CHAPTER 1

INTRODUCTION

1.1 GENERAL

In recent years, Brushless DC (BLDC) motor drives are increasingly popular in industrial applications due to rapid progress of technologies in power electronics and growing demand for energy saving. A BLDC motor is a type of permanent magnet synchronous motor that uses position decoders and an inverter to control the armature current. Instead of using a mechanical commutator as in the conventional dc motor, the BLDC employs electronic commutation without the mechanical commutators and brushes which makes it a virtually maintenance free motor know as “Brushless Direct Current Motor”. The operating characteristics of BLDC motor resemble that of conventional commutated dc permanent magnet motor. Hence many problems associated with brushes such as radio-frequency interference and sparking which are the potential sources of ignition inflammable atmosphere are eliminated.

A motion system based on the Direct Current (DC) provides a good, simple and efficient solution to satisfy the requirements of a variable speed drive. Although dc motors possess good control characteristics and ruggedness, their performance and applications in wider area inhibited due to sparking and commutation problem. Squirrel cage induction motor does not possess the above mentioned problems, but they have their own limitations
such as low power factor and non-linear speed torque characteristics. With the advancement of technology and development of modern control techniques, the Permanent Magnet Brushless DC (PMBLDC) motor is able to overcome the limitations mentioned above and satisfy the requirements of a variable speed drive.

The concept of the BLDC motor is actually very old, going back to 1962 when T.G. Wilson and P.H. Trickey made a DC machine with solid state commutation. It is highly suitable for special applications such as tape and disk drives for computers, robotics, positioning systems and aircraft where high torque and fastness of response are very much essential. In addition, it is more suitable in applications where wear is intolerable due to low humidity. Unfortunately, the technology to make such a motor practical for industrial use over 5 H.P simply did not exist until a number of years later. With the advent of powerful and permanent magnet materials and high power, high voltage transistors in the early to mid 80’s the ability to make such a motor practically became a reality. The first large BLDC motor (50 H.P or more) was designed by Robert E. Lordo at POWERTEC Industrial corporation in the late 1980s. Simple construction is a prime feature of this motor.

BLDC motor eliminates brushes, commutators and hence the excellent overall performance of BLDC motor makes it an efficient competitor for AC drives. It has been widely used in drive systems and servo control because of its fast response, lower Electromagnetic Interference (EMI), high power density, high efficiency, high reliability, quiet operation and maintenance free. The motor consisting of permanent magnet rotor and distributed stator windings are wound such that electromotive force is trapezoidal. They have better speed torque characteristics and low inertia, which improves their dynamic performance when compared to a dc motor.
BLDC motor is usually supplied by a hard-switching Pulse Width Modulation (PWM) inverter, which normally has relatively low efficiency since the power losses in switching devices are high. The high $dv/dt$ and $di/dt$ will result in severe EMI and rigorous problems with the reverse recovery of the freewheeling diodes, especially in high switching frequency. As the switching frequency of the hard-switching is not very high when the switching frequency is within audio spectrum, it may produce severe acoustic noise. Furthermore, there is “turning off current spike” for inductive load or “turning on voltage spike” for capacitive load with a hard-switching inverter, which can produce excessive localized hot spots and damage power semiconductor switches. In order to solve these problems, many soft-switching inverters have been designed in the past but they have their own limitations (Muruganantham & Palani 2011). To overcome all these problems, the soft-switching inverter using transformer is used, which can generate dc link voltage notches during chopping and minimize the drawbacks of existing soft-switching. Hence all switches work in zero-voltage switching condition.

The transient and steady state solutions are the two parts of a differential equation for any physical system. The steady state response of any system gives an idea of the accuracy of the system and if there is deviation between the input and output, the system is said to possess a steady state error and tends to zero at infinity. On the other hand, the transient solution of
control systems and such systems are said to be sluggish. So the controllers are used in the system to produce a control signal necessary to reduce the error signal (deviation) to zero or to a small value and increase the fastness of the response.

In this thesis, the performance of the hybrid intelligent controllers are compared with conventional PI controller, because conventional PI controller requires exact mathematical model of the system and are very sensitive to parameter variations. Therefore, the use of conventional PI controller does not meet the requirements for the robust performance. In recent years, there has been an increasing interest in the development of efficient control strategies to improve dynamic behavior of the BLDC motor by using Fuzzy Logic Controller (FLC), Hybrid Fuzzy-PI, Genetic Algorithm based PI (GA-PI), and Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. Both the simulation and experimental results show that the ANFIS controller based soft-switching inverter is designed for BLDC motor drive systems which is easy to implement in industries and it has the advantages of low switching power loss, low inductor power loss, low dc link voltage ripple, small device voltage stress, low switching noise and simple control scheme. Moreover the system provides low torque ripples, high starting torque, better transient response with negligible overshoot, smaller settling time and rise time.

1.2 OBJECTIVE OF THE THESIS

BLDC motor is usually supplied by a hard-switching PWM inverter, which normally has relatively low efficiency since the power losses across the switching devices are high. The high dv/dt and di/dt will result in severe EMI and rigorous problem with the reverse recovery of the freewheeling diodes, especially in high switching frequency. As the switching frequency is within
audio spectrum, it may produce severe acoustic noise. In order to solve these problems, many soft-switching inverters have been designed in the past. Unfortunately, high device voltage stress, large dc link voltage ripples, complex control scheme and so on are noticed in the existing soft-switching inverters (Muruganantham & Palani 2011).

The objective of the work is to minimize the switching power loss, inductor power loss, dc link voltage ripple, device voltage stress, switching noise and complex control scheme. These variables are calculated and shown in appropriate places. Moreover, the system should provide low torque ripples, high starting torque, better transient response with negligible overshoot, smaller settling time and rise time. This can be achieved by implementation of intelligent techniques like fuzzy, hybrid fuzzy-PI, genetic based PI and ANFIS controller based soft-switching inverter using transformer, which can generate dc link voltage notches during chopping which minimize the drawbacks of existing soft-switching inverter. Hence all switches work in zero-voltage switching condition. In this thesis, five different speed controllers have been proposed and their performances are compared. Among all these five controllers, ANFIS controller renders a better transient response than the one obtained using other controllers with negligible overshoot, smaller settling time and rise time. Further the ANFIS controller provides low torque ripples and high starting torque.

1.3 LITERATURE REVIEW

Brushless direct current motors possess several advantages over other motors, such as low inertia, fast response, high power density, high reliability, excellent performance of speed-control, high efficiency and maintenance-free reputation. The rotor will not generate significant heat, resulting in easy cooling. Further, due to the advancement in the design of
small size, simple structure and large output torque, BLDC motors have attracted many users. The operating characteristics of BLDC motor resemble that of a conventional commutated dc permanent magnet motor but without the mechanical commutators and brushes. Hence many problems associated with brushes such as radio-frequency interference and sparking which is the potential source of ignition inflammable atmosphere are eliminated. Therefore, they offer a viable option for variable speed electrical drives, particularly for applications with high temperature and hostile operating environment. In the past two decades, many soft-switching converter techniques were proposed and they have the combined advantages of conventional PWM converters and resonant converters. The existing soft-switching inverters/drives have been taken for comparison and study.

In Soft-switching converter, resonance is allowed to occur during commutation period (i.e., turn-on and turn-off process) so as to have ZVS and ZCS conditions. During conduction period it behaves just like a conventional converter. Hence with simple modifications, it is possible to design control circuits for the soft-switching converters. Due to above features, researchers were attracted toward implementation of this soft-switching techniques to both AC and DC drive motors. However, the main drawback of soft-switching techniques is, high voltage stress on the device. With the development of power electronic components the soft-switching techniques were successfully implemented to the special machines with voltage stress minimized. One such special machine is the BLDC motor. The control technique aims at low switching power loss, low dc link voltage ripple, small device voltage stress and torque ripple minimization.

The intelligent systems have the advantages of being fast, working relentlessly over complex systems. Controlling and optimizing the performance of such a motor is a difficult task, due to severe non-linearity
encountered in its torque production mechanism. Recently, an increasing interest in combining artificial intelligent control tools with classical control techniques for BLDC motor has been observed. The primary motivation for such a hybrid implementation is that with fuzzy logic and neural networks, issues like uncertainty or unknown variations in plant parameters and structures can be dealt with more effectively, and hence improving the robustness of the control system. Conventional controls have on their side well-established theoretical backgrounds on stability and allow different design objectives such as steady state and transient characteristics of the closed loop system to be specified. Several works have been contributed to the design of such hybrid control schemes.

1.3.1 Modeling

BLDC motor uses position decoders and an inverter to control the armature current. Instead of using a mechanical commutator as in the conventional dc motor, the BLDC employs electronic commutation without the mechanical commutators and brushes. The modeling and simulation analysis of BLDC motor depends on computing design and it effectively develops BLDC motor control system and evaluates rationality of the control algorithm imposed on the system. This provides a good foundation for system design. Hence good modeling is very essential and it offers potential cost saving.

Jeon et al (2000) simulated a new model for BLDC motor with real back EMF waveform. In conventional simulation model of BLDC motor, the real back EMF is some degree deviated from the ideal trapezoidal back EMF. In this approach, error in conventional simulation was reduced and as a result nearly real back EMF waveform was obtained through simulation. Other researchers (Navidi et al 2009) have modeled a BLDC motor based on
transfer function description. Though the transfer function model provides us with simple and powerful analysis and design techniques, it suffers from several drawbacks.

Rakesh Saxena et al (2010) modeled and simulated a BLDC motor using PSIM soft computing technique. This simulation provides good soft computing technique and saves time. Further, it requires less manpower in making hardware models at initial stages and reduces the cost of the research work. The torque characteristics of BLDC motor plays an important role in the model of the BLDC motor. The BLDC motor was modeled using MATLAB GUI by considering its behavior during commutation (Balogh Tiber et al 2011).

1.3.2 PWM Techniques

Subhashish Bhattacharya et al (1999) compares motor bearing currents due to PWM hard-switched and soft-switched Voltage Source Inverters (VSI). The bearing currents were identified by the approach based on direct excitation of the motor bearing with sinusoidal and square wave signals to characterize the bearing. To monitor bearing behavior in a clean noise-free environment and gave valuable insight into possible bearing current mechanisms, a small signal excitation test was conducted. Due to soft-switched VSI they analyzed bearing currents and they had lower dv/dt currents and lower circulating currents with the real-real or real-shorted bearing cases and improved performance.

The PWM inverter and variable DC link inverter schemes were compared for a high speed sensorless control of BLDC motor (Kyeong Hwa Kim & Myung Joong Youn 2002). In this scheme, the practical issues related to commutation delay were discussed at high speed. The results show that
more stable sensorless operation was obtained using the variable DC link inverter scheme at high speed. Masataka Miyamasu & Kan Akatsu (2011) have compared the sinusoidal back EMF and the trapezoidal back EMF motor. Both the motors were driven by BLAC and BLDC drives. FEA and the circuit simulator were used to calculate the PWM loss in the motor. From the compared results, the BLDC motor with BLDC drive has high efficiency than BLDC motor with BLAC drive.

Wei Kun et al (2004) have introduced a novel PWM scheme to eliminate the diode freewheeling in the inactive phase in BLDC motor. In this method, the switch is in PWM mode in the beginning of 30° mode and in the last 30° mode and it will be continuously in ON condition in the middle 60° zone. This method can be applied to any incident and any advanced control principles. Shanmugasundram et al (2009) have presented a high performance PWM control strategy implemented with flexible Aduc812 microcontroller. The authors claim that this drive was less affected by EMI and noise signals. The output speed response was very faster for even small change in input reference speed.

Dhawale et al (2010) have proposed a position control of four switch inverter for three phase BLDC motor using PWM control. In this method, the desired dynamic response and static speed-torque characteristics were obtained. Further, the conduction losses were reduced by implementing reduced number of controllable switches and freewheeling diodes. In order to increase the efficiency, reliability and reduce the maintenance Alphonsa Roslin Paul & Mary George (2011) have proposed a simple digital PWM technique for BLDC motor. With the help of two predefined state variable techniques, the proposed digital control treats BLDC motor as digital system and regulates speed. Hence the controller design was very simple and further reduces the cost and complexity of the motor control.
The nonlinear simulation model of BLDC motor drive with four switch three phase inverter was presented by Krishnakumar and Jeevanandhan (2011). In this scheme, MATLAB/ Simulation platform was used for nonlinear model. For speed controller they used conventional PI controller. Besides the four switch inverter topology was studied to provide a possibility for realization of low cost and high performance three phase BLDC motor drive system. Further, a novel direct current controlled PWM scheme was designed to produce the desired dynamic and static speed-torque characteristics.

Kamran Tabarraee et al (2011) compared VSI driven BLDC motor with trapezoidal and sinusoidal back EMF. The effect of back EMF harmonics in establishing relationship for the stator phase current and electromagnetic torque were properly considered into account. From the result, it shows that the trapezoidal back EMF model had improved efficiency when compared to sinusoidal back EMF model.

1.3.3 Torque Ripple Minimization

By back EMF method, the accurate value of torque was determined. Sung Jun Park et al (2000) proposed a novel approach to minimize torque ripples and to increase the BLDC motor efficiency. In this approach, the phase back EMF waveforms in a-b-c reference frame were transformed to the d-q-0 reference frame. Accordingly, the optimum phase current waveforms were obtained by transforming the d-q-0 variables to a-b-c. Further the optimum phase current waveforms obtained are used as reference values and the motor winding currents were forced to track it by delta modulation technique.
Tae Sung Kim et al (2001) have proposed a new algorithm for conventional BLDC motor drive to reduce torque ripple which is generated by Unipolar PWM method. In this algorithm, the current harmonics were calculated within a permitted degree using Fourier series coefficients. After transforming these harmonic components into stationary frame, phase current similar to rectangular waveform was generated by applying Space Vector Pulse Width Modulation (SVPWM) method. Hence it reduces current ripple and also noise and vibration.

Byoung Hee Kang et al (2001) deal with torque ripple reduction of BLDC motor with the help of decaying phase back EMF. In many control methods, the torque ripple reduction was considered from the point of current control. But the torque ripple in commutation period of BLDC motor is unavoidable, even if the current control is successful. In this scheme, torque model with decaying phase back EMF was considered and the causes of commutation torque were analysed.

Sang Hyun park et al (2003) have introduced a novel current control algorithm for torque ripple reduction of BLDC motor using four switch three phase inverter. The proposed scheme was compensated for the commutation current slopes of the incoming and outgoing phase during the commutation interval of the phase currents in various speeds. Hence torque ripple was not produced during commutation. Moreover by reducing the switch counts, it is possible to make the drive of BLDC motor cheaper and smaller for industrial applications. An effective approach of BLDC spindle motor system was presented by Quan Jiang et al (2003) to predict its performance accurately. In this approach, a mathematical model based on direct analytical solutions is used for both characteristics analysis of spindle motor and MOSFET switches of the inverter.
Many researchers have proposed Direct Torque Control (DTC) to BLAC motor. Yong Liu et al (2005) have investigated the DTC to BLDC motor for reduced torque ripple. The main difference between the DTC of BLAC and BLDC drives was in the estimation of torque and inverter voltage vectors. This scheme provides reduced torque ripple and faster torque response.

Halvaei Niasar et al (2006) present an comprehensive study on the generated torque ripples with respect to phase commutation in the Four Switch, Three Phase Inverter (FSTPI) for BLDC motor drives which are suitable for low cost applications (Part I). Drive characteristics during its six operation modes were different due to unbalanced phase voltages in FSTPI topology. A novel torque ripple minimization technique was proposed (Part II) to improve the performance of the BLDC motor drive during low and high speed regions. In this scheme, cogging torque and slot effect were not considered.

Ki Yong Nam et al (2006) have proposed a torque ripple reduction method for BLDC motor by varying input voltage after making circuit analysis using the Laplace transformation. The circuit analysis is used to obtain the period of freewheeling region and the input voltage to be varied. In this method, the torque ripple was reduced to 10%. Dae Kyong Kim et al (2006) proposed a novel approach for reducing commutation torque ripple in position sensorless BLDC motor drives. In conventional approach, commutation interval was measured with the help of current sensor and current control loop. But in this proposed scheme, commutation interval was directly measured from motor terminal voltage waveforms. Hence it does not require current sensor and current control loop.
Liu et al (2006) have proposed an improved approach for reducing commutation torque ripple in direct torque controlled BLDC motor drives. In this scheme, the commutation torque ripple was analysed and minimized by combining the conventional two phase switching mode with a controllable three phase switching mode during periods when the current is being commutated. In this approach, commutation torque ripple was successfully eliminated at high speed.

Parag Upadhyay & Rajagopal (2006) have analyzed torque ripple reduction of Interior Permanent Magnet brushless DC (IPM BLDC) motor using rotor pole shaping along with pole shifting. The authors claim that proper design and geometry of the motor reduces the cogging torque and proper excitation reduces the mutual torque ripple. Jianfei yang et al (2009) have proposed a novel DTC method for BLDC motor without flux linkage observation. In this approach, the torque is calculated based on back EMF and three phase current.

The ideal BLDC motors have trapezoidal back EMF. However in practical situation it was hard to produce trapezoidal back EMF due to non-uniformity of magnetic materials and design trade-off. Somesh Vinayak Tewari & Indu rani (2009) have proposed a method to minimize the torque ripple of the BLDC motor with un-ideal back EMF. Chuang et al (2009) have analyzed the phase current and torque ripple which are generated during current commutation in BLDC motor with trapezoidal back EMF. In this analysis, the amplitude of the torque ripple for four different kinds of PWM pattern was verified.

Salih Baris Ozturk et al (2010) have proposed a novel DTC scheme including the actual pre-stored back EMF constants versus electrical rotor position look-up table for BLDC motor drive with two phase conduction
scheme using four switch inverter. Compared to conventional four switch PWM current and voltage controlled BLDC motor drives, the low frequency torque ripples and torque response time were minimized.

Salih Baris Ozturk & Hamid Toliyat (2011) have analysed a simple position sensorless DTC control scheme for BLDC motor. Similar to conventional DTC scheme used for sinusoidal AC motors both torque and flux were controlled simultaneously. The commutation torque ripple depends on current ripple. Sangsefidi et al (2011) presented a commutation torque ripple reduction in BLDC motor drives by adding an extra voltage source to the non-commutating phase during commutation. This extra voltage source was provided by capacitor that discharges during commutation period and was charged during non-commutation period. In this method, 48% of torque ripple was reduced in the BLDC motor drives.

Kai Sheng Kan and Ying YU Tzou (2011) have proposed adaptive wide angle control scheme with adjustable modulation waveform to obtain wide speed control range by efficiency optimization. Under the same testing condition, the RMS value of phase current was lower than conventional 120° conduction mode. Besides the torque ripple was significantly reduced. (Cao Minh Ta 2011) have provided an alternative approach to reduce torque ripple in BLDC motor drives. The proposed approach is called Pseudo-Vector Control (PVC). In order to minimize torque ripple to minimum, principle of vector control was used instead of conventional square wave form to optimally design the waveform of reference current. By this approach, torque ripple was significantly reduced.
1.3.4 Controllers

Luk et al (1994) developed a low cost simulation package for the design of a BLDC motor servo controller. The proposed mathematical model was implemented in MATLAB environment. This package aims to offer high portability and cost effectiveness in terms of software development. Further it allows the user to trade-off implementation details of the drive system at the design stage and it is particularly useful for minimum cost projects. This simulation package is useful for designing BLDC motor control systems and also for teaching purpose.

In order to drive the motor and to determine the position of the rotor BLDC motor uses Hall sensors. Without additional hardware, the velocity measurement depends on the consecutive sensor outputs. In such a case, speed measurement in a BLDC motor is velocity dependant. In conventional approach, shunt resistor is used to allow constant current sampling rate. However, the sampling time for the velocity measurement is still variable. In order to overcome the above problem, Jia Yush Yen et al (2002) have proposed a variable sampling frequency observer for the velocity estimation of BLDC motor. The Variable Sampling Frequency Observer (VSFO) was designed based on singular value assignment method. This proposed scheme provides accurate velocity measurement and also freedom in the controller design.

Lei Hao & Hamid Tolivat (2003) proposed a method for full speed range of BLDC motor control system using sliding mode observer. In this scheme, the average model of BLDC motor was developed in rotor Multiple Reference Frame (MRF) based on line-to-line variable model and then a sliding mode observer is used to estimate the rotor position and motor speed used in the MRF transformation block. Further full speed range control
algorithm was developed based on average motor model. As a result the behavior of BLDC motor resembles that of the sine-wave PM motor during constant torque and power regions except that the former has a trapezoidal back emf and the later has a sinusoidal back emf.

The BLDC motor when operated at high speed both torque and speed response characteristics are deteriorated by the motor inductance components in the stator windings. To solve this problem, conventional phase advance angle control method was used for forward motoring mode. But during reverse motoring mode, the position information error of rotor was doubled and torque performance was drastically destroyed. In order to overcome this problem, a control method using adjustment of phase advance angle was proposed by Sung In Park et al (2003). This scheme improves the torque and speed response characteristics by minimizing delay of current at high speed operation.

Aboul Naga et al (2003) have introduced a novel low cost, high performance single phase adjustable speed motor drive. The proposed scheme minimizes the starting current and inrush current. Chung-Jin kwon et al (2003) gave a speed controller for BLDC motor drives with different load conditions using adaptive fuzzy tuning scheme. The adaptive fuzzy tuning scheme was used to adjust the parameters of PI controller during on-line. The scheme improves the adjusting capability of PI controller.

Gwo Ruey Yu and Rey Chue Hwang (2004) have proposed a novel tuning formula that uses Linear Quadratic Regulator (LQR) methodology to find the optimal PID parameters for BLDC motor drives. The proposed PID controller receives only error signals and it does not require complete state feedback. Junhyuk Choi et al (2004) have proposed adaptive fuzzy control scheme for velocity control of developed small BLDC motor. The Adaptive
Fuzzy Control (AFC) scheme through Parallel Distributed Compensation (PDC) is developed for Multi-Input/Multi-Output (MIMO) plant model represented by Takagi Sugeno (TS) model. For the systems with uncertain or slowly time-varying parameters, the alternative AFC scheme was proposed to provide asymptotic tracking of a reference signal. The developed control law and adaptive law guarantee the boundedness of all signals in the closed loop system. Further, for any bounded reference input signal, the plant state tracks the state of the reference model asymptotically with time. A Simple on-line trained Neuro-Controller (SNC) for a BLDC motor was presented as a speed controller (Salem et al 2004).

The BLDC motors are driven by either Unipolar or bipolar driving method. To get large starting torque two phases are energized out of its three phases in every commutation period. To achieve high speed of operation, one phase is energized out of its three phases in every commutation period. Gunhee Jang and Kim (2005) have proposed a novel method to drive a BLDC motor both in large starting torque and high speed of operation using bipolar starting and unipolar running algorithm. Rusu & Birou (2006) gave a real-time MATLAB toolbox used to control a BLDC motor. On host PC and under the user interface of MATLAB, the synthesis, code generation and the implementation of the control program were carried out. The target was DSK24X development, connected on serial port to the host PC. In order to validate the effectiveness of this real time library, speed control application for a BLDC motor was presented.

In the past, to design a controller for single phase fan motor was based on trial and error method. Wei Chao Chen & Ying Yu Tzou (2009) have developed both modeling method of parameter identification and an efficiency optimization control scheme for single phase BLDC fan motor. This scheme developed an efficient optimization method based on a closed
loop current control by using the Hall sensor feedback. Halvaei Niasar et al (2009) have proposed an effective model based on Switching Function Concept (SFC) for a four switch inverter BLDC motor drive. By eliminating two power switches, Direct Phase Current (DPC) control method was carried out. Using the above concept, the author showed detailed electrical variables, such as phase current, line voltages, phase voltages, diode and switch currents.

Hai Lin et al (2009) have investigated a novel nonlinear speed controller for BLDC motor drive with high performance Model Reference Adaptive Backstepping (MRAB) Approach. In this approach, to obtain the reference voltage for the PWM control, an adaptive backstepping controller was designed. The traditional PI controller was not required in this method to track the speed. Shanmugasundram et al (2009) designed a fuzzy logic speed controller with low cost, compact in size and robust using ADUC812 microcontroller. In this controller, over voltage, over current and thermal protection to protect the BLDC drive can also be implemented.

Byungwoon Jang et al (2009) investigated the effect of fuzzy membership function’s slope for PI-like fuzzy control system. By increasing the slopes of the triangular membership function (left and center) for fuzzifying the error and the sum of error can improve the starting and steady state performance. Similarly by decreasing the slope of right membership function shows worse performance in the fuzzy control of BLDC motor drive system. Particle Swarm Optimization (PSO) for PID tuning of a BLDC motor was investigated by Alberto A. Portillo et al (2009). The PSO was used to adjust the parameters of PID controller. The scheme improves the adjusting capability of PID controller. PID values derived from PSO algorithm were found to be an improvement from the PID values found using the Windows Servo Design Kit (WSDK). By using this scheme the peak time, settling time
and percentage overshoot were improved. In addition, PSO-PID converges faster than WSDK-PID values towards stability.

Ting Yu Chang et al (2010) have proposed a novel module structure of Phase Locked Loop (PLL) speed controller for PMBLDC motor drives to attain both fast response and high accuracy. Besides a phase current sensing scheme was used to properly incorporate with the PWM control of the PLL controller to reduce the drive cost. Albert Rajan et al (2010) designed a novel reconfigurable digital controller for BLDC motor using fuzzy logic. This technique was implemented using reconfigurable Vertex II Pro developed board. Compared with conventional controllers, this proposed energy efficient controller consumes less power (70 mW).

Tan Chee Siong et al (2010) compared PI and fuzzy logic controllers for the speed control of a phase controlled converter dc excited motor-generator system. By comparing two controllers, the fuzzy logic controller reduces starting current overshoot by limiting overshoot in speed. Further, it reduces computational time, learns faster and provides less error than other method. A comprehensive simulation model with fuzzy logic controller for PMBLDC motor drives was presented by Tan Chee Siong et al (2010). MATLAB/fuzzy logic toolbox was used to design FLC, which was integrated into simulations with simulink. Even in different load conditions or disturbance, it was seen that the desired real speed and torque values could be reached in a short time by FLC controller.

Yan Xiaojuan & Liu Jinglin (2010) have presented a novel sliding mode control for BLDC motor network control system. Adaptive Fuzzy Sliding Mode Control (AFSMC) was used to decrease the delay in the networked control system and to improve the traditional slide mode control. In this scheme, time varying disturbances of the network control system was
reduced and the stability of the system was improved. Chung-Wen Hung et al (2010) have described a sensorless scheme for six-space-vector four switch three phase BLDC motor drive. The authors proposed fuzzy gain scheduling PI controller and sensorless speed estimation. Based on fuzzy logic, three PI controllers separately for different sampling time intervals in low, medium and high speed were combined simply to create an effective control output. This scheme shows that fuzzy-gain scheduling controller was effective and robust in variable sampling situation.

Artificial Intelligence based speed control of BLDC motor was presented by (Naga Sujatha et al 2010). The results of neural network controller are compared with conventional PI and fuzzy PI controllers. Among these controllers, neural network controller shows better speed response and also reduces torque ripples. Daryabeigi et al (2010) have introduced a novel emotional intelligent controller for speed control of BLDC motor. It is also called as Brain Emotional Learning Based Intelligent Controller (BELBIC). This controller has simple structure with high auto learning features.

Mohammad Reza Faieghi & Mohammad Azimi (2010) have developed two controllers for BLDC motor. First, an ANFIS with Non-linear Auto-Regressive Moving Average with eXogenous input (NARMAX) system identification was developed. Second, PSO was used to adjust the parameters of PID controller. The ANFIS developed here was simple, accurate and easy to train. Hence it can be used for reference to model identification of other complex systems. The PSO based PID controller was also beneficial for other non-linear systems because it was a fast convergence and easy to implement optimization algorithm.
Alexandra-Iulia Stinean et al (2011) have proposed a cost effective speed controller for BLDC motor drives using T-S state feedback scheme. Using model equivalence principle, the discrete time dynamic Takagi-Sugeno fuzzy models of the process were derived to merge the discrete time linear process models in the rule base. In this scheme, linear matrix inequalities were solved and the global stability of the fuzzy control system was guaranteed.

A minimal fuzzy gain scheduling speed controller with torque compensation for variable sampling system of BLDC motor was presented (Chung-Wen Hung et al 2011). With torque compensation, time index for fixed and variable sampling is done. Muhammad Firdaus Zainal Abidin et al (2011) gave a comparative study between PI, fuzzy and hybrid PI-fuzzy controller for speed control of BLDC motor drive. By using switch, fuzzy controller was activated in the case of sufficiently large reference input changes and PI controller was activated in the case of small speed error. Hence the advantages of both fuzzy and PI controller were incorporated. Maoli Wang et al (2011) have designed single neuron self-adaptive PID controller for BLDC motor. By this self-learning scheme, the single neuron self-adaptive PID controller has better static and dynamic performances than conventional PID controller.

Pei Chung Chen & Chi Ruei Chen (2011) gave a robust fuzzy-neural control scheme for BLDC motor drives. To guarantee the stability of BLDC motor control system, tuning laws were derived in the sense of Lyapunov theorem. To validate the concept digital signal processor (TMS320F2812) was used. The results indicate that the proposed control scheme for speed control of BLDC motor was feasible and effective in different loading conditions.
Uzair Ansari et al (2011) have proposed extensive modeling of a three phase BLDC motor and GA-based PID scheme and was used for position control. Comparative study was carried out between GA based PID controller and Ziegler Nichol’s (ZN) based PID controller. It is found that the performance of GA based PID controller is much more efficient than ZN based PID controller in terms of rise time, settling time, overshoot and set point tracking. Varatharaju et al (2011) have developed matlab based speed controller for BLDC motor drive using ANFIS. The neural network based architecture was described for fuzzy logic control. Using back propagation algorithm, fuzzy logic rules and their membership were tuned. Under various operating conditions, the performance of the proposed ANFIS controller was evaluated.

Srikanth & Raghu Chandra (2012) modeled a three phase BLDC motor with GA based PI controller. GA was proposed as a global optimizer to find the optimized PID gains for position control of BLDC motor. This controller provides more efficient closed loop response for the position control of BLDC motor in terms of rise time, settling time, overshoot and set point tracking. Arulmozhiyal & Kandiban (2012) have proposed a voltage source inverter with improved fuzzy PID controller for speed control of BLDC motor. Fuzzy logic concept was used to adjust the parameters of PID controller. This Scheme improves the adjusting capability of PID controller.

Vinodhini et al (2012) presented a Neuro-GA based adaptive PID controller for position control of BLDC motor drive system. This controller was tuned to compensate for changes in inertia and friction at different load conditions. Self tuning of PID controller for different set of loads was achieved through neural networks and controller gains were optimized using GA.
1.3.5 **Soft-Switching Inverter**

In order to overcome the problems in hard-switching inverter such as high power loss across switching devices and low efficiency, Zhi Yang Pan & Fang Lin Luo (2004) have proposed a novel resonant dc link inverter for BLDC motor. In this topology, twelve inverter main switches and three auxiliary switches were used to guarantee all switches work in zero voltage condition. Hence all switches had low power losses with reduced voltage stress and less constraint on insulation requirement. In this scheme, only conventional controller was used for analysis.

Zhi Yang Pan & Fang Lin Luo (2005) have introduced a novel specially designed resonant pole inverter for BLDC motor drive system. In this topology, six inverter main switches and three auxiliary switches were used to guarantee all switches work in zero voltage condition. This inverter topology has low switching power loss, low inductor power, low switching noise and simple control scheme. In this scheme also, only conventional controller was used for analysis. The dynamic response of conventional controller was not satisfactory while compared with hybrid intelligent techniques.

Ching & Chan (2008) a novel Zero-Voltage-Switching Pulse-Width-Modulated (ZVS-PWM), so called Zero-Voltage-Transition (ZVT) converter was proposed for BLDC motor drives. In this topology, all main switches and diodes were operated with ZVS conditions. Also, all the switching devices have equal voltage and current stresses. Besides EMI was reduced and with minimum hardware count, low cost and simple circuit topology. This topology is suitable for high frequency switching power converter. Shahbazi et al (2009) have proposed a resonant pole inverter which is specially designed for battery fed BLDC motor drive systems. In this
topology, six inverter main switches and three auxiliary switches were used to guarantee all switches work in zero voltage condition. This inverter topology has low switching power loss, low inductor power, low switching noise and simple control scheme. In this scheme, only conventional PI controller was used for analysis. The dynamic response of conventional PI controller was not satisfactory while compared with hybrid intelligent techniques.

HE Hucheng et al (2009) have proposed a novel Zero Voltage Transition Parallel Resonant DC Link Voltage Source Inverter (ZVT-PRDCL-VSI) for BLDC motor drive system. In this topology, six inverter main switches and three auxiliary switches were used to guarantee all switches work in zero voltage condition. This inverter topology has low switching power loss, low inductor power, small device voltage stress, simple control scheme and no unbalancing problem of neutral point voltage. In this scheme also, only conventional controller was used for analysis.

Samitha Ransara & Madawala (2011) presented a novel single phase to three phase converter without an intermediate DC link capacitor for driving a BLDC motor. The proposed technique uses a unique switching sequence. Though this scheme provides low cost BLDC motor drive system it generates high torque ripples.

1.4 ORGANIZATION OF THE THESIS

This thesis is composed of eight chapters. The overall organization of rest of the chapters is as follows

In Chapter 2, drawbacks of transfer function model and merits of state space model are discussed. The construction and working principle of BLDC motor and determination of motor equivalent model parameters are discussed. The state space model of the BLDC motor is derived. Using the
state space model of BLDC motor with hard-switching inverter together with conventional PI controller, the performance characteristics such as three phase back EMFs, three phase currents, rotor angle and rotor speed are obtained using MATLAB simulation software. This study is useful for the comparison purpose when intelligent controllers with a new proposed soft-switching inverter are used in the subsequent chapters.

From literature survey, it is well known that the performance of the BLDC motor with conventional PI controller and hard-switching inverter has many drawbacks. The operating principle of the proposed soft-switching inverter topology with PI controller is discussed in detail in Chapter 3. Its design considerations and hardware implementation are analysed clearly in order to achieve ZVS and ZCS conditions. Proportional plus integral controller is designed and it is tuned with Ziegler Nichols method. The simulation characteristics of the BLDC motor are obtained and they are validated by experimental study.

The performance characteristics of the BLDC motor has been discussed in chapter 3. It is observed that there are few overshoots in the transient response and the starting torque is also less. Further, more torque ripples are observed. In chapter 4, the fuzzy logic integrated with proposed soft-switching inverter to provide better dynamic performance and control of PMBLDC motor is discussed. The detailed discussion about fuzzy set theory and fuzzy set operations are done. The design of fuzzy logic controller is explained in detail with its block diagram. The concepts such as fuzzification, membership function, scaling factor, fuzzy rule base, fuzzy variables, inference engine, defuzzification and design of fuzzy logic controller are discussed briefly. Both the simulation and validation by hardware implementation are included for the proposed inverter topology.
In BLDC motor, it is important to have high starting torque with faster time response with reduced delay time, rise time, peak time and settling time. This is achieved using Internal Model Control (IMC) scheme. In Chapter 5, the principle of Internal Model Control, IMC approach is discussed in detail. Further, series approximation, pade approximation for the time-delay and sensitivity and complementary sensitivity function for IMC are discussed. MATLAB simulation of performance characteristics are validated through hardware implementation and their results are included in this chapter.

Since optimization avoids the occurrence of local minima, a genetic based PI controller for soft-switching inverter of BLDC motor is discussed and implemented in chapter 6. The basic concept of population size, reproduction, crossover, mutation and elitism are discussed. Genetic algorithm process, its characteristics, initializing the population, setting the parameters, performing the GA and objective function of the GA are discussed in detail. From the results, the BLDC motor with GA based PI controller gives better transient and steady state performance.

Fuzzy based controllers develop a control signal which is obtained on the selection of the rule base. This rule base is written on the previous experiences and these rules are selected which is random in nature. As a result, the outcome of the controller is also random and optimal results may not be obtained. Selection of the proper rule base depending upon the situation can be achieved by the use of an ANFIS controller, which becomes an integrated method of approach for the control purposes and yields excellent results. It has both the advantages of fuzzy logic which has a role as an excellent tool for modeling human thought and neural network for the learning capability. An ANFIS is developed and implemented for soft-switching inverter of BLDC motor in chapter 7. Artificial neural
network learning, types of fuzzy reasoning systems, ANFIS structure with block representation, its five layer architecture and learning algorithm are discussed in detail. Design of ANFIS controller for the proposed soft-switching inverter for BLDC motor are also discussed in detail with MATLAB simulation software. The simulation results are analyzed for ANFIS controller based soft-switching inverter for BLDC motor. Finally, the performance comparison of the proposed soft-switching inverter with different controllers such as PI, fuzzy, hybrid fuzzy-PI, GA-PI and ANFIS based controller of PMBLDC motor are discussed.

Chapter 8 concludes the main work of proposed soft-switching inverter using control techniques such as conventional PI, fuzzy, fuzzy-PI, GA-PI and ANFIS for BLDC motor. The simulation studies using MATLAB are validated by hardware results. Finally, the applications of BLDC motor and the future scope of the research in this area are discussed.

1.5 SUMMARY

The BLDC motor is a type of permanent magnet synchronous motor that uses position decoders and an inverter to control the armature voltage supplied to the motor. It employs electronic commutation without the mechanical commutators and brushes. The operating characteristics of BLDC motor resemble that of conventional commutated dc permanent magnet motor.

Though dc motors possess good control characteristics and ruggedness, they produce sparking and commutation problem. Induction motor has low power factor and non-linear speed torque characteristics. Hence the PMBLDC motor offers viable solution to overcome the limitations
of dc and induction motor and satisfy the requirements of a variable speed drive using recent control techniques.

BLDC motor eliminates brushes, commutators and hence provides excellent overall performance. It is an efficient competitor for AC drives. It has many advantages such as fast response, lower electromagnetic interference, high power density, high efficiency, high reliability, quiet operation and maintenance free.

The detailed literature survey reveals that, in the past analysis of BLDC motor characteristics was done using transfer function model. However, recent control techniques which give improved performance uses state space model. It is therefore necessary that the BLDC motor is represented in state space model. It is also learned, that inverters are employed to control the armature voltage of the BLDC motor. In the past, hard-switching inverters were invariably used. However they have several drawbacks. Some authors have attempted to design soft-switching inverters. In these inverters, more number of switching devices are used. Hence, high device voltage stress, large dc link voltage ripples with complex control scheme are observed and they are to be eliminated for the proper design of the inverter with the use of appropriate controllers.

Performance evaluation of BLDC motor is done based on power loss across switching devices, efficiency, inductor power loss, switching noise, control scheme, dc link voltage ripples, torque ripples and voltage stress across switches. The drawbacks with the lack of these parameters are noticed in the literature survey. In this thesis, an attempt has been made to rectify the above drawbacks using soft-switching inverter with intelligent controllers. The next chapter explains in details about the state space modeling of BLDC motor with MATLAB simulation software.