CHAPTER 2

LITERATURE SURVEY

The research work carried out by various researchers in the field of modeling, control and implementation of speed control of IMs using various control strategies is presented in this chapter. Various researchers have worked on the speed control of IMs using various control techniques. Some of the techniques are the SVPWM method, the PI method, the sliding mode control method, the Mamdani-FLC method, the Takagi–Sugeno method, the ANFIS method, etc. These are discussed one after the other in succession along with their advantages and disadvantages. This is followed by motivation for carrying out the research work and the problem definition.

2.1 REVIEW OF CONVENTIONAL-TYPE CONTROL METHODS

The classical or conventional type of control is used in most of the electrical motor drives. It requires mathematical model to control the system. When there are system parametric variations, the behavior of the system is unsatisfactory and it deviates from the desired performance **[5]**.

The dynamic behavior of a closed-loop, variable-speed induction motor drive that uses 3 SCRs (Δ-connected) was investigated by Ahmed and Farag in **[6]**. The use of a linear, state-variable feedback controller and the choice of the controller parameters with the purpose of optimizing a performance criterion related to the dynamic operations of the drive were used in their method. The transient responses for load and reference speed perturbations were obtained analytically using the theory of state variables. The choice of the coefficients of the linear combination to minimize the given functional was also suggested by them.

Pillay and Levin **[7]** developed mathematical models like the *dq* model and the *abc* models incorporating the various forms of impedance and/or voltage unbalances and designed controllers to control the various parameters of the IMs using the *d–q* method and the *abc* method.

The new minimum-time, minimum-loss speed control algorithms are developed for IM to obtain better performance, efficiency, under FOC with practical constraints on voltage and current in **[8]**.

A novel control technique for controlling some of the parameters of IM using the SVPWM method is presented in **[9]** and **[10]**. Also an excellent 3Φ bridge inverter, which was used to apply a balanced 3Φ voltage to the SCIM, was developed.

Maamoun **[11]** presented an SVPWM technique based inverter for v/*f* control method, and it was used for open loop speed control of IM. Ben-Brahim proposed a modified '*v*/*f*' method of developing a controller for high-rating IMs in his paper in **[12]**, which yielded excellent results.

Scalar control is another type of control scheme used to control various IM parameters while operating in the steady state. In this method, the amplitude and frequency of the supply voltage are varied **[13]** to control the speed of IM.

FOC or vector control **[14]** of an IM results in decoupled torque and flux dynamics, leading to independent control of the torque and flux as for a separately excited DC motor. FOC have a major disadvantage: they are sensitive to rotor time constant and incorrect flux measurement or estimation at low speeds **[15]**. Consequently, performance deteriorates and the conventional controller may be unable to maintain satisfactory performance. Furthermore, an efficient method of controlling the speed of an IM by considering a specific example was proposed by Zhang and Jiang in **[16]** using indirect field control coupled with synergetic control.

The parameter sensitivity of the rotor flux oriented system (FOC) with rotor flux estimation was discussed by Xingyi Xu in **[17]**. There, a stator-flux orientation strategy was proposed. It is a well-known fact that the estimation of stator flux of an IM is independent of flux leakage. Because of this, the IM's performance in the steady state is not sensitive to leakage inductance. The authors proved that the previously mentioned concept improved the dynamic performance of the IM system. They also carried out digital simulations in Matlab and showed that the stator flux-based IM system's performance was superior/excellent compared to that of a de-tuned motor flux-based IM system.

Compared to vector-controlled drive or field-oriented control drive, the scalar-controlled drive is very easy to implement, with the disadvantage being inferior performance of the drive. There is limited speed accuracy in the control design, particularly when the range of speed is low. Another disadvantage is the poor dynamic response of the torque.

Moreover, the design and tuning of the conventional controller mentioned in the previous paragraphs increase the implementation cost and add additional complexity in the control system and, may reduce the reliability of the control system. The main drawbacks of the linear control approaches were sensitivity in performance to the system parameters variations and inadequate rejection of external perturbations and load changes **[19]**.

2.2 REVIEW OF DTC METHOD

Brahmananda Reddy *et. al.* **[20]**, proposed a new concept of hybrid SV PWM scheme for the control of IM using DTC methods. They considered reduced switching losses in the inverter coupled with ripples in the torque, flux, current in the steady state while designing the controller. The designed pulse width modulation technique was based on the concept of stator flux ripples. Stator flux ripples were taken as a measure of line current ripples in their research work.

They performed the simulation in Matlab/Simulink and the results showed the superiority of the method proposed by them compared to the conventional method.

Ming Meng presented a voltage vector controller for the speed control of IMs using the concept of motion EMF in **[21]**. Furthermore, he also showed that not only constant power but also constant torque control could be achieved by his method. The rotor motion electromotive force was evaluated using 3 categories: FOC, DTC and DSC.

Jagadish Chaudhari *et. al.* **[22]** proposed the conceptual view of an SPWM of the voltage applied to the IM's stator. By using the SVPWM concept, the duty cycle of the inverter was calculated. This method was considered as one of the excellent methods for torque control and it was completely different from the FOC method.

However, the above-mentioned methods presented by the authors in **[6] - [8]**, **[11]**, **[17]** are classical in nature. The controller is designed on the transfer function approach and the steady-state vector method. In the classical control methods, the systems parameters are assumed to be linear, but in actual practice, the systems parameters are purely non-linear in nature. The system parameters are time-dependent; moreover, based on the disturbance, the values will vary. However, the IM is highly non-linear in nature. Hence, proper control through the classical control techniques may not yield appropriate results.

Usually, classical control used in motors drives has certain drawbacks. There are a number of difficulties involved in the design and implementation of conventional controllers for induction machines. Few of them are as follows **[23]**:

- The conventional control uses an accurate mathematical model, which is very difficult to obtain. Of course, it can be obtained using system identification techniques.
- The performance of classical control system drop off for non-linear systems (drives).
- The variations of some of the parameters of the IM are caused due to the sudden disturbance in load variations, due to thermal or temperature changes or due to motor saturation effects.
- In the case of classical control (PI) using linearity concepts, high performance is achieved only for unique operating points.
- Classical control cannot produce good results when improper coefficients are chosen during the simulation. Especially when the set point varies, the problem may still deteriorate and optimum results may not be obtained.

One of the conventional methods, namely the DTC, gives faster and robust responses of various parameters in the IMs, as seen in **[20] - [23]**. The drawbacks in this conventional method are the output responses of torque, flux is noisy due to the noise effects and improper estimation of speed.

There are two advantages of using the DTC method for control of IMs: constant torque control and constant power control. The DTC method improves the performance of IM to a very great extent, when compared with the conventional speed control methods. The DTC scheme presents many disadvantages like variable switching frequency, violence of polarity consistency rules, current and torque distortion caused by sector changes, start and low-speed operation problems, and high sampling frequency needed for digital implementation of hysteresis comparators. Hence, to overcome the drawbacks of these classical approaches (PI/DTC/*v–f*, etc), the fuzzy method can be used along with the classical control approaches.

2.3 REVIEW OF PI CONTROL METHODS USING FUZZY

Design of an FLC-based self-tuning proportional integral controller for control of speed in IMs was addressed by Mokrani and Abdessemed in **[24]**. The tuning of the conventional proportional integral controller was obtained using the fuzzy rules obtained from tests. A number of operating conditions were considered in the controller design. Some of the operating conditions were steep change in load torque, speed reversion, decrease or increase in rotor resistance, change in the inertia of the system or self-inductance of the system.

Bhim Singh and S.C. Choudhari **[25]** presented a comparative study of PI, FL, Fuzzy pre-compensated PI, Fuzzy PI and hybrid speed controllers for vector control of IM drives in their research paper. They used an indirect vector-controlled strategy for the control of current-controlled voltage source inverters. They studied the responses using these 5 types of controllers for starting, speed reversal and load perturbations.

However, there are certain drawbacks of the PI-based fuzzy approach **[24]**, **[25]** regarding control of the various parameters of the IM: e.g. the fixed gain in PI as a result of which optimal results may not be obtained. By using fuzzy, appropriate gain can be selected by using the fuzzy rule base.

2.4 REVIEW OF MAMDANI-BASED FLC METHODS

Many researchers had carried out extensive work on the control of various parameters using the Mamdani controller. Mao-Fu Lai *et. al.* **[26]** developed a new type of FL control system for variable speed drive using a PWM inverter with minimum number of components and significantly less circuit complexity. Speed responses of a realized system were also investigated.

Anti-overshoot M-FLC design for yaw angle control of a model helicopter was presented in **[27]** by Morteza and Ali. Design of VSI-type SVPWM for controlling the speed of an IM using dSPACE through the Simulink approach is presented **[10]**. In this method, the speed of the IM was controlled by controlling the amplitude and frequency of the stator voltage, first using simulation and then by experimentally validating the same in real-time environment. Ramon, Guillermo and Luis **[28]** presented a rule-based FLC scheme applied to a scalar closed-loop IM system with slip regulation. The results were obtained in the presence of strong non-linearity in the IM model. This method used a new linguistic rule table in FKBC to adjust the motor control speed, and they further showed that it is possible to implement a PI fuzzy logic controller instead of the traditional PI controller.

Bimal K. Bose *et. al.* **[29]** described a speed and flux-based sensor-less vector-controlled IM drive, which was primarily aimed at electric vehicle-type applications. The problem of integration at low stator frequency was solved by cascaded low-pass filters with programmable time constants.

Ouiguini *et. al.* **[30]** developed a novel method of speed control technique of an IM using an FLC and validated it using an experimental approach on a PC/286-AT microcomputer.

SMC had a couple of drawbacks, when high gains and chattering were considered. Because of the advantages of the fuzzy controller, the variable structure form of the sliding mode control was merged with the fuzzy control strategy to obtain a hybrid control, namely, the fuzzy sliding mode control. Further, genetic algorithm was used by the authors along with this FSMC, which yielded excellent results. The use of genetic algorithm in the FSMC yielded a near-optimal control of speed. Low overshoots were present in the response and in the control signal. Furthermore, the control action was smooth and robustness was retained with the use of FSMC.

Haider *et. al.* **[32]** presented the Fuzzy-SMCPI methodology to control the flux and speed of an IM. This method was basically a combination of Sliding Mode Control and PI control methodologies with fuzzy logic, but there was a drawback: chattering during the time of switching.

In **[33]** and **[34]**, the researchers implemented a FLC to adjust the boundary layer width according to the speed error. The drawback of their controller is that it depends on equivalent control and on system parameters.

Haider Mohammed *et. al.* **[35]** proposed the use of a FLC to combine two controllers of opposite performances in the transient and steady-state areas, and this solves the chattering problem of the SMC for IMs.

Hakju Lee *et.al.* **[36]** presented a novel method of fuzzy controller design of an indirect field-oriented IM drive for high performance with the help of Matlab/Simulink by building a model of an IM.

Arulmozhiyal **[37]** presented a novel design and implementation of a VSI-type SVPWM for controlling the speed of IMs using the FOC concepts in their work. They even discussed in brief a number of fuzzy control logic applications on various plants. The developed controller had high efficiency and good PF.

Sanjeevkumar *et. al.* **[38]** presented an FL-based speed controller and its design for vector controlled induction motor drive. This controller was implemented on a 3-phase, 415V, 0.75 kW SCIM. Julio Rojas and Roberto Sukez **[39]** described the FLC on an induction inverter-motor assembly to obtain variable speed and torque with good dynamic response. This was authenticated by simulations and experiments.

The above-mentioned works **[26]**-**[39]** were related to the classical control methods using the FLC-based Mamdani method. The drawbacks of the classical control of IMs could be overcome by the use of fuzzy control techniques. In general, the FLC does not require mathematical model of the controlled object. It is an ideal flexible non-linear type of controller that can overcome the influence of only non-linear variations and has a strong robustness, as it is not sensitive to parametric variations of the controlled process. In all the works cited above, the time–response curves (system parameters) attained stability (settles) between 1 and 3 secs.

However, the fuzzy method suffers from certain disadvantages. The rules are written on the basis of experience of the observer and are random in nature. These rules may not be adequate in those circum-stances. Hence, the result obtained from the fuzzy controller may not be optimal. Furthermore, there are no specific design tools to develop the control strategy due to the non-availability of numerical and analytical methods to tackle the control problem.

FL controllers are less sensitive to system parameters variation and it may be difficult to obtain robustness for the various system parameters. FLC performance can be further improved by auto-tuning of the fuzzy controllers or make use of the fuzzy adaptive controller.

The above-mentioned drawbacks of the Mamdani-based FLC controller could be further taken care of by using the Takagi–Sugeno FLC method. A brief review of the work carried out by various authors regarding the TS method is next discussed.

2.5 REVIEW OF TAKAGI–SUGENO-BASED FLC METHODS

An excellent control scheme is developed by Takagi and Sugeno **[40]**, for the control of various applications in the industrial sector in 1990s. Many researchers started using TS models for their applications. Zie, Ling and Jhang **[41]** presented a TS model identification method by which a great number of systems whose parameters vary dramatically with working states can be identified via fuzzy neural networks (FNN).

Chen and Wong **[42]** investigated a new type of fuzzy controller using the Takagi–Sugeno method. The proposed adaptive gain controller for Takagi–Sugeno fuzzy control, which results from the direct adaptive approach, was employed to directly adapt the appended gain parameters in the IF–THEN part of the TS model.

Ernesto Araujo **[43]** employed the TS-fuzzy approach to treat uncertainty in the mapping procedure. It can yield a completely different input–output mapping. Allouche Moez *et. al.* **[44]** dealt with the synthesis of fuzzy state feedback control of induction motor with optimal guaranteed performance in their paper. The gains of TS-FLC were obtained by solving a set of Linear Matrix Inequality (LMI), which produced good results.

The T–S fuzzy model-based impulsive control of chaotic systems with exponential decay rate was discussed by X. Liu and S. Zhong in **[45]**. In their paper, they presented a new approach for stability analysis of the fuzzy impulsive controllers in which the fuzzy system was presented by the Takagi–Sugeno model.

Iman Zamani and Masoud Shafie **[46]** proposed a new approach for stability analysis of fuzzy impulsive controller for controlling the various parameters in which the fuzzy system is represented by a Takagi–Sugeno model. An affine impulsive controller was considered based on the Lyapunov criterion and some sufficient conditions were derived to guarantee asymptotic stability of fuzzy affine impulsive controllers. These conditions were shown in terms of some matrix inequalities and Bilinear Matrix Inequalities (BMIs).

The main advantages of the fuzzy-based TS method involve the approximation of the non-linear terms as linear parameters. The TS fuzzy approach is conservative, since it employs a crisp input–output mapping. The TS-based fuzzy approach improves the results without changes in the system already working and it is necessary only to alter the new parameter of the setting. TS-fuzzy based feedback control guarantees both stability and disturbance rejection **[44]**.

A couple of drawbacks were found in the above-mentioned works using fuzzy-based TS control of IMs **[40]-[46]**.The number of parameters in the controller is proportional to the number of rules and states. Theoretically, the approximation error between the input and the output will be small if enough fuzzy rules are given. However, in such a process, a heavy computational load is required, and this may lead to the control system becoming unstable in the requirement of real-time control. In all the works cited above, the time response curves (system parameters) attained stability (settles) in a couple of second. An alternative method to rectify some of the issues related to TS-based fuzzy could be the incorporation of the neural network control or the neural network combined with fuzzy concepts.

2.6 REVIEW OF NEURAL NETWORK-BASED CONTROLLERS

ANN controller is one of the intelligent controller, which is usually utilized for two purposes: for constructing non-linear controllers and for adding human intelligence to controllers, such as perception (sensory information process), understanding, recognition, inference, learning, diagnosis and others.

Kung and Liaw **[47]** developed an adaptive speed control of drives using neural networks in their paper. The effectiveness of the proposed controller was confirmed by some simulated and experimental results.

Sharma *et. al.* **[48]** developed an ANN to predict the operating voltage and frequency when the load torque and speed of the IM were changed. Matlab/Simulink based models were developed by the authors and simulations were performed. Also, the simulated results were evaluated by performing some experiments.

A recurrent ANN-based self-tuning speed controller was proposed for the high-performance drives of IMs by Won Seok Oh *et. al.* **[49].** The designed controller compensate the uncertainties of the nonlinear IM control system since the real output values were directly used for parameter identification and tuning and it gave excellent results.

Hu Hong Jie and Li Dedi **[50]** developed a model reference control scheme by introducing a PI controller and RBF neural network (RBFNN) controller for speed control of high-precision motion control system in their paper. The control strategies developed were verified through simulation and experimental approaches, thus demonstrating the effectiveness in the control design.

Keerthipala *et. al.* **[51]** developed two types of observers (based on the linear and non-linear model of the machine) and used it in torque and speed control of IM's control schemes and it gave excellent results.

A couple of drawbacks were found in the above-mentioned works **[47]**-**[51]**, using neural network based speed control of IMs. Some of them are as follows:

1. It is found that many of the schemes proposed by the authors reduced the sensitivity of the plant due to noise/disturbance and some parameter variations; thus, those schemes were not robust.
2. Moreover, the motor worked on the best performance at certain voltage and frequency levels for certain loads only.
3. The settling times of the various response curves were in between 0.7second and 2 second.
4. NN has the learning capability, but does not have any knowledge of the system (adaptability).

To rectify the above-mentioned drawbacks, an alternative method would be the use of neural network with adaptability, which would lead to the concept of Adaptive Neuro-Fuzzy Inference Scheme (ANFIS). A brief review of the work carried out by various authors regarding the ANFIS method is described next.

2.7 REVIEW OF THE ANFIS CONTROL METHOD

Syed Abdul and Muhammad Asghar **[52]** presented a soft starter applied to an IM system, which was based on ANN and ANFIS. The latter was used to implement the feedback estimator while the former was used to adjust the firing angle of SCRs under different loading conditions. The presented soft starter was implemented using DSP and with neural networks tools and its performance was compared. The performance was found to be satisfactory in terms of the firing angle of the SCRs.

Miloudi *et. al.* **[53]** presented a new control technique of controlling the speed of IM using 2 methods, viz., variable gain PI (VGPI) controller and a direct torque adaptive neuro-fuzzy controller (DTANFC) in **[53]** and compared them. The motor reached the set speed rapidly without overshoots, and load disturbances were rapidly rejected by the designed controller.

Neuro-fuzzy robust controllers for AC drive systems using predictive controllers were developed by Yashuhiko *et. al.* **[54]**, the predictive linear controller was changed using FL such that the controller makes the system respond quickly and vice-versa, thus making the controller insensitive to plant noise. Furthermore, a variable structure PI controller using FL for drive systems was implemented by them using neural networks, which showed very promising experimental results compared to the predictive ones.

Bimal Bose, Nitin Patel and Kaushik R **[55]** extended the work done in **[56]** to a stator flux-oriented electric vehicle induction motor drive and then implemented the fuzzy controller by a dynamic back-propagation neural network-based controller. They further verified the simulated results using a DSP-based hardware. The proposed control was the fast convergence with adaptive step size of the control variable.

A simple DTC neuro-fuzzy control of PWM inverter-fed IM drive was proposed by Grabowski, Marian and Bose in **[57]**. They applied an ANFIS to achieve high-performance decoupled flux and torque control using an experimental approach coupled with a DSP TMS320C31 card. Aware *et. al.* **[58]** proposed a new type of ANFIS for voltage source inverted fed IMs. In this paper, they replaced the conventional PI/PID controller by the fuzzy controller in speed controller loop and implemented using a DSP interfacing card. ANFIS, which tunes the fuzzy inference system with a back-propagation algorithm based on a collection of input–output data, is implemented.

An IM spindle motor drive using synchronous PWM and dead time compensatory techniques with an ANFIS controller was proposed by Faa and Rong for advanced spindle motor applications by performing a real-time experiment **[59]**. The plant here was identified by a fuzzy NN identifier to provide the sensitivity info of the drive system to the adaptive controller using a back-propagation algorithm to train the network online.

An adaptive speed control of hybrid fuzzy-neural network for a high-performance IM drive was presented by Mokhtar and Sofiane **[60]**. The 3-layered NN using a back-propagation algorithm was used to provide real time adaptive estimation of the motor's unknown parameters and another 3-layered NN was used to produce an adaptive control. The performance and robustness of the IM drives under non-linear loads, parameter variations and uncertainties were highly improved in their case. Simulation results showed excellent tracking performance. Mihoub *et. al.* **[61]** proposed an ANFIS controller to obtain high dynamic performance in AC machines. In their work, they used the fuzzy controller first and then the neuro-fuzzy controller. Finally, they proved that the latter one is better than the former one in terms of dynamism.

Farzan Rashidi developed a sensor-less adaptive neuro-fuzzy speed controller for IM drives in **[62]**. An ANN was adopted to estimate the motor speed and to provide a sensor-less speed estimator system. The performance of the proposed ANFIS controller was evaluated for a wide range of operating conditions of the IM and also showed robustness to the parameters' variations. A model reference adaptive flux observer-based neuro-fuzzy controller for an IM drive was presented by Nasir Uddin in **[63]**. The observer model was developed based on a reference flux model and a closed loop Gopinath flux observer, which combines current and voltage model. They investigated the performance of the designed drive at different dynamic operating conditions.

Consoli *et. al.* **[64]** dealt with MRAC-based speed controller for indirect field-oriented IM drive based on Fuzzy laws (for the adaptive process) and a Neuro-Fuzzy procedure (to optimize the Fuzzy rules). An adaptive vector-based control of IM drives based on the NF approach was dealt with in their paper. Furthermore, the variation of the rotor time constant was compensated by performing a fuzzy fusion of 3 simple compensation strategies. A prototype based on an IM drive was assembled and used to practically verify the features of the proposed control strategy.

Rezvan and Mehran applied the Fuzzy-based General Regression Neural Network (FGRNN) concept to the speed control of IM in **[65]**. A General Regression Neural network (GRNN) was adopted to estimate the motor speed and to provide a sensor-less-based speed estimator system. The performance of the proposed FGRNN speed controller was evaluated for a wide range of operating conditions. After going through an exhaustive literature survey of the work carried out by various researchers using different control strategies across the globe, it was finally concluded that the ANFIS strategy to control the various parameters of the IM was promising as it yielded very good results. Some drawbacks were found in the works carried out by various researchers **[52]-[65]**:

1. At steady state, the operation will oscillate about the optimum point.
2. Speed control performance of IM is affected by parameter variations and non-linearities.
3. Oscillations in the response curves exist even during the steady state.

Furthermore, the speed response curves in **[52]-[65]** stabilized above 0.5 second and hence took much time. The rise times was found to be larger in some cases.

The speed curve in **[52]** took more than 5 second to reach the set value. Here, the parameters were measured using the approximation method, which may be a random process. The speed curve in **[53]** took more than 0.5 second to reach the set value. Here, the gains vary along a particular tuning curve. The speed curve in **[54]** took more than 2s to reach the set value.

The speed curve in **[55]** is nearly 10 second to reach the set value. At steady state, the operation will oscillate about the optimum point. In this paper, at every decrementation of flux, a pulsating torque is likely to develop, which is not acceptable to EV drive. The speed curve in **[60]** is nearly 1 second to reach the set value. The authors have used the minimum fuzzy rules in this case.

In **[63]**, the speed curve took more than 0.8 second to reach the set value and the authors used the minimum fuzzy rules in their work.

One of the problems associated with their work was the detuning of the controller, which was required due to rotor time constant variations. In **[65]**, the speed curve took more than 0.6 second to reach the set value.

The principal advantage of neuro-fuzzy control (ANFIS), i.e., fast convergence with adaptive step size of the control variable, is retained. The neural network combines the advantage of fast control implementation and computation, either by a dedicated hardware chip or by digital signal processor (DSP)-based software. Such a neuro-fuzzy control combines the advantages of fuzzy and neural controls.

Recently, an increasing interest has been observed in combining artificial intelligent (AI) control tools **[65]** with classical or conventional control techniques **[66]**. The principal motivations for such a hybrid implementation of both the conventional and the AI-based approach are that with fuzzy logic, neural networks and rough sets issues, such as uncertainty or unknown variations in plant parameters and structure, can be dealt with more effectively, hence improving the robustness of the control system. Several works contributed to the design of such hybrid control schemes, as shown by various researchers in **[67]**, **[68]** and **[69]**.

Hence, comparing the 4 control strategies (PI, Mamdani, Fuzzy, ANFIS), which are basically used in our research work, it can be concluded that finally, the adaptive neuro-fuzzy scheme is the ideal choice as it has the advantages mentioned above combined with faster settling times. In our research work, we have tried to further improvise the results by developing compact Simulink models and leading to faster settling times, as will be proved in the subsequent chapters.

2.8 MOTIVATION FOR THE RESEARCH

The advent of computers and sophisticated signal processing electronics in the modern-day world has made the use of DT/digital system representation of the plant more suitable for the design of controllers than its CT (analog) counterpart. Much of the research work carried out in the area of power electronic drives so far is mainly concentrated in the modeling of induction motors and control techniques, static and dynamic analysis, which makes use of state feedback, output feedback principles, linear quadratic regulator, LQG techniques, optimal feedback, PID-based techniques, etc. Since most of these types of control techniques may need all the states for feedback, which may not be available for measurement, they may suffer from real-time implementation and might need a state observer for control purposes.

Currently, the design and analysis of complex power electronic systems such as motor drives are usually done using modern simulation software, which can provide accurate predictions of the systems behavior in reality. Some of the software tools used for designing modern power electronics drives and its systems include Matlab, Labview, Ansys, Pspice, FE analysis, etc. Consequently, computer modeling of such systems at a desired level of accuracy becomes an essential part of the design process. A satisfying system model usually serves as a prototype for system behavior simulations, as well as for signal analysis and control design.

A common approach to the modeling of power electronic systems is to develop several independent system models, on different complexity levels, which serve for the analysis of some particular stages of the design. The typical levels are: switching (detailed), average, and small signal (linear) levels. A small-signal model serves for the control design from the stability analysis perspective. A large-signal average model usually includes ideal component models for the large-signal control design and system behavior simulations over long time periods. Several techniques are applied in order to narrow down the trade-off gap between result accuracy and simulation speed.

Finally, the detailed model includes component models at a high level of accuracy and it serves component behavior analysis rather than the analysis of the whole system. It focuses on short time periods, usually several switching cycles, because of the necessity of an extensive simulation time. A design, then, proceeds according to the results of independent analysis at each level. A problem with such an approach is that for large system analysis, the model of the entire system must be developed at each level. One of the most popular control methods of three-phase motor drive systems, which evolved during the last decade is the field-oriented control and was realized with a digital PWM controller in rotating d–q coordinate space.

Furthermore, many of the performance specifications, such as speed, torque, current, flux, etc., had taken a long time to stabilize and reach the set point. Also, many of the control schemes were sensitive to parametric variations and were not robust. These drawbacks could be rectified by the use of some advanced control schemes such as the PWM, SVPWM, hybrid control strategies (like fuzzy, neural, genetic algorithms, neuro-fuzzy, etc.). This has motivated us to consider the problem of designing sophisticated controllers for the speed control of induction motors and improve the dynamic stability and robustness.

2.9 PROBLEM IDENTIFICATION

The first part of the research step is to assess the existing information and literature in the relevant field to date and to identify the problem and solve it along with some practical implementation (if possible). In the previous sections, an attempt was made to study the works of various authors and researchers across the world in the field of speed control of electrical machines, as it finds much application, especially in the industrial drives. Thus, the problem of controlling the speed of electrical machines, i.e., an induction motor, was considered. The main objective was to design an effective controller for the speed control of IM drives, which will overcome all the drawbacks of the controlling methods employed by various researchers so far.

The second part of the research step is to solve the identified speed control problem that has been defined. There are various methods to solve the defined problems, which has changed through the ages from the classical control methods, to the conventional methods to the hybrid control methods. In recent years, neural networks and fuzzy logic have attracted a number of researchers to work on the speed control of IMs as these methods had yielded very good results. Numerous advances have been made by various researchers on this topic so far. A combination of fuzzy logic and artificial neural networks was thus believed to be an effective method to control the speed of motors, which is the focus of the research work considered, and this has led to the final problem statement of the thesis, **"*Design and implementation of neuro-fuzzy based speed control of induction motor drive by space vector pulse width modulation for voltage source inverters*"**.

Various stages are considered in arriving at the design of the sophisticated ANFIS scheme for the control of speed of an IM drive in this thesis work. To start with, a PI-based controller is designed. Then, a fuzzy-based Mamdani controller is designed, which is compared with the PI method. Finally, the sophisticated controller, viz., the adaptive neuro-fuzzy controller (ANFIS), is designed, The designed controllers develops the control commands to control the firing angle of the inverter; this, in turn, controls the speed of the IM, which is simulated in Matlab/Simulink and compared with the previous three methods. The robustness issues are also considered in the controller design. Finally, the proposed work is compared with the work done by other researches.