CHAPTER 1

INTRODUCTION

1.1 GENERAL

New types of electric motors like Permanent Magnet (PM) Motors, Switched Reluctance Motors (SRM) and Stepper Motors (SM) have emerged due to the development in engineering material technology and tremendous improvement in solid state devices and circuits. Due to the technical improvements in motors, controllers and feedback techniques, electronically commutated motors (ECM) (also known as brushless motors) are replacing brushed motors in many applications. The advantages of the ECM over the brushed motors are reduced maintenance cost, environmental effects and electromagnetic radiation.

During the last three decades, several improved magnetic materials are developed for high performance PM motors. Rare-earth magnets which are usually Samarium Cobalt alloys are still among the best performing magnetic materials. The most recent developments are the Neodymium-Iron-Boron alloys. The magnetic performance of these alloys is about 30% better compared to Samarium Cobalt magnets. Brushless DC motor is one kind of permanent magnet synchronous motor, having permanent magnets on the rotor and trapezoidal shape back-EMF(Electromagnetic Force). PMBLDC (Permanent Magnet Brushless Direct Current) motor drives have received considerable attention recently as their performance is superior to those of the
brushed DC (Direct Current) motors and AC (Alternating Current) motors for servo and adjustable speed applications.

When compared with induction motor drives, Brushless DC motor (BLDCM) drives possess some distinct advantages such as high power density, higher efficiency, and simpler controllability. Also these motors have a operating temperature lower than that of induction motors. That is especially true for the comparison between BLDC and single phase induction motors such as shaded pole or permanent-split capacitor motors. Lower operating temperature also means lower bearing temperature. Due to this lower bearing temperature, the BLDC motor has significantly higher life time expectancy. A further important feature of this motor is the easy speed controllability. Hence BLDCM drives are becoming more and more attractive for many industrial applications, such as compressors, electrical vehicles, and DVD (Dissociated Vertical Deviation) players etc. In general Permanent Magnet Brushless motors have found wider applications due to their high power density and ease of control.

In general,

- The most obvious advantage of the Brushless configuration is the removal of brushes.
- Brush maintenance is no longer required and many problems associated with brushes are eliminated.
- The Radio frequency interference and sparking associated with them are eliminated.
- Another advantage is that more cross-sectional area is available for the power (or) armature winding.
- The Brushless DC motor has better efficiency and power factor, and therefore a greater output power compared to induction motor drives.
Further the control circuitry involved in PMBLDC drive is simple compared to other drives.

The BLDC motor employs a DC power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from the rotor position. The phase current of BLDC motor normally rectangular shape, which is synchronized with the back-EMF to produce constant torque at a constant speed. The mechanical commutator of the brushed DC motor is replaced by electronic switches, which supply current to the motor windings as a function of the rotor position. This kind of AC motor is called brushless DC motor, since its performance is similar to the traditional DC motor with commutators.

The speed of the motor is directly proportional to the applied voltage. These brushless DC motors are generally controlled using a three phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter. These position sensors can be Hall sensors, resolvers, or absolute position sensors. Using Pulse Width Modulation (PWM) for switching the transistors on and off, a varying average voltage can be applied to the motor. This average DC voltage determines the motor speed. When both the high side and low side transistors were permanently ON for the 100% commutation period, the motor will run at rated speed provided the rated DC voltage is supplied. For operating the motor at a desired speed below the rated speed, the commutation pattern applied at either high side or low side should be pulse width modulated. There are two control schemes possible:

1. Open-loop speed Control (Voltage Control)
2. Closed-loop speed Control
In open loop speed control, the duty cycle is calculated based on the set reference speed. In case of closed loop speed control, the actual speed is measured and compared with the reference speed to find the error difference. This error difference will be supplied to the PI controller. The output from the PI controller gives the desired duty cycle. BLDCMs use permanent magnets for excitation, rotor position sensors are needed to perform commutation. Usually, three Hall Effect sensors are used as rotor position sensors for a BLDCM. Due to the presence of rotor position sensors there are several disadvantages, such as sensor increases the cost and the size of the motor, and a special mechanical arrangement needs to be made for mounting the sensors. These sensors, particularly Hall sensors, are temperature sensitive, limiting the operation of the motor to below 75°C. On the other hand, they could reduce the system reliability because of the components and wiring. In some applications, even it may not be possible to mount any position sensor on the motor. Therefore, sensorless control of BLDC motor has been receiving great interest in recent years from the stand point of total system cost, size, and reliability. For this reason, it is desired to eliminate these sensors from the motor, that is, sensorless control. During the last two decades, a lot of research on sensorless control techniques for brushless DC motors (BLDCMs) has been conducted. This research can be divided into four categories.

1. Detection of the Zero Crossing Point (ZCP) of the motor terminal to neutral voltage with a precise phase shift circuit.


3. Sensing of the third harmonic of the back-EMF.

Among the various techniques, the back-EMF zero crossing detection method is the most popular. It is possible to determine when to commutate the motor drive voltages by sensing the back-EMF voltage on an undriven motor terminal during one of the drive phases. The obvious cost advantage of sensorless control is the elimination of the Hall position sensors.

There are several disadvantages to back-EMF sensorless control:

- The motor must be moving at a minimum rate to generate sufficient back-EMF to be sensed.

- Abrupt changes to the motor load can cause the back-EMF drive loop to go out of lock.

- The back-EMF voltage can be measured only when the motor speed is within a limited range of the ideal commutation rate for the applied voltage.

- Commutation rates faster than the ideal rate will result in a discontinuous motor response.

The Position estimation is obtained from zero crossing of back-EMF with respect to a virtual neutral point. The neutral point will not be stable during PWM switching. Low pass Filters have been used to eliminate the higher harmonics and to convert the terminal voltages into triangular waveform signals. Therefore the zero crossing of back-EMF can be found by line voltage difference.

The difference of line voltages provide an amplified version of the back-EMF in appropriate phase near the zero crossing. The position detection from line voltage difference method is simple, reliable and does not involve any integration. Further, since line voltages are used, the requirement of
neutral potential has been eliminated. This also eliminates the common mode noise and device drops and their variations. Unlike the other method, this scheme is easy to implement, since no derivative operations are involved. The position detection found by means of line voltage difference can be implemented using microcontroller or FPGA or DSP. For some applications it is important to reduce the manufacturing cost of the drive. Cost reduction is usually achieved by the elimination of drive components such as power switches and sensors.

1.2 BACKGROUND RESEARCH

Iizuka et al (1985), presented the microcomputer control of a brushless motor without a shaft position sensor. The method of motor terminal voltage sensing was done at steady-state operation. The starting at standstill has been realized by the technique which uses the brushless motor as a separately controlled synchronous one. The PWM signal generated in the computer has chopped the motor voltage by the commutator transistors to control the motor speed. The whole control system needs a 4-bit single-chip microcomputer and two quad-comparators. Any way this proposed control system has been used for the drive of brushless motor in compressors alone and also it needs three low pass filters and three comparators for position detection.

Ogasawara and Akagi (1991), described a brushless DC motor without a position sensor. Variable speed is achieved by adjusting the average motor voltage, just like chopper control of DC motors. The position sensorless drive proposed was based on detection of the conducting interval of free-wheeling diodes connected in anti parallel with power transistors. This approach makes it possible to detect the rotor position over a wide speed range, especially at a lower speed. A starting procedure of the motor was also discussed because it is impossible to detect the rotor position at a standstill.
Although it gave a novel starting algorithm and wide speed control especially in the lower range, the inverter must work in the chopping mode to implement this algorithm.

Becerra, Jahns and Ehsani (1991), presented a four-quadrant brushless Electronically-Commutated Motor (ECM) drive with high quality torque control without the discrete current sensors. The combined use of a custom VLSI controller chip, HVIC gate drivers, and power MOSFET’s with integrated current sensors provide the basis for a compact, robust drive without sacrificing performance. Experimentally the authors proved, the prototype “sensorless” ECM drives were having good performance in motoring and regeneration operation. To achieve this good performance, a universal ECM (UECM) chip was designed which need the three phase voltage of the motor. The neutral voltage was virtually created in the UECM to find the back-EMF. The virtually created neutral voltage had never been at zero voltage, so exact zero crossing detection was not obtained and hence the position information.

Moreira, (1996) described an indirect sensing, or sensorless, method for rotor flux position for Brushless Permanent Magnet (BPM) motors operating over a wide speed range. Maximum torque per ampere and/or maximum efficiency method described was particularly applicable to trapezoidal back- EMF type of BPM motors. The typical trapezoidal waveform of the motor internal voltages (or back- EMF) contains higher order frequency harmonics. In particular, the third harmonic component was extracted from the stator phase voltages while the fundamental and other higher order components were eliminated via a simple summation of the three phase voltages. The resulting third harmonic signal keeps a constant phase relationship with the rotor flux for any motor speed and load condition. This was practically free of noise that can be introduced by the inverter switching,
making this a robust sensing method. The indirect sensing methods based on
detection of the back-EMF signal that require heavy filtering. But the third
harmonic signal needs only a small amount of filtering to eliminate the
switching frequency and its side bands. As a result, the method described was
not sensitive to filtering delays, allowing the motor to achieve a good
performance over a wide speed range. Motor starting was also superior with
this method since the third harmonic signal was detected and processed at
lower speeds than for the conventional method of back-EMF sensing.
Moreover, an alternative way to acquire the third harmonic signal without the
need to access the stator neutral terminal was discussed. It clearly described
the rotor flux position detection for brushless permanent magnet AC motor
operating over a wide speed range.

Kettle et al (1998), gave the comparison between the two sensorless
control algorithms applied to brushless DC motors with trapezoidal back
electromotive force (EMF)

1) The Extended Kalman Estimator (EKE)

2) The back-EMF Integration (BEI).

The observation model was provided based on the expressions of
the back -EMF in the unexcited phase. The BEI algorithm senses the back-
EMF in the unexcited phase. EKE offers an estimation of the rotor position
and velocity every half of a PWM cycle. BEI algorithm only estimated the
rotor position when it detect a back-EMF zero crossing and the integration
threshold was reached. EKE is able to operate at higher speeds and loads
where the BEI algorithm would fail, because the decay period of the current
in the open phase increase and the zero crossing point is no longer available.
In general it concluded EKE is able to operate at higher speeds and torques,
but requires more computing power. BEI is easy to implement and suitable
for less demanding applications. Even though both the methods are having its
own advantage and disadvantage, these two methods must need a separate speed sensors, which surely increase the overall cost and that made the system to be complex.

Johnson et al (1999) provided a review of literature addressing the methods of sensorless operation of brushless DC machines which includes

1. Using measured currents, voltages and fundamental machine equations and algebraic manipulations
2. Using observers
3. Using back-EMF methods
4. Sensorless starting techniques
5. With novel techniques not in the previous categories.

Jung and Ha (2000), described a sensorless control of brushless DC motor using a Frequency Independent Phase Shifter (FIPS) which can shift the zero crossing point of the input signal with the specified amount of the phase. The detection performance was independent of the frequency of the input signal and quite robust with respect to the measurement noise. This control scheme needs only simple voltage sensing circuits, but not any special chopping patterns. This scheme needs once again three low pass filters, comparators, capacitors and resistors. The phase shift was produced using the filter only, but the phase shift induced by the filter depends on motor speed. So the exact commutation instant was difficult to achieve. Also the values of $P(t)$ and $N(t)$ depend on the rotating speed, and if the value of $y$ is less than one, a long bit-length divider must be realized to compute $P(t)$ and $N(t)$ precisely. However, a long bit-length divider may increase the total chip size.
Cheng and Tzou (2003), gave the design methodology to implement a sensorless commutation IC for brushless DC (BLDC) motors by using mixed-mode IC design technology. The special purpose IC was developed to generate optimal commutation signals for BLDC motors without Hall-effect sensors and can be easily interfaced with a microcontroller or a Digital Signal Processor (DSP) to complete the closed-loop control system. Furthermore, this IC solution requires less analog compensation circuits than other commercial motor control ICs. Therefore, high maintainability and accurate control was achieved. But for zero crossing detection it needs sample and hold circuit and counters. Once again this system also senses the position information from the phase voltage which create the harmonics and hence it was not possible to get the accurate speed. Starting procedure was based on open loop method only.

Amano et al (2003), jointly presented a sensorless drive system for Brushless DC (BLDC) motors using a Digital Phase- Locked Loop (DPLL). The Back Electromotive Force (BEMF) voltage was measured from the motor winding to determine the permanent magnet rotor position using the DPLL, and Pulse Width Modulation (PWM) limits the motor current to control the speed of BLDC motors. It can drive BLDC motors using an open loop control without stepping out. Also, this was compared experimentally with a control method that used the Hall sensors. Experimental results for the BLDC motor shows the effectiveness. The stability of the DPLL open loop was verified. The DPLL is a negative feedback device, and if the output signal phase delay of the DPLL open loop is $180^\circ$ then the corresponding gain of the open loop DPLL is 1, which made the DPLL open loop become unstable.

Bhim Singh et al (2003), analyzed the performance of a power factor correction (PFC) converter fed voltage source inverter (VSI) supplying Permanent Magnet Brushless DC (PMBLDC) motor drive for the variable
speed operation of an air conditioner (air-con). A single-phase diode bridge rectifier together with a boost converter was considered as a PFC converter, which improves the quality of the current drawn from the ac mains. This converter was capable of supplying a constant DC link voltage to VSI fed PMBLDC motor, even when the voltage of the AC mains fluctuates. The closed loop control of PFC converter and VSI fed PMBLDC motor provides a better control and facilitates energy conservation in AC distribution system, PMBLDC motor and the compressor of an air conditioner. This PFC converter fed variable speed VSI-PMBLDC motor drive was capable of smooth starting at full load and the speed of the drive can be controlled over a wide range to provide precise control of the air conditioning system alone.

Shao et al (2003), gave a novel back-Electromotive-Force (EMF) detection method for sensorless brushless DC (BLDC) motor drive systems. The true back-EMF signal was directly extracted for each phase without sensing the neutral point of the motor which is not sensitive to switching noise and requires no filtering. Good motor performance was achieved over a wide speed range as well. The high-frequency switching noise was rejected by the synchronous sampling, since the back-EMF was sampled during the PWM off time. Therefore, this back-EMF sensing method was immune to switching noise. This unique back-EMF sensing method has superior performance to others which rely on neutral voltage information, providing much wider motor speed range with low cost. This novel sensing scheme is implemented into a hardware macro cell inside a mixed-signal microcontroller. This microcontroller based sensorless BLDC drive system has been successfully applied to automotive fuel pump applications, which require high reliability and intelligence at a low cost. For position detection three comparators and filters were required, which makes the position detection circuit as complex.
Gui-jia Su and McKeever (2004), worked on Brushless DC motor and provided the low cost position sensorless control scheme. Rotor position information is extracted indirectly sensing back-EMF from only one of the three motor terminal voltages for a three-phase brushless DC motor. Low pass filter or high pass filter have used depending upon the sensing position. This leads the significant reduction in the component count of the sensing circuit. The cost saving is further increased by coupling the sensing circuit with the single chip microprocessor or Digital signal processor for speed control. In addition, they introduced the look up table based correction for the non-ideal phase delay introduced by the filter, to ensure accurate position detection even at low speed. So the operation speed range is also increased and this will improve the efficiency. The speed control achieved by this method is limited up to 1500 rpm.

Lelkes and Bufe (2004), described methods for the automatic optimization of motor efficiency by changing the commutation angle. In case of constant commutation angle, this angle can be optimized only for one operating point. Through this optimization, motor current and power consumption can be reduced. However, if the motor works in another operating point (different supply voltage, speed and/or torque), its efficiency will be lower than that of a motor with a commutation angle optimized for the new operating point. For fan application alone commutation angle method was optimized.

He et al (2004), presented the hardware and software architectures of the HIT/DLR Hand. The hand has four identical fingers and an Extra Degree of Freedom (D.O.F) for palm. In each finger, there was a re-configurable Field Programmable Gate Array (FPGA) for data acquisition, Brushless DC (BLDC) motors control and communication with palm's FPGA by Point-to-Point Serial Communication (PPSeCo). The kernel of the
hardware system was a PCI-based high speed floating-point Digital Signal Processor (DSP) for data processing, and FPGA for high speed (up to 25Mbps) real-time serial communication with the palm's FPGA. In order to achieve high modularity and reliability of the hand, a fully mechatronic integration and analog signals in-situ digitalization philosophy are implemented to minimize the dimension, number of the cables and protect data communication from outside disturbances. Furthermore, according to the hardware architecture of the hand, hierarchical software architecture has been established to perform all data processing and control of the hand. The software structure provide a basic Application Programming Interface (API) functions and skills to access all hardware resources for data acquisition, computation and tele-operation.

Chen and Cheng (2005), presented the design, analysis, implementation of a high performance and cost effective sensorless control scheme for the extensively used brushless DC motors (BLDCMs). Taking into cost consideration and ease of implementation, the commutation signals were obtained without the motor neutral voltage, multi-stage analog filters, A/D implementation, which were indispensable in the conventional sensorless control algorithms. Instead of detecting the zero crossing point of the non-excited phase back-EMF to the neutral voltage, the commutation signals are extracted directly from the specific average terminal voltages with simple RC circuits and comparators in this study. Since the neutral voltage was not needed, the extracted commutation signal is insensitive to the common mode noise, hence the low speed performance is superior to the conventional methods. Moreover, the complex phase shift circuit has been eliminated. As a result, the control algorithm can be easily interfaced with the cost effective commercial Hall effect sensor based commutation ICs. Because of the inherent low cost property, this is particularly suitable for cost sensitive products such as air purifiers, air blowers, cooling fans, and related home
appliances. Theoretical analysis and experimental results showed that the proposed control algorithm exhibits superior performance over a wide operation range when compared with the conventional solutions for water pumping application.

Jiang et al (2005), introduced a new rotor position detecting method for the sensorless control of spindle motors in hard disk drives. The method applies a digital filtering procedure to identify the true and false zero-crossing points of phase back electromotive forces, the latter of which are caused by the terminal voltage spikes due to phase commutations. The proposed method is phase-delay free and independent of motor parameters. It is especially suitable for high-speed sensorless brushless dc motors. This method used to drive many kinds of spindle motors for different hard disk drives alone.

Faeka et al (2005), introduced application of multi degree of freedom fuzzy (MDOFF) controller in permanent magnet (PM) drive system. The drive system model was developed for FO control. Simulation of the system alone carried out to predict the performance at no load and under load, hence it was found the application of MDOFF controller was ineffective for sensorless PM drive system.

Somanathan et al (2006), modelled and simulated the sensorless control of permanent magnet Brushless DC motor using zero crossing back-EMF technique. Simulation was done for different commutation angle and for different load conditions. From the result it was observed that the torque developed by the motor at larger delay angles was more pulsating due to more peak to peak currents. But no proposal for reduction of torque ripple was stated.

Shen and Iwasaki (2006), proposed that the Application-Specific Integrated Circuit (ASIC) should integrate the third harmonic back EMF
instead of the terminal voltage, such that the commutation retarding was largely reduced and the motor performance was improved. Basic principle and implementation of the new ASIC-based sensorless controller was presented. On the other hand, phase delay in the motor currents arose due to the influence of winding inductance, reducing the drive performance. Therefore, a novel circuit with discrete components was proposed. It also uses the integration of third harmonic back EMF and the PLL technique and provides controllable advanced commutation to the BLDC motor. This made the control circuit to be complex.

Wang and Liu (2006), presented the study about a design of an integrated new speed-sensorless approach that involved a torque observer and an adaptive speed controller for a brushless dc motor (BLDCM). This system based on the vector control drive strategy. The speed-sensorless approach first employs a load observer to estimate the disturbed load torque, and then the estimated load torque was substituted into the mechanical dynamic equation to determine the rotor speed, and thus developed a speed-sensorless algorithm. Additionally, the mechanical rotor inertia constant and the friction coefficient, which were the inputs of the load observer, were estimated using the recursive least-square rule. Therefore, this speed-sensorless approach was unaffected by the time-variant motor parameters and not affected by the integrator drift problem. It also has a simpler computing algorithm than the extended Kalman filter for estimating the speed. The modified model reference adaptive system algorithm, an adaptive control algorithm was adopted as a speed controller of the BLDCM to improve the performance of the speed-sensorless approach. The motor did not operate in a synchronous speed.

Kim et al (2006), presented a novel method to reduce commutation torque ripple in a position sensorless brushless DC (BLDC) motor drive. To
compensate the commutation torque ripple considerably, conventional methods should know commutation interval, so that current sensors are needed. However, the proposed method measures commutation interval from the terminal voltage of a BLDC motor, calculates a pulse width modulation (PWM) duty ratio using the measured commutation interval to suppress the commutation torque ripple, and applies to the calculated PWM duty ratio only during the next commutation. Experimental results are verified and the proposed method implemented in an air conditioner compressor controller alone and found that this method considerably reduces not only the pulsating currents but also vibrations of a position-sensorless BLDC motor.

Kumar et al (2006), presented the fuzzy pre-compensated PI (FPPI) speed controller for permanent magnet brushless DC (PMBLDC) motor drive. Various aspects of DSP based implementation of PMBLDC motor drive system such as inverter, position and current sensing, reference current generation and PWM current control are discussed in detail. The fuzzy logic algorithm used in this work particularly suitable for digital control because of the simplified way of handling the rule base and considerable reduction of computation during defuzzification process.

Thepsatorn et al (2006), implemented the speed control of a separately excited DC motor using fuzzy logic control (FLC) based on LabVIEW(Laboratory Virtual Instrumentation Engineering) program. LabVIEW, is a graphical programming environment suited for high-level or system-level design. Therefore, the principle that are data flow model, different from text-base programming and a sequential model. The user-friendly interface and toolbox design are shown the high level of suitableness and stability of LabVIEW and fuzzy logic on speed control of DC motor. The fuzzy logic controller designed to applies the required control voltage that sent
to DC motor based on fuzzy rule base of motor speed error (e) and change of speed error (ce).

Chen and Cheng (2007), designed a high performance cost effective sensorless control scheme for brushless DC motor. Design was simple and cost reduction was achieved by means of obtaining the commutation signals without motor neutral voltage, multi-stage analog filters, A/D converters and complex digital phase shift circuits. Performance was analyzed and stated that this scheme was suitable for cost sensitive products such as air purifiers, air blowers, and cooling fans and related home appliances. In this method some non continuous voltage spikes were created by the residual current when the armature current was blocked by the power switches. To avoid that voltage spikes some complex circuits to be needed.

Rodriguez and Emadi (2007), gave the novel concept for digital control of trapezoidal BLDC motors. The digital control was implemented in two different methods, namely conduction angle control and current mode control. Motor operates only at two operating points. Alternating between the two operating points results in an average operating point that produces an average operating speed. The controller design procedures were derived from Newton’s second law. This concept was simulated and verified experimentally using DSPACE and proved that this scheme had low cost and effective speed / torque regulator. The speed control was achieved only for low range speeds.

Katlain and Maior (2007), developed the virtual instruments to visualise the currents, voltages and to determine the commutation points. The developed VI Block connected to another VI which generates the switching signal. The current was measured using three current sensors and DAQ is used to send the data. The derivative of the current signal gave the switching
points which were produced through DAQ. A small BLDC drives in frequency control mode used in this concept. However two DAQ were used, which makes the system very costly.

Thirusakthimurugan and Dananjayan (2007), proposed a multirate based general predictive control (GPC) law performed for the conventional cascaded PI-PI scheme. Usually speed and position of a Permanent Magnet Brushless Direct Current Motor (PMBLDCM) rotor was controlled in a conventional cascade structure. The inner current control loop runs at a larger bandwidth than the outer speed control loop to achieve an effective cascade control. Both speed and torque tracking objectives were achieved in matched and mismatched parameter case. The measured and unmeasured disturbances was effectively rejected and the motor was run at desired speed at constant load. In addition, non-minimum phase characteristics and system constrains were effectively handled by proposed GPC algorithm. The simulation results were provided to show that the proposed GPC strategy results in better performance than that of the conventional well tuned cascade PI- PI control strategy.

Lin et al (2008), described a position sensorless control scheme for four-switch three-phase (FSTP) brushless DC (BLDC) motor drives using a field programmable gate array (FPGA). A novel sensorless control with six commutation modes and novel pulse width modulation scheme was developed to drive FSTP BLDC motors. The low cost BLDC driver was achieved by the reduction of switch device count, cost down of control, and saving of hall sensors. The feasibility of the sensorless control for FSTP BLDC motor drives were demonstrated by analysis and experimental results. However the estimated commutations may cause commutation torque ripple.

Bharathi et al (2008), proposed a controller systems consist of multi-input fuzzy (two-and three-input) logic controller (FLC) and multi-input
Integrated Fuzzy Logic Controller (IFLC) for the speed control of brushless DC servomotor drive. The input for the controllers are error e(k), change in error ce(k) and change of change in error cce(k) with a single-output. The error cce(k) was substantial at the overshoots / undershoots and therefore essential for accurate speed control of brushless DC motor. The error cce(k) has been introduced for the first time in the literature as one of the input in the FLC and IFLC design. The IFLC was designed using FLC and Proportional Derivation Integral (PID) controllers. The controller systems have been studied systematically for the transient and steady-state conditions. The three-input IFLC was found to be superior, more robust, faster, flexible, and insensitive to the parameter variations as compared with the FLC (with two- and three-input) and conventional two-input IFLC by using DAQ board of virtual Instrumentation. This made the system very costly.

Halvaei Niasar et al (2009), developed interest towards high efficiency, good performance, ease of control for many applications and reducing the drive components of a BLDC motor drive using the TMS320LF2407A Digital Signal Processor (DSP). Part reducing was achieved by elimination of three Hall Effect position sensors and reducing the number of power switches. The performance of the proposed reduced parts BLDC motor drive was verified via some simulations. Then, hardware and software details of the system were explored. An experimental setup based on TMS320LF2407A DSP controller was implemented to verify the theoretical results. This makes the system to be very costly compared to sensored control.

Abolfazl Halvaei Niasar and Abolfazl Vahedi (2009), explained a position sensorless control scheme for a four-switch, three-phase brushless DC motor drive, based on the zero crossing point detection of phase back-EMF voltages using newly defined Error Functions (EFs). The commutation instants are 30° after detected zero crossing points of the EFs. Developed EFs
had greater magnitude rather than phase or line voltages, so that the sensorless control worked at a lower speed range. Moreover, EFs have smooth transitions around zero voltage level that reduces the commutation errors. EFs were derived from the filtered terminal voltages $v_{ao}$ and $v_{bo}$ of two low-pass filters, which were used to eliminate high frequency noises for calculation of the average terminal voltages.

Xia et al (2009), jointly developed a four switch three phase brushless DC motor system to lower cost and improved performance. The system’s whole working process was divided into two groups. In first mode only the phase ‘c’ current was sensed to control the phases ‘a’ and ‘b’. In second mode phase ‘c’ current was maintained constant and other two phase currents were regulated for speed circle. To improve the control performance a single-neuron adaptive Proportional Integral (PI) algorithm was adopted to realize the speed regulator. For position detection the hall sensors were used which was not compatible for all environments and makes the system very costly.

Srinivas and Rajagopal (2009), gave the alternate solution for fixed gain PI speed controller being suitable for a limited operating range around the operating point and having inherent overshoot. They presented fuzzy based gain scheduled PI speed controller which eliminate these problems by enabling online tuning of the controller gains depending on the operating point. They described the application of a fuzzy gain scheduling algorithm for the PI type controller for the speed control of a PMBLDC motor. The controller has been implemented on a TMS320F2812 DSP for a 100 W PMBLDC motor.

Keshri et al (2010), observed that adoption of different possible switching patterns/schemes affects the transient behaviours such as phase current and torque of a PMBLDC motor. Four possible switching patterns
were achieved by modulating only upper/lower switches and incoming/outgoing phase switches. For the purpose of control of PMBLDC motor low cost ATMEGA 32 micro-controller was used to generate all the four possible switching schemes. Use of dummy hall sensor was a near ideal and cheaper approach to prepare micro-controller for the control of PMBLDC motor. Dummy Hall sensor signals were generated for variable speed reference with the help of micro-controller to analyze inverter voltages. Provisions were made to bypass the generated dummy hall sensor signal with actual hall sensor signal from the motor for the control purposes.

Narmadha and Thyagarajan (2010), presented a multi level inverter fed Permanent Magnet Brushless DC Motor (PMBLDCM) with a simplified voltage control technique. The technique was based on the “indirect position sensing,” which was justified by the observation that position sensing came indirectly from voltage and current waveforms. The switching angle for the pulse was selected in such a way to reduce the harmonic distortion. This drive system has advantages like reduced total harmonic distortion and higher torques. PI, Fuzzy and Hybrid (Fuzzy and PI) controllers were discussed. Closed loop simulation response was obtained for PI, Fuzzy and Hybrid controller with a disturbance in the input source. The conventional circuit was improved by introducing Hybrid controller. In Industrial application the physical integration of Hybrid controller in the motor body itself was able to make them most suitable for low power (0.5hp) blowers and low power (50W) tube axial fans for cooling the electronic equipment. The performance of the PMBLDCM system was simulated and implemented. Simulation results of these systems were presented and the performance measures were compared. The simulation results with Hybrid controller indicate the improved performance. The experimental results were compared with simulation results.
Varatharaju et al (2011), presented a tuning methodology for the parameters of adaptive speed controller in a permanent-magnet brushless DC (BLDC) motor and drive system. Discussion was done about a design of the closed loop drive system employing the adaptive-network-based fuzzy interference system (ANFIS) from a mathematical model of the BLDC drive system. The ANFIS based control with nonlinear simulation model of the BLDC motors drive system was simulated in the MATLAB/Simulink platform. The necessary data for training the ANFIS control was generated by simulation of the system with conventional PI controller.

In all previous methods the speed control was limited to lower ranges (ie) below 5000 rpm only. In high speed application the circulation current produced create the over shoot problems. In order to run the PMBLDC motor at high speed at reduced cost, the six switch inverter is converted in to four switches and for the speed control the controller like micro controller (or) DSP is completely eliminated. Instead of that the fuzzy controller virtually created in the virtual instrumentation software LabVIEW is used.

The position information is detected indirectly by using line voltage difference. Hence the sensors (Hall sensors) are completely eliminated. The line voltage difference zero crossing points gave the position information by using filters and comparators. By this position detection method the harmonics are eliminated and torque ripples are reduced.

The difference of the line voltages increases the gain of the back-EMF which enables better zero crossing detection resulting in a faster start up of the motor from standstill. The line voltage difference is directly given to the filters which filter out the other harmonics and then the comparator will detect the zero crossing which is directly given to the LabVIEW program through RS232 using simple DAC. The other costly DAQ devices suited for virtual instrumentation is also eliminated. The data fed from the common DAQ is
used to calculate the actual speed. The reference speed is given in LabVIEW, which is compared with actual speed and produces the error signal. Depending upon the error signal the frequency at which the PWM Gate pulses for the inverter switches are produced is also generated from the LabVIEW. This frequency signal is initially given to the microcontroller which produces the corresponding PWM pulses. Hence the output voltage from the inverter is varied which is given to BLDC motor directly. By this way depending upon the output voltage of the inverter, the speed controlled was achieved only up to 5000 rpm.

To increase the speed, the FPGA controller is used because of the following advantages:

(i) FPGA contains a matrix of reconfigurable gate array logic circuitry that when configured is connected in a way that creates a hardware implementation of a software.

(ii) Unlike processors, FPGA’s use dedicated hardware for processing logic and do not have an operating system.

(iii) The processing paths use parallel, different operations do not have to complete the same processing resources.

(iv) Hence by using FPGA the operating speed can be very fast, and multiple control loops can run on a single FPGA device at different rates.

Because of the parallel processing ability the speed control achieved very quickly without any peak over shoots. To achieve the reduction in cost, two of the inverter switches are completely eliminated, instead of that two single capacitors are used. The speed control achieved by this method is up to 7000 rpm without any peak over shoots.
Further to reduce the cost, the processor is completely eliminated, the virtual fuzzy controller in LabVIEW is used. The fuzzy tool in the LabVIEW produces the switching PWM pulses. Thus by using virtual fuzzy controller in LabVIEW the speed control of PMBLDC motor is achieved up to 8000 rpm, with reduced cost.

1.3 OBJECTIVE OF THE THESIS

Objective of this research work is in three fold: firstly the sensorless speed control of PMBLDC motor using microcontroller and LabVIEW. By this indirect position detection method the speed control is achieved only up to 5000 rpm.

Secondly to achieve the high speed and fast response, the FPGA controller is used. To reduce the total cost, instead of six switch inverter, four switches and two capacitors are used. This reduces the total switching losses also. By means of this control the speed control is achieved up to 7000 rpm.

Thirdly to achieve better performance and high speed with reduced cost the virtual fuzzy controller in virtual instrumentation software LabVIEW is used. The peak over shoot is eliminated and speed control up to 8000 rpm is possible with less settling time.

1.4 ORGANIZATION OF THE THESIS

The remaining chapters of the thesis are organized as follows:

Chapter 2 provides a wide report on FPGA architecture, overview of the Virtual Instrumentation and a graphical development environment with built-in functionality for simulation, data acquisition, instrument control, measurement analysis, and data presentation, the LabVIEW programme.
Chapter 3 gives a detailed study on the realization of indirect position detection of permanent magnet brushless DC motor and torque ripple minimization. Digital simulation was carried out to simulate the indirect position control by line voltage difference using PSIM. This novel position detection reduced the torque ripples using filters. The entire work is simulated in PSIM. The indirect position detection and speed control of PMBLDC motor Using LabVIEW and microcontroller also discussed in detail.

Chapter 4 presents the remaining research contribution of the thesis. In the first part of thesis the indirect position control for six switch inverter fed PMBLDC motor is achieved with the help of the FPGA and the waveforms were seen in virtual instrumentation programme. In the second part of the thesis the same method of control is implemented for four switch inverter fed PMBLDC motor to reduce the cost. All the above techniques are implemented and the results are shown with evident output waveforms.

Chapter 5 deals with the cost effective speed control of PMBLDC motor. The fuzzy controller is virtually created and implemented in real time sensorless control. Experimental results proved that this design reduces the cost by means of virtually creating controller and zero crossing detection circuits. Compared to conventional methods wide range of efficient speed control is effectively achieved.

Chapter 6 is the general conclusion which summarizes the work presented in this thesis, and the main contribution of the present work are highlighted. A different potential research directions about the cost effective indirect position detection and wide range of speed control of PMBLDC motor using FPGA and Virtual Instrumentation is also presented.
1.5 SCOPE OF THE THESIS

Nowadays the field of power electronics has developed to a great extent, that the performance of the drive motor can be increased with the increase in triggering signals. In addition, the DSP processors play a vital role which goes hand in hand with the power electronic tools. In this thesis indirect position detection technique using line voltage difference is implemented in FPGA with the help of Virtual Instrumentation with certain constraints with system generator tools. Further if only the new virtual instrumentation tools are created depending on the necessity then the efficiency and the performance of the PMBLDC motor can be controlled to a larger extent resulting in the reduction of harmonic level.