CHAPTER 1

INTRODUCTION

1.1 ELECTRICAL MOTORS

Electrical motor is an electromechanical energy converter that translates its input electrical energy into output mechanical energy. They are available for more than a century and are playing a very vital role in the development of modern technology. Better understanding of the energy conversion principles coupled with the evolution of new and improved materials have contributed to advanced machine design. The theory of finite element analysis which is introduced recently has helped in further development and design optimization of electrical motors. The advent of modern digital processors and massive development of power electronics and semiconductor devices have made revolutionary contribution in the control and application of these devices. The direct current (dc) motor, induction motor and synchronous motor are the most commonly used in industrial applications. As a result of tremendous research and advancements in technology, special machines such as brushless dc motor (BLDC), switched reluctance motor (SRM), permanent magnet synchronous motor (PMSM) and permanent magnet hysteresis motor are being successfully developed and used for industrial and commercial applications (Bose 2011).

The dc motor was dominating the field of variable speed drives until 1980. They are still used in industries for the advantages in terms of control. The drive configuration is simple with a converter. Torque control in
dc motor is very fast because of the inherent decoupling of field flux and armature magneto motive force (MMF). Below the rated speed, the dc armature voltage is controlled at constant field flux to control the torque for speed regulation. Above the rated speed, the field current is weakened at the rated armature current in order to control the speed at reduce torque. However, there are some limitations associated with dc motors such as low efficiency, high inertia, narrow range of speed variations, low load capability, inherently fast torque response and problems associated with commutators and brushes. They require periodic maintenance, which makes them less reliable (Bose 1994).

In the recent years dc motors have become obsolete and alternating current (ac) motors are invariably preferred. Before the advent of power semiconductor devices, they are commonly accepted for fixed speed operation. However, the advancements in power semiconductor devices and processor technology have expanded the use of them for variable speed applications in industries (Bose 1988). Among the ac motors, the induction motor, particularly the cage type, are by far most commonly used in constant and variable speed drives. They are simple in construction, economical, rugged, reliable and are available in a wide power range, including fractional kilowatt (kW) to multi-mega watt capacities. A substantial amount of utility energy is consumed by them. The dynamic control of induction motor drive depends on the exact modeling and estimation of motor parameters in addition to the complicated control circuits. But due to the technological advancements in control, signal estimation, digital signal processing (DSP) and application specific integrated circuits (ASIC), these drives are made economical and superior in performance, and their applications are fast increasing (Bose 2009).
A considerable amount of interest is developed on synchronous motor for variable speed drive in the recent years. Since the field of the synchronous motor is excited separately by dc source, they can operate at lagging, leading and unity power factor. Operating them near unity power factor not only reduces the armature copper loss but also the size of inverter with simple commutation and control circuits. The conventional wound field synchronous motor (WFSM) is large in size (Bose 1994). The dc excitation for the rotor can be provided through slip ring and brushes from dc supply. The excitation can be also made brushless with an ac exciter and a rotating bridge rectifier. Synchronous motor always runs at synchronous speed. The speed of the synchronous motor can be varied by varying the supply frequency, but if the speed is increased at constant voltage, because of the reduction in the air gap flux, the torque developed will be reduced. The requirement of extra dc supply, slip rings and brushes discourage this type of motor for high performance applications (Stemmler 2009).

Permanent Magnet (PM) synchronous motors are of more interest in the recent years. The stator winding of this motor is the same as that of WFSM, but the rotor winding is replaced by a permanent magnet. The advantage is the elimination of rotor loss, but at the same time the flexibility of field control is lost. PMSMs are more expensive than induction motors but have the advantage of higher efficiency (Bose 2006). PM synchronous motors are classified on the basis of the wave shape of induced emf as PM ac synchronous motor (PMSM) and PM dc synchronous motor commonly known as brushless dc motor (BLDC). PM dc synchronous motors have 15 % more power density than the PM ac synchronous motors. This is due to the fact that the ratio of the root mean square (RMS) value to peak value of flux density is higher in PM dc synchronous motors. Another major reason for the popularity of BLDC over PMSM is simplicity in control. In contrast to the PMSM which requires continuous and instantaneous absolute rotor position,
the BLDC motor requires only six absolute position feedback for its control operation, resulting in major cost reduction in the feedback sensor (Krishnan 2001).

1.2 SPEED CONTROL OF AC MOTORS DRIVES

The control and estimation of high power variable speed drives have gone through dynamic revolution over a long period of time. The advent of space vector theory of ac machines, advanced control estimation techniques, powerful digital signal processors, application specific integrated circuit (ASIC) chips, computer aided analysis, design and simulation tools and field programmable gate array (FPGA) have mainly contributed to these advancements. Fortunately, this control evolution has progressed in parallel with the advancement of power circuit elements such as high performance power semiconductor devices, multi-level converters and advance pulse width modulation (PWM) techniques. Modern artificial intelligent (AI) techniques, particularly neural network and fuzzy logic, are now advancing the frontier of ac drive technology (Bose 2011).

Traditionally cage type induction motors have been the main workhorse for high power drives. For higher end of power, wound field synchronous motors are preferred because of efficiency considerations. In general, an ac drive can have one, two or four quadrant capability. They can perform torque, speed or position control in the primary loop or outer loop. Also there are considerations of single and multi-motor drive, control accuracy, response time, robustness with load torque and parameter variation, sensor based and sensor less control, efficiency, reliability and line harmonics (Bose 1988).
1.2.1 Control Classification

The general control classification of ac drive is shown in Figure 1.1. Very broadly, the control can be classified as scalar control and vector control. In the first generation of ac drives, simple and generally low performance scalar control techniques were developed. In scalar control, only the magnitude of the space vector will be controlled and not the phase alignment. The simplest, inexpensive and extensively used scalar control is the open loop volts/Hz control. This control technique does not involve any complex feedback signal measurement or estimation. However, performance of the drive is poor. A drop in the input voltage decreases the air gap flux that reduces torque and speed. Similarly, higher load torque also reduces speed.

An advanced scalar technique, known as Direct Torque Control (DTC) or Direct Self Control (DSC) was introduced during 1980. In this scheme, the direct control of the torque and stator flux of the drive is made possible by the inverter voltage selection through a look up table. The DTC has considerably fast response than the traditional scalar control. It is somewhat simple to implement, since there is no feedback current loop, no need of PWM technique and no vector transformation is involved. The drive can easily operate in all the four quadrants. Sensor less control is also possible with this method. The DTC control is widely applied in both induction and synchronous motor drive and they have established considerable superiority over the open loop volts/Hz method. However, the drawbacks of DTC control are harmonic ripple in current, flux and torque that cause efficiency loss.

The vector control is a revolutionary invention that has brought resurgence in the high performance control of ac drives. With the present
trend, it appears that the vector control will emerge as a universal controller for ac drives. Using vector control, an induction motor drive can be made to operate like a separately excited dc motor. It is also known as decoupling, orthogonal or trans-vector control. The stability and sluggish response in a
scalar control drive vanish due to ideal vector control. There are two methods of vector control, direct and indirect method depending upon the method of unit vector generation for vector rotation. Sensor less vector control is also getting popular in the recent years. It is possible to estimate speed signal from motor voltages and currents by number of methods such as slip calculation, model reference adaptive system, speed adaptive flux observer, extended kalman filter and slot harmonics. All these estimation methods are complex and depend on machine parameters. Although sensorless vector control drives are commercially available, the parameter variation problem imposes a challenge in the accuracy of speed estimation.

A number of advanced control techniques for ac drives are represented in Figure 1.1. Most of the advanced controls use field oriented control (vector control) in the inner loop. One such is the adaptive control, which tends to adapt the drive control according to motor model and parameter variations and makes the system robust against parameter variations and load disturbances. Examples of this type of control are sliding mode control, model reference adaptive control and self-tuning control. Recently AI techniques are making a serious impact in electrical engineering, particularly in the area of intelligent control of ac motor drives. With a control based on AI, a system is said to be intelligent, adaptable and self organizing. Among all the AI techniques, fuzzy logic and neural networks have gained more popularity in the control applications of ac motors (Bose 2011). Although intelligent control is now in the frontier of advanced control technology, and shows a promising future, currently real time implementation of these control techniques in industries is very limited. This is the motivation for this thesis work.
1.3 LITERATURE REVIEW

The induction motor is the principal workhorse in industrial drives. Variable speed control of induction motor drives constitutes a vast, complex and evolutionary technology which has grown continuously during the last five decades. Detailed literature review pertaining to the following aspects is presented here:

- Conventional Controllers
- Adaptive Controllers
- Intelligent Controllers
- Wavelet based Controllers

1.3.1 Conventional Controllers

The conventional proportional integral (PI) and proportional integral derivative (PID) controller based control techniques were used in industrial drives for many years. These controllers are still being used due to their simple control environment, ease of design and low cost. They are also easy to implement and the gain values of the controllers can be fine tuned.

Classical frequency domain techniques such as the Bode plots and Nyquist diagrams are also used for designing fixed structure speed controllers for motor drives, the design would normally be done around a nominal value of the controlled plant. Generally, a sensitivity analysis would subsequently be done to ensure that the design specifications are met when the plant parameters change. Nichols chart lends itself rather well to the particular problem of representing parameter variations in a drive. The Nichols chart represents both phase and magnitude information on the same diagram unlike Bode plots which represent them separately (Balda and pillay 1990).
Shin et al (2003) proposed a new method of PI controller design for induction motor with parameter variation. The design is made in such a way that the controller compensates the electrical parameter dynamics as well as the inertia variation that exist in the motor. The design approach guarantees stable and reliable operation only for a specific range of parameter variation. Lin (1996) implemented a DSP based robust integral proportional (IP) induction motor servo drive and the dynamic model of the system at the nominal condition was identified by a curve fitting technique. Based on this model, an IP controller is designed according to the prescribed time domain position tracking specifications. The proposed system showed good performance but the design steps were complex and time consuming.

Jung et al (1997) investigated a PI type decoupling control scheme for high speed operation of induction motors. The system is investigated in simulation only for certain command speed. Liaw et al (1998) presented a quantitative design and implementation of PID controller with model-following response for motor drive. A quantitative design procedure was presented to derive the parameters of the controller. The effects of command change rate as well as control effort were also considered in the proposed design procedure.

Chou and Soltani (2006) presented a robust direct torque control and flux control of induction motor using a PI predictive controller. The PI predictive controller generated the voltage command vector for the inverter using the torque error signal and stator flux reference signal. But an additional PI controller was used to generate the torque reference signal. The tuning rule for PI gains of field oriented control (FOC) of induction motor was investigated by Gi-Won Chang et al (2000). They proposed a simple algorithm that, for each setting of PI gains, the maximum range of values of the relative rotor resistance was estimated for which global stability is guaranteed. However, the assumption of zero load torque is a drawback to this approach.
Hu et al (2004) presented the stability analysis and PI controller tuning for a speed sensorless vector controlled induction motor drive. The complete dynamic model of the sensorless vector controlled induction was derived and linearized around a chosen operating point. The characteristics equation is derived based on the stability conditions, from which the controller parameter values were obtained. But the drawback is that the performance of the drive is investigated for a particular operating point and not for a wide range of speeds. Lin (1996) has developed a robust speed controller for induction motor using extended Kalman filter (EKF) and recursive least square (RLS) method. The rotor resistance of the induction motor is identified using EKF estimator and the rotor inertia constant, the damping constant and the distributed load torque of the induction motor were estimated using RLS estimator. The PI controller parameters were tuned online using the estimated values.

Shin (1998) proposed an anti-wind up PI controller with integral state predictor for variable speed motor drives. He analyzed the windup phenomenon that happens in a conventional PI controller and proposed a new anti windup PI controller to improve the control performance of variable speed motor drives. Experimental results have been presented to prove the effectiveness of the proposed controller. Shin and Park (2012) further investigated an anti-wind up PID controller with integral state predictor for variable speed motor drives. They used the PID controller instead of PI controller. Tista et al (2010) have presented a particle swarm optimization (PSO) method to determine the optimal PI and PID controller parameters for a vector controlled induction motor drive. The tuning of the controller parameters was done offline. However, the effects of parameter variation and moment of inertia have not been considered.
Wang et al (2011) developed a weighted tuning of PI speed controller for induction motor. The weighted tuning of the PI controller is based on Zeigler-Nichols tuning formula. However, the performance of the drive was investigated only for step change in speed and not with load disturbances and other parameter variations. Mermoud et al (2010) presented a work on the evaluation of fractional order PI controller applied to induction motor speed control. The fractional order PI controller is simulated with in a field oriented control scheme using the mathematical model of induction motor.

Balda and Pillay (1990) proposed a speed controller design for vector controller permanent magnet synchronous motor drive with parameter variation. The frequency-domain technique known as quantitative feedback theory in conjunction with Nichols chart was applied to the design of fixed-structure speed controllers for a vector-controlled PMSM drive where the motor parameters vary between known limits. In order to check the ability of the controller to perform in the presence of parameter variations, the design was conducted with one set of motor parameters but implemented on another motor whose parameters were within the uncertainty range of the first. Experimental results were presented validating the design procedure and implementation.

Liu et al (2003) presented a novel two-degree-of-freedom optimal controller design for a permanent magnet linear synchronous motor position-control system. The parameters of the controller are obtained by using a frequency-domain optimization technique. A systematic design of the controller and the detailed implementation of the proposed system are discussed. The closed-loop control system had good transient responses and good load disturbance responses. In addition, the system has a good tracking ability. Several experimental results are provided to validate the theoretical analysis.
The PI and PID controllers are the more commonly used for industrial applications. Even though they are simple to design and easy to implement, tuning the controller parameters to get optimum gain values is not an easy task. They are very sensitive to parameter variations, change in load, change in command speed and other uncertainties. Moreover, the performance of these controllers varies with the operating conditions. They are usually designed in the linear region without considering the saturation region. For high performance applications of induction motor, the saturation region was also to be considered. To overcome the drawbacks of these conventional controllers, many adaptive control techniques started emerging.

1.3.2 Adaptive Controllers

Several adaptive control algorithms were developed and implemented in the recent years. Liaw et al (1988) designed and implemented an adaptive controller for current-fed induction motor drive. This model reference speed adaptive controller uses only the available information of the states and output of the reference model for its control action. The controller was designed using a reduced reference model to simplify the design without degrading the performance of the controller.

time-constant estimation and a recursive least square estimator. They also
designed an on-line IP controller using the estimated rotor parameters.

Jie and Thomas (1990) proposed a fast variable structure controller
(VSC) for induction motor drive. They presented a new current loop modeling
and control method which enhances the overall system performance. Shyu et
al (1999) have presented a robust variable structure speed control algorithm
for induction motor drive. They introduced an adaptive algorithm for tuning
the rotor time constant, in order to eliminate the effect of parameter variation
in the FOC of induction motor drive. Using this algorithm a novel variable
structure control for robust speed control was achieved.

Pan et al (1994) developed a fixed structure discrete time sliding
mode controller (SMC) for induction motor drives. The design is made in
such a way that the computation burden is less and the chattering
phenomenon and steady state error are eliminated. Zhang et al (2000)
proposed the idea of speed and flux sensorless sliding mode control of
induction motor. This approach combines the observer and controller action
such that sensorless sliding mode control is achieved. Adnan et al (2002)
designed and implemented a new sensorless sliding mode control algorithm
for field oriented control of induction motor. This control algorithm estimates
the rotor time constant along with the rotor speed and problems related to
integration process are eliminated. The speed estimate is made simple and
robust to parameter uncertainties. However the algorithm suffers from high
computational burden for real time implementation.

Slobodan and Milic (1993) proposed novel adaptation mechanism
for on-line tuning of the FOC of the induction motor. The proposed
adaptation scheme is based on the measurement of the terminal voltages that
are used as auxiliary information. The scheme is designed in such a way that
stator resistance fluctuations and nonlinearities within the analog processing
circuitry do not affect the estimated value of the rotor time constant. Seok and Sul (2001) presented a new approach adaptive for parameter tuning of induction motors used in high performance applications. In this approach, the tuning of each parameter is inherently independent of the information of other parameters.

Hang and sin (1991) developed an on-line version of the auto-tuning PID controller based on the cross-correlation technique. This new auto tuner is designed in such a way that it causes only minor perturbation on the normal operation of the process, needs little a priori information, and is robust to noise. However, the performance of the drive was not investigated in real time. Sazali and Faisal (1999) presented a self-tuning speed controller for induction motor drives. A PI controller combined with RLS parameter estimation method is used to regulate the speed and load variation. In order to obtain good tracking and control characteristics, the self-tuning PI controller is adopted and a design procedure is developed to find its parameters according to RLS method systematically.

Ziqian (2006) proposed a hybrid speed control algorithm with sliding-mode and self-tuning PI for induction motors. The self-tuning PI control is embedded into the sliding-mode control to avoid the chattering problem in the sliding-mode control. In addition, the PI parameters are adjusted automatically online to make the system robust. Simulation and experimental results of the proposed hybrid control technique is presented and compared with conventional control techniques.

Park and Kwon (2004) presented a simple and robust speed sensorless vector control of induction motor using stator current based model reference adaptive control (MRAC). In this algorithm the stator current is used as state variable for estimating the rotor speed. This method produced excellent speed estimation performance at low speed region and at zero speed.
However, the rotor time constant uncertainty still remained as a problem. Another simulation and experimental studies of model reference adaptive system for sensorless induction motor was done by Madadi Kojabadi (2005). In this scheme, an adaptive pseudo reduced-order flux observer is used instead of the adaptive full-order flux observer. Simulation and experimental results demonstrated that the convergence for the speed estimate is faster. However higher order harmonics and noises were present in the estimated speed.

Rashed et al (2006) developed an adaptive non-linear state feedback speed control scheme of a voltage fed induction motor in which, the control of torque and flux is decoupled. The estimation of rotor resistance is made in such a way that it is insensitive to stator resistance variation. However, in the generating mode of operation, the estimator is found to be at non minimum phase and thus the selection of estimator correction gain remained as a difficult task. Fabrice et al (2009) proposed an adaptive controller that locally achieves robust regulation of speed and flux in an induction motor with online estimation of all the electrical parameters. The performance of this controller was evaluated for different speed and changes in motor parameters. However the model suffers from high computational burden.

Ravi Teja et al (2012) proposed a new model reference adaptive controller for four quadrant vector controlled induction motor drives. The speed estimation does not involve computation of stator and rotor flux. The proposed MRAC-based speed sensorless vector control drive as well as the stator resistance estimation technique is simulated in Matlab/Simulink and implemented in real time using the DSPACE-1104 controller. Cristian et al (2006) performed a comparative study of adaptive and inherently sensorless observers for variable speed induction motor drives. Both these methods are theoretically investigated and implemented and the salient features are discussed.
A large number of adaptive control techniques and algorithms have been reported in the literatures in the recent years. These control techniques are relatively complex. The number of calculations involved in the estimation and design steps of these control algorithms is large. The computation burden is more and it also occupies more memory. Although good performance can be achieved using these methods, the performance will not be satisfactory under conditions such as large change in inertia, speed transients and large sampling time.

1.3.3 Intelligent Controllers

In the recent years, tremendous work is done by researchers on intelligent control of induction motor drives. They include fuzzy logic based controllers, neural network based controllers and hybrid controllers. The main advantages of them are adaptability and high performance. They can implement 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 of these controllers over the conventional controllers.

Vas et al (1997) presented the full fuzzy control of a DSP based high performance induction motor drive. They used four interacting fuzzy controllers to generate the input signals to the space vector PWM modulator. A fuzzy rule base with 64 rules was used in the fuzzy control structure. The control algorithm is implemented in a DSP based hardware environment. However, the control scheme was found to be more complex. Fonseca et al (1999) described the use of fuzzy logic control (FLC) for speed control of induction motor drives. The speed error and change in speed error are used as the inputs. Triangular membership function with overlapping is used to define the fuzzy rules. The FLC controller was been implemented in a 16/32 bit controller. Simulation and hardware results are presented for step change
in command speed. However, there is only a marginal improvement in the speed response of the fuzzy based controller when compared to the conventional PI controller.

Singh et al (1999) developed and implemented a fuzzy controller for integrated current controlled, converter–inverter fed cage induction motor drive. A fuzzy based PID controller was designed for the vector control of induction motor. However, the performance of the drive is investigated only for rated speed. Robyns et al (2000) presented a fuzzy logic based multi-model field orientation of an induction motor drive. The fuzzy logic was used to combine two different models of computing the stator frequency. The fuzzy logic controller is designed based on a theoretical sensitivity analysis taking into account, the magnetic saturation. The control scheme is implemented in a DSP controller. Chao and Liaw (2000) presented a fuzzy based robust speed controller for detuned field oriented induction motor drive. The control algorithm uses a PI controller with two degree of freedom along with a fuzzy robust controller (FRC), which compensates the dynamic speed response during parameter variations. Simulation and experimental results are presented to prove the effectiveness of the proposed controller.

Dragan et al (2001) presented a novel method for the design of a fuzzy logic controller with near-optimal performance for a variety of operating conditions. The first stage of the control structure encompasses PID-like fuzzy controller and the second stage consists of placing an additional fuzzy controller in parallel with the PID-like fuzzy controller. The complete vector control scheme with FLC is implemented in real time. However, the computation burden of the control scheme is very high. Nasir Uddin et al (2002) proposed a novel speed control scheme of induction motor using FLC. In order to minimize the real-time computational burden, simple membership functions and rules were used. The complete induction
motor drive incorporating the FLC was implemented in real time using a DSP controller board DS 1102 for a 0.74 kW motor.

Rehman (2004) proposed a fuzzy logic enhanced, robust torque controller for induction motor drives. The proposed control scheme includes a robust flux and torque estimator and a direct fuzzy controller to enhance the torque regulation. Simulation and experimental results were presented to prove the effectiveness of the control scheme. Laroussi and Zelmat (2004) have presented a fuzzy adaptive PI controller applied for induction motors. An adaptation mechanism was used to tune the conventional PI controller gains, thereby introducing a certain degree of intelligence in the control strategy. Computer simulation of the proposed method was presented for various conditions. However, the drive system is not investigated in real time.

Hazzab et al (2006) implemented the fuzzy gain scheduling of PI controller for induction motor control. Fuzzy rules are utilized on-line to determine the controller parameters based on tracking error and its first time derivative. The adaptive mechanism is implemented in real time using AD2S100 AC vector processor. Lai and Lin (2003) presented a new hybrid fuzzy controller for induction motor control. The control algorithm consists of a PI controller which is active during steady state and a fuzzy logic controller which is active during transient state. A switching mechanism was used to switch between steady and transient states and to achieve satisfied performance under both the conditions. However, the complexity of the control mechanism is high due to the switching mechanism.

Masiala et al (2008) presented a self-tuning fuzzy controller for FOC of induction motor drives. The controller had the ability to adjust its parameter online according to the error between the machine speed and a reference model. A comparative analysis of PI controller, fuzzy PI controller and the proposed self-tuning fuzzy controller was presented. Moallem et al
(2001) proposed a multi-objective optimization method based on genetic fuzzy algorithm (GFA) for induction motor drives. GFA is used to optimize the five PI controller gains used in the indirect FOC of induction motor. Lin et al (2003) presented an adaptive sliding-mode controller based on real-time genetic algorithm (GA). A real time GA was developed to search the optimal adaptation parameters of the sliding mode controller online.

Ramadan et al (2004) implemented a new genetic based PI like fuzzy logic speed controller for induction motor. The controller was integrated in the vector control scheme of induction motor. However, the performance of the drive system was investigated in simulation only. Rubaai et al (2008) proposed the real-time implementation of a genetic-based hybrid fuzzy PID controller for industrial motor drives. The principle of this hybrid controller is to use a PID controller, which performs satisfactorily in most cases, while keeping in the background a FPID controller, which is ready to take over the PID controller when severe disturbances occur. The complete drive system is implemented in real time using the DSP control board ds1104.

Yang et al (1994) developed an artificial neural network (ANN) based identification and control technique for speed control of induction motor. Two ANNs were used to handle the uncertainties due to load disturbances and variation of rotor resistance. However, only simulation results were presented. Kung et al (1995) proposed an adaptive controller for speed control of induction motor using neural network. The parameters of the controller corresponding to various drive parameter sets were found off-line and used as the training patterns to estimate the connection weights of neural networks. The controller is implemented in real time and experimental results were presented. Abdellfattah et al (1997) presented a novel approach to the field oriented control of induction motor using neural network decouplers. Two ANNs were trained to estimate the stator flux for direct control and map
the nonlinear behavior of the rotor-flux decoupler for indirect control. However, the performance of this approach is investigated in simulation only.


Rubaani and David Kankam (2000) proposed an adaptive tracking controller for induction motor drives using online training of neural networks. The control and identification parameters of the controller were adjusted simultaneously online using a three-layer dynamic neural network. However, the real time implementation of the work is not done. Shi et al (2001) presented an ANN based direct self control scheme for an inverter-fed three-phase induction motor. Based on the fundamental principle of direct self control, an individual training strategy that involves both the fixed weight and supervised networks is used for the ANN controller design. The performance of the control scheme was verified by simulation. Kim et al (2001) proposed a novel speed estimation method of an induction motor using neural networks. The neural network speed estimator is trained online by using the error back propagation algorithm, and estimated speed is fed back to the speed control loop. The validity and the usefulness of the proposed algorithm are verified with experiments on a fully digitalized induction motor drive system.
Chen and Sheu (2002) implemented a novel speed control method for induction motor drives based on a two-layered neural network plant estimator and a two-layered neural network PI controller. The widely used projection algorithm is used as the learning algorithm for the neural networks in order to automatically adjust the parameters of the neural network PI controller and to effectively reduce the system sensitivity for both parameter variations and load torque disturbances. Mustafa et al (2003) developed a novel neural network based controller for vector controlled induction motor drives. The control algorithm was implemented on TMS320C30 digital signal processor and experimental results were presented. Wlas et al (2005) developed two architectures of ANNs, used to improve the performance of sensorless nonlinear control of induction motor drives. The method is based on the use of ANN to get an appropriate correction for improving the estimated speed. The control approach was implemented in a DSP based hardware environment. However, the drawbacks of this approach are the complicated network structure and the training procedure.

Ren and Chen (2006) proposed a recurrent neural network speed controller for induction motor drive. This speed controller consists of a recurrent neural network identifier (RNNI) and recurrent neural network controller (RNNC). The RNNI is used to provide real-time adaptive identification of the unknown motor dynamics. Alanis et al (2011) proposed a real time discrete back stepping neural controller for induction motors. The controller is based on a high-order neural network, trained online using Kalman filter learning, to approximate a control law designed by the back stepping technique. The proposed work is successfully implemented using the DSP board ds 1104. Nasir Uddin and Wen (2007) implemented a novel adaptive neuro-fuzzy based speed controller for an induction motor. The neuro fuzzy controller incorporates fuzzy logic laws with a five-layer artificial neural network scheme. Only three membership functions were used for each
input in order to reduce the computational burden. Simulation and experimental performances of the proposed work were presented and compared with conventional control techniques.

Intensive research is done on the design and implementation of fuzzy logic controller (FLC), neural network controller (NNC) and hybrid controller for high performance applications of induction motor drives. The FLC is the simplest of all the intelligent controllers for induction motor speed control applications. However, FLCs have difficulties in determining appropriate control laws and tuning the parameters of the membership function according to the changes in the system. NNCs on the other hand, have the capability to adapt itself to changes in the control environment using the system input and output. It does not require complicated control theories and exact model of the system. However, NNC synthesis requires design of the control structure which includes selecting the neural network structure, weight coefficients and activation function. The selection of neural structure as the initial step is done by trial and error method, since there is no proper procedure for this. The complexity of the selected neural network structure is a compromise between the high quality of control robustness and the possibility of control algorithm calculation in real time. Hybrid controllers like neuro fuzzy controller exploits the high level learning and low computation power of neural network to enhance the performance of fuzzy control system. However, a well defined procedure for finding the optimum network topology for induction motor drives still remains as a challenge.

1.3.4 Wavelet based Controllers

Recent literature has reported work on the use of time frequency localization of wavelet transform in the speed control of electrical drives. Wavelet transform has the ability to decompose wide band signals into time
and frequency localized sub bands. The wavelet transform is used in the modeling, analysis, diagnostic and control of electrical motors such as dc motor, PMSM, BLDC motor and induction motor.

Wai (2002) proposed a robust wavelet neural network (WNN) controller to control the rotor position of an induction motor. A novel training algorithm was developed for the WNN controller. Simulation and experimental results were provided to validate the effectiveness of the robust control scheme. Wai et al (2003) implemented an adaptive observation system and a WNN control system for achieving the favorable decoupling control and high-precision position tracking performance of an induction motor drive. The WNN control system is developed using the principle of sliding-mode control to increase the robustness of the indirect field-oriented induction motor drive. The control scheme was implemented in real time using TMS 320C31 DSP processor.

Wai and Chang (2003) designed and implemented a robust WNN sliding-mode control system for an indirect field-oriented induction servo motor drive to track periodic commands. Wai and Chang (2004) proposed a WNN based back stepping control technique for the position control of indirect field oriented induction motor drive. A model reference adaptive system is used for estimating the rotor time constant. Simulation and experimental results of the proposed work were presented. Lin et al (2005) developed an adaptive WNN control system to control the position of a permanent magnet linear synchronous motor servo drive system to track periodic reference trajectories. An adaptive learning algorithm that learns the parameters of weight, dilation and translation of the WNN on line, based on the Lyapunov stability theorem was used. In the design of this adaptive WNN
control system, no constrained conditions and prior knowledge of the controlled system are required.

Shanlin and Yuzhe (2007) proposed a novel flux and torque estimation method based on wavelet network for an induction motor control system. The input nodes of the wavelet network are the current error and the change in the current error. The output node of the wavelet network is the stator resistance error, which is used to obtain the accurate estimation value. However, the estimated values of flux and torque were verified only by simulation results. Abdesh Khan and Azizur Rahman (2007) developed and implemented a wavelet based multiresolution PID controller in real time for the rotor position control of the indirect field oriented induction motor drives under system uncertainties. The proposed controller is based on the multiresolution decomposition property of the discrete wavelet transform (DWT) of the error signal between the command and actual speed. The proposed method is designed and implemented in real-time using the ds1102 digital signal processor board.

Rizwan Khan et al (2007) presented a wavelet based de-noising scheme for induction motor. Wavelet transform technique was used to remove the noises from the sensor and receivers used in induction motor control scheme. Simulation results of the proposed work have been presented. Abdesh Khan and Azizur Rahman (2008) developed and implemented a novel diagnostic and protection algorithm based on wavelet neural network for inverter faults in the vector controlled induction motor drives. The inverter single phasing and shoot through faults were investigated in this work. The WNN based diagnostic algorithm is tested on-line on a laboratory 0.74 kW squirrel cage induction motor and simulation and experimental results were presented. Li and Ruan (2008) proposed a novel control method based on
WNN for direct torque control of induction motor drive. A novel architecture of nonlinear autoregressive moving average model based on WNN was used in order to enhance the performance of the induction motor. However, the performance of this novel control method is investigated in simulation only.

Khan and Rahman (2008) implemented a wavelet based multiresolution PID (MRPID) controller in real time for the precise speed control of the interior PMSM drive. The proposed wavelet based PID controller for interior PMSM drive was successfully implemented in real time using DSP hardware environment. Saleh and Rahman (2009) designed and implemented a novel wavelet modulated inverter for single-phase induction. The wavelet modulated inverter was operated by switching pulses generated by a unique nondyadic wavelet basis function based multiresolution analysis (MRA). The performance of the proposed work is investigated through simulation and experimental results.

Yousef et al (2010) developed wavelet network based controllers for motion control of dc motor. Khan and Rahman (2010) implemented a novel self-tuning neuro-wavelet based MRPID speed controller for high-performance interior PMSM drive. The neuro-wavelet based MRPID controller was trained online with adaptive learning rates in the closed loop control of the interior PMSM drive. The complete vector control scheme incorporating the proposed self-tuning MRPID controller was successfully implemented in real time using the DSP board ds1102 for the laboratory 1-hp interior PMSM drive. They have also presented a novel WNN based robust controller for speed control of interior PMSM drives (Abdesh Khan et al 2011). The proposed speed controller was trained using an adaptive control algorithm of the WNN. Simulation and experimental results of the proposed
WNN controller were presented and compared with conventional fixed-gain and adaptive speed controllers.

Based on the above discussion, it can be concluded that there is a recent trend in the research work on the application of intelligent wavelet-fuzzy-neural based controller for speed control of electrical drives. Various works have been reported for the speed control of electrical drives like dc motor drives, PMSM drives, interior PMSM drives, BLDC motor drives and switched reluctance motor drives using wavelet techniques. However, a systematic research on the development and implementation of a wavelet fuzzy based speed controller for induction motor control, which is one of the most familiar industrial drives, is yet in the stage of infancy. Thus, there exists a need to develop a controller combining the advantages of wavelet transform and fuzzy logic control for speed control of induction motor drives. This work presents a novel wavelet fuzzy based self-tuning controller for the speed control of indirect field oriented induction motor drive.

1.4 RESEARCH MOTIVATION AND OBJECTIVES

Induction motor is one of the most widely used machines in industrial applications. 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 and hence the rotor time constant, vary with the operating conditions. The conventional controllers such as PI and PID controllers with fixed gain values are traditionally used for the speed control of induction motor drives. However, the performance of these controllers is affected by parameter variations, load disturbances and system uncertainties. Their performance also changes depending up on the system operating conditions. Moreover, it is very difficult to fix the gain values of these controllers if the
exact model of the system is not available (Nasir Uddin et al 2002). In order to overcome the drawbacks of the conventional controllers, many adaptive control techniques are proposed. They include self-tuning regulator (STR), model reference adaptive controller, sliding mode controller, variable structure controller and H \(-\) infinity controllers. Unfortunately, these adaptive control algorithms are relatively more complex in terms of computational effort and they require prior knowledge of the system. Moreover, they use the approximate model parameters in the design, and as a result they are not suitable for wide speed range applications.

In the very recent years, wavelet transform is used in identification and control of electrical motor drives. Combining wavelet transform with intelligent techniques such as neural network and fuzzy logic yields very good results in the high performance applications of electrical motor drives. Much works have been reported on combining the advantages of wavelet transform and neural network for the high performance applications of induction motor drives. However, no works have been reported combining the advantages of wavelet transform and fuzzy logic for speed control of induction motor drives. Therefore, an effort is made in this work to develop a hybrid wavelet fuzzy based controller for the speed control of induction motor drives.

The main objective of this work is to develop and implement a wavelet fuzzy based self-tuning controller for speed control of an induction motor drive. In this hybrid controller, the discrete wavelet transform is used to decompose the speed error between the command speed and the actual speed into different frequency sub bands. These transformed sub band coefficients are scaled by their respective gains and then combined together to generate the control signal. A fuzzy logic based self-tuning algorithm is used for the online tuning of scaling gains.
1.5 ORGANIZATION OF THE THESIS

Chapter 1 provides an overview of ac motors and their control classification. The merits and demerits of each control scheme are highlighted and the need to develop a wavelet fuzzy based controller is presented.

Chapter 2 deals with conventional controllers and fuzzy based controller for IFOC of induction motor drive. A fuzzy based self-tuning PID controller is presented. The simulation results are presented for IFOC of induction motor drive with conventional controllers and fuzzy based self-tuning PID controller.

In chapter 3, the wavelet based controller and their mathematical formulations are described. The procedure for selecting the appropriate mother wavelet and the optimal level of decomposition are discussed. Finally, the concept of wavelet based controller for IFOC of induction motor drive is presented. The wavelet based controller is simulated using Matlab/Simulink and the results are compared with conventional and fuzzy based controller.

Chapter 4 presents the proposed novel wavelet fuzzy based self-tuning speed control scheme for induction motor drive. The structure and the mathematical formulations of the control scheme are given. The self-tuning algorithm using fuzzy logic for on line tuning of the scaling gains are presented. In order to predict the performance of the proposed wavelet fuzzy based self-tuning controller, extensive simulation studies are carried out using Matlab/Simulink software and the results are presented.

In chapter 5, the real time implementation of the speed control scheme incorporating the proposed controller is presented. The hardware implementation steps of the proposed speed control scheme are described in
detail. The proposed speed controller is implemented in real time on a 1.47 kW squirrel cage induction motor. Experiments are carried out on the hardware setup at different speed ranges and various operating conditions. The experimental results are compared with the simulation results under same operating conditions. The experimental results are also compared with conventional PI controller to prove the effectiveness of the proposed controller.

In the concluding chapter 6, the major contributions of the research work are summarized. It further, discusses the possible future scope for extension in the related area.