rotor inertia, at no load with a command speed of 180 rad/sec
(a) Speed (b) Line current (c) q-axis Command current
Figure 4.15 Simulated starting responses of the proposed WFST controller based induction motor drive for doubled stator resistance, at no load with a command speed of 180 rad/sec

(a) Speed (b) Line current (c) q-axis Command current
Comparing the speed response of the proposed WFST controller shown in Figure 4.6 - 4.15 with the results of the conventional PI, the fuzzy controller and the wavelet controller discussed in chapter 2 and 3, the performance of the proposed WFST controller is better in terms of less steady state error, quick settling time and lesser overshoot.

The comparative performance for simulation results of the induction motor drive using the propose wavelet fuzzy based self-tuning controller and the controllers discussed in chapter 2 is shown in Table 4.1 - 4.4 for different operating conditions. The rise time, speed overshoot, speed undershoot, settling time and steady state error of the induction motor drive are used for comparative analysis.

Table 4.1  Comparison of the simulated starting performance of the induction motor drive at no load and the rated command speed of 183.3 rad/sec

<table>
<thead>
<tr>
<th>Controller</th>
<th>Rise Time (msec)</th>
<th>Overshoot (%)</th>
<th>Steady State Error (rad/sec)</th>
<th>Settling Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Controller</td>
<td>122</td>
<td>2.4</td>
<td>2.6</td>
<td>0.86</td>
</tr>
<tr>
<td>PID Controller</td>
<td>118</td>
<td>1.8</td>
<td>1.8</td>
<td>0.78</td>
</tr>
<tr>
<td>Fuzzy based self-tuning Controller</td>
<td>112</td>
<td>1.2</td>
<td>0.4</td>
<td>0.26</td>
</tr>
<tr>
<td>Proposed Controller</td>
<td>87</td>
<td>0</td>
<td>0.2</td>
<td>0.087</td>
</tr>
</tbody>
</table>
Table 4.2  Comparison of the simulated starting performance of the induction motor drive with a load of 2.5 Nm and the rated command speed of 183.3 rad/sec

<table>
<thead>
<tr>
<th>Controller</th>
<th>Rise Time (msec)</th>
<th>Overshoot (%)</th>
<th>Steady State Error (rad/sec)</th>
<th>Settling Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Controller</td>
<td>130</td>
<td>3.1</td>
<td>3.4</td>
<td>0.95</td>
</tr>
<tr>
<td>PID Controller</td>
<td>125</td>
<td>2.6</td>
<td>2</td>
<td>0.82</td>
</tr>
<tr>
<td>Fuzzy based self-tuning Controller</td>
<td>121</td>
<td>1.8</td>
<td>0.8</td>
<td>0.31</td>
</tr>
<tr>
<td>Proposed Controller</td>
<td>90</td>
<td>0</td>
<td>0.3</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 4.3  Comparison of the simulated speed performance for sudden change in load at the command speed of 180 rad/sec

<table>
<thead>
<tr>
<th>Controller</th>
<th>Undershoot (%)</th>
<th>Steady State Error (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI Controller</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td>PID Controller</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Fuzzy based self-tuning Controller</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Proposed Controller</td>
<td>0.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The comparative performance for simulation results of the induction motor drive using the propose wavelet fuzzy based self-tuning controller and the controllers discussed in chapter 2 is shown in Table 4.1 - 4.4 for different operating conditions. The rise time, speed overshoot, speed undershoot, settling time and steady state error of the induction motor drive are used for comparative analysis.

The comparison of the starting performance of the induction motor drive at the rated command speed is shown in Table 4.1 and 4.2 at no load and loaded conditions respectively. The comparative performance for sudden change in load is shown in Table 4.3.

**Table 4.4 The RMSE Results**

<table>
<thead>
<tr>
<th>Change in Speed</th>
<th>PI Controller</th>
<th>Fuzzy Controller</th>
<th>Wavelet Controller</th>
<th>Proposed WFST Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 183.3 rad/sec</td>
<td>32.48</td>
<td>29.32</td>
<td>29.29</td>
<td>27.42</td>
</tr>
<tr>
<td>0 - 120 rad/sec - 180 rad/sec</td>
<td>19.56</td>
<td>17.44</td>
<td>17.38</td>
<td>16.86</td>
</tr>
<tr>
<td>0 - 150 rad/sec - 90 rad/sec</td>
<td>22.85</td>
<td>21.18</td>
<td>21.09</td>
<td>20.42</td>
</tr>
<tr>
<td>0 - 180 rad/sec, Load applied at t = 0.5 sec</td>
<td>33.21</td>
<td>32.67</td>
<td>32.46</td>
<td>32.12</td>
</tr>
</tbody>
</table>

The effectiveness of the proposed controller is also validated by considering the root mean square error (RMSE) between the command speed and the
actual speed as the performance indicator. The RMSE values are shown in Table 4.4. It can be clearly seen that the RMSE values of the proposed WFST controller is lesser than the conventional PI controller, fuzzy based self-tuning controller and the wavelet controller.

4.6 SUMMARY

A novel wavelet fuzzy based self-tuning controller for IFOC of induction motor drive is developed and presented in this chapter. A new self-tuning structure is developed for the wavelet based controller in order to improve the drive’s performance. The drive system with the proposed controller is simulated using Matlab/Simulink software.

The performance of the controller is compared with conventional controller, fuzzy based self-tuning controller and wavelet based controller. The proposed controller gives fast responses to command speed and settles to the steady state without any overshoot. Further, it responds quickly to sudden changes of command speed. The drive system shows almost zero steady state error when the load is suddenly applied or removed.

The performance of the induction motor drive with the proposed controller is investigated also for change in system parameters like rotor inertia and stator resistance. The simulated results for the proposed controller are found to be better than conventional controller, fuzzy based self-tuning controller and wavelet based controller.