CHAPTER 1

INTRODUCTION

1.1 GENERAL

For almost three quarters of the twentieth century, most of the AC drives for industrial and domestic uses have been designed to operate at constant speed. DC machines were used extensively in variable speed drive over the past decades mainly because of the decoupled control of flux and torque that could be achieved by the field and armature control respectively. They are mostly used in variable speed applications to give a fast and good dynamic torque response because the commutator maintains a fixed torque angle at all times. However, DC motors have disadvantages of higher cost, higher rotor inertia and maintenance problem with commutators and brushes. In addition they cannot operate in dirty and explosive environments (Bimal Bose 2002, Krishnan 2005).

AC drives are nowadays dominating the drive market in high performance applications where variable speed and torque control is needed. AC drives have several advantages over DC machines. They are robust, require less maintenance, cheaper and operate at high speed. Therefore, in last three decades the DC motors are progressively replaced by AC drives (Ward Leonard 2001, Fitzgerald and Umans 2003).

Now, with the availability of economical variable frequency electric supplies, resulting from advances in power electronic switching
devices and the development of high computation capability digital controllers such as digital signal processor (DSP) and field programmable gate array (FPGA), etc, electric drives are increasingly being used for operating industrial load at any one of a wide range of speeds. In many modern applications such as electric vehicles, elevators, robotics, wind generation system, ship propulsion, paper and steel mills, etc, are required for precise and continuous control of speed, torque, or position, with long term stability, good transient performance and high efficiency (Bimal Bose 2002, Boldea et al 1992, Naouar et al 2007, Idkhajine et al 2009, Toh et al 2005).

1.2 MOTIVATION

An electrical motor is the workhorse in a variable speed drive system, and its function is to convert electrical energy into mechanical energy in various industrial applications. Induction Motors (IMs), particularly the cage type, is commonly used in variable speed drives among all types of AC motors. The IMs are simple in construction, economical, rugged, reliable, and are available in a wide power range (Ward Leonard 2001, Fitzgerald and Umans 2003).

Variable speed drives require variable voltage and frequency supply which is invariably obtained from a three phase voltage source inverter (VSI). A number of pulse width modulation (PWM) schemes are used to obtain variable voltage and frequency supply from an inverter. The most widely used PWM schemes for a three phase VSI are carrier based sinusoidal PWM (SPWM) and space vector PWM (SVPWM). There is an increasing trend of using space vector PWM because of their easier digital realization and better dc bus utilization (Holtz 1992, Fukuda et al 1990, Van der Broeck et al 1988, Murphy et al 1983).
In scalar control IM speed and torque can be controlled using inverters by regulating the voltage and frequency of the inverter AC output. To maintain constant torque at wide speed range, the voltage to frequency ratio is kept almost constant, to maintain constant air gap flux. The scalar control methods of IM drive is simple to implement but have the disadvantages of sluggish control response because of the inherent coupling effect in the machine and easily prone to instability (Bimal Bose 2002, Krishnan 2005).

Vector techniques are used to adjust the instantaneous values, thus permitting high dynamic performance of the drive. Field oriented control (FOC) and Direct torque control (DTC) are the two most popular vector control methods for high performance AC drives. Based on vector control theory, the FOC appeared to have similar performance to the DC machine over a wide range of speed and load conditions, but the performance of a FOC implementation depends critically on very accurate co-ordinate transformations and flux angle estimation, which are complex calculations and sensitive to variations in motor parameters (Blaschke 1972).

Compared to FOC, DTC can provide extremely high dynamic response with very simple structure, that is, no need of rotary co-ordinate transformation, inner current regulator, or pulse width modulation block. However, conventional DTC employs two hysteresis comparators and a heuristic switching table to obtain quick dynamic response, which causes undesired torque and flux ripple, variable switching frequency and acoustic noise (Takahashi et al 1986, Buja et al 2004, Casadei et al 2002).

In the past decades, numerous schemes have been proposed to address these problems of DTC. Many of them (Habetler et al 1992, Casadei et al 2003, Lai et al 2001, Lascu 2004) employ space vector pulse width modulation (SVM) to produce continuous voltage vectors, which can adjust
the torque and flux more accurately and moderately, hence the torque and flux ripples were reduced while obtaining fixed switching frequency. All of these techniques however increase the complexity of the drive systems. Thus, the inherent simple control structure of the conventional DTC drive is lost.

The motor flux is the main component to calculate torque and speed. Therefore, accuracy of the estimation flux is very important. Flux estimation is significant task in implementing of high-performance motor drives. The flux estimator algorithms can be divided into two groups in terms of the input signal. The currents and voltages are the input signals to the voltage models (VM), while the currents and speed or position information are the input signals to the current models (CM). Obviously, for sensorless control schemes general voltage models with many different modifications and improvements are used. The voltage model, on the other hand, is normally used in a high speed range since at low speed some problems arise (Habetler et al 1998, Jun Hu and Bin Hu 1998, Hust et al 1998). In classical VM-PI model a small dc off-set present in the back emf due to noise or measurement error inherently present in the current sensor, can cause the integrator to saturate. To overcome this problem, one tends to favor a technique based on low pass filters (LPF) with fixed or variable cut-off frequency instead of a pure integrator. The replacement can largely alleviate the dc offset problem on pure integrator while the magnitude and phase angle error are significantly reduced in the lower frequency range (Gaolin Wang and Dianguo 2008, Kun Zhao and You 2009).

The use of SVM in conjunction with DTC has been proposed as a solution to overcome the above mentioned drawbacks. The SVM-DTC with LPF based flux and torque estimator requires the information of stator flux, which can be easily obtained from the voltage model with LPF. This control scheme is simple in structure and employed instead of hysteresis controller as
for conventional DTC, a PI controller, a LPF based flux and torque estimator and SVM. It allows to achieve fixed switching frequency, what considerably reduce switching losses as well as torque and current ripples as in FOC. Therefore, this new scheme SVM-DTC with LPF based flux and torque estimator is the subject of this thesis.

It is currently a popular tendency to introduce advanced very large scale integration (VLSI) techniques such as field programmable gate array (FPGA) into AC drive control (Rodriquez et al 2007, Monmasson et al 2007, Idkhajine et al 2009, Naouar et al 2008, Zhengwei et al 2005, Zhang et al 2008, Fratta et al 2004, Bueno 2009). Compared with DSPs and application specific integrated circuits (ASICs) those dominate the most available motor control applications, FPGA technique provides a relatively low cost solution by combining the advantage of both two methods. Different from DSP, all the internal logic elements of the FPGA and all the control procedures are executed continuously and simultaneously (Fratta et al 2004, Bueno et al 2009).

1.3 LITERATURE SURVEY

Generally, the AC motor drive system is categorized into scalar and the vector control. Referred to as Voltage/Frequency control (V/F control), scalar control uses the pulse width modulation (PWM) directly to control a frequency converter’s output voltages for indirect control of a motor’s rotational speeds, scalar control methods has drawbacks such as small start torques, slow response rates, poor accuracy, and influences from the load (Bimal Bose 2002, Krishnan 2005).

The vector control group allows not only control of the voltage amplitude and frequency, like in the scalar control methods, but also the instantaneous position of the voltage, current and flux vectors. This improves
significantly the dynamic behavior of the drive. However, IM has a nonlinear structure and a coupling exists in the motor between flux and the produced electromagnetic torque. Therefore, several methods for decoupling torque and flux have been proposed. These algorithms are based on different ideas and analysis (Ward Leonard 2001, Trzynadlowski 2002).

The invention of vector control FOC in early 1970 by Blaschke enables rugged induction machines to be controlled similar to that of DC machines (1972). FOC provides similar decoupled control of torque and flux, which is inherently possible in the DC machines. The motor input currents are adjusted to set a specific angle between fluxes produced in the rotor and stator windings. The rotor flux position angle with respect to the stator must be known in this method. Once the flux angle is known, an algorithm performs the transformation by changing three-phase stator currents into the orthogonal torque and flux producing components. These components are controlled in their d-q axis and an inverse transformation is used to determine the necessary three-phase currents or voltages (Lipa 1988, Shieh et al 1999).

Although, the FOC enables an induction motor to attain good torque response, some problems still exist. An accurate flux estimator had to be employed to ensure the estimated value used in calculation does not deviate from the actual value. Besides, the co-ordinate transformation had increased the complexity of this control method (Bimal Bose 2002, Casadei et al 2002).

DTC was first introduced by Takahashi in 1986 and it enables both quick torque response and efficient operation (1986). It has many advantages compared to FOC, such as less machine parameter dependence, simple implementation and quicker dynamic torque response. It only needs to know the stator resistance and terminal quantities like voltage and current in order

Although DTC has many advantages over vector control, it still has some drawbacks as reported in recent literature. The switching state of the inverter is updated once only in every sampling interval. The inverter keeps the same state till the outputs of the hysteresis controllers change states. As a result, the ripples in torque and flux are relatively high when compared with those of the vector control drive system (Depenbrock 1988, Foo et al 2010, Ambrozic et al 2008, Andreescu et al 2008). Furthermore, the switching frequency of the inverter is not constant it changes with rotor speed, load torque and the bandwidth of the two hysteresis controllers. In order to overcome these problems, a number of methods had been proposed in the literature.

Basically these can be divided into hysteresis based and non-hysteresis based solutions (Kazmierkowski et al 1995, Nash 1997, Maes et al 2000). In hysteresis band based solutions comparators had been designed where the band can be adjusted to maintain constant switching frequency. For non-hysteresis based solutions, a few techniques have been proposed, including the use of intelligent control techniques, predictive control schemes and space vector modulation which had been published in (Habetler et al 1992, Lai et al 2001, Tang et al 2003, Bird et al 1997).

Another problem normally associated with conventional DTC scheme is the high torque ripple. Ideally, small torque hysteresis band will produce small torque ripple. However, for microprocessor based implementation, if the hysteresis band is too small, the possibility for the torque to touch the upper band is increased. As a result, the possibility of selecting a reversed voltage vector instead of zero voltage vector will also

In conventional DTC, the current is not fully under control, since there is no current controller in the inner loop of the closed system like FOC. The problems in the low speed operation are due to the fact that, in conventional DTC, there is no PWM and a single space vector is directly selected from a look up table in order to correct instantaneous errors on the torque and stator flux magnitudes, by confining their evolution in time within predefined hysteresis band. Since the switching frequency remains unchanged, the duration of voltage vector is too long, which results in the notable torque and flux ripples.

In contrast to hysteresis comparator employed in the conventional DTC for the determination of voltage vectors, fuzzy control or the neural network are used in DTC. But they had worse efficiency in control than the method of applications of a hysteresis comparator significantly (Attaianese and Tomasso 1999, Maes and Melkebeek 2000). According to different conditions, a different voltage vector selection table is designed to satisfy the requirements. However, it complicates the hardware circuit and loses the original easy implementation of conventional DTC, because of using a sophisticated switching table.

Lee et al (1990) presented a survey of fuzzy logic controllers and a methodology for constructing a fuzzy logic control and assessing its performance is described and the areas that need further research are pointed out.

Adnanes (1990) developed the torque analysis of induction machine in per unit mode and obtained the detailed mathematical relationship between the flux and torque.
Raymond and Lang (1991) presented the real time adaptive control of the induction motor by using the Motorola 68020 microprocessor. The motor model was linearized for the proposed controller and the non linear effects of the inverter and system dynamics that cannot be modeled were omitted. The mechanical parameters were estimated so that they could be taken into account for the controller.

Pelczewski et al (1992) performed the optimal model tracking control of Induction Motor. In order to have the controller doing the computations, motor model and its linearization were required.

Habetler et al (1992) presented dead-beat controllers to control stator flux and torque, and to generate the reference voltage of the SVM modulator. In order to generate the voltage command of SVM, the so-called deadbeat controller is invoked. However deadbeat controller requires calculating several complicated equations in real time.

Matsui and Ohashi (1992) proposed a DSP based adaptive controller for Induction Motor. Therefore they proved that the DSPs can be implemented in motor controls as well.

Chern and Wu (1993) presented the position control of the Induction Motor by using the variable oriented controller. The controller instantaneously does the calculations depending on the unknown load and motor parameters. The system model is required and computations require very long periods of time.

Kim et al (1994) proposed a fuzzy logic based pre compensation approach for conventional PID controller which is widely used in industrial application and exhibit poor performance when applied to system containing the unknown nonlinearities.
Ogasawara and Akagi (1996) realized the position estimation of the Induction Motor for zero and low speed conditions according to the saliency. The position estimation is 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.

Buja et al (1998) presented a predictive controller to generate the reference voltage, which consists of a feed-forward controller, a dead-beat controller and two integrators. However, these two schemes require calculating many complicated equations on-line, depend on the accuracy of IM parameters. Rahman et al (1999) achieved the direct torque control by using a method based on obtaining the d and q-axis voltages using certain coefficients.

Jun Koo and Seung-Ki (1999) proposed a new direct torque control of induction motor for minimum ripple and constant switching frequency. Three PI controllers one each for speed, torque and flux feedback loops are used. Luukko (2000) developed the switching table for the direct torque control by adding the zero vectors to the vector selection algorithm.

Akatsu and Kawamura (2000) presented online rotor resistance estimation using the transient state under the speed sensorless control of induction motor but they made overall control system complicated. Vaez-Zadea (2001) experimentally achieved the constant torque control on a vector controller by using the TMS320C31 DSP. In this study, the torque did not respond well in terms of the desired torque value and response time, since the DSP technology was not sufficient to implement the dynamic behavior of the motor.
Tan et al (2001) and Martins et al (2002) proposed to reduce the torque ripples and fix the switching frequency in AC drive systems by using a multi-level inverter. These methods result in better waveforms, reduce the distortions, and are capable of operating in lower switching frequency. However, on the other hand, they require more number of switching devices. Moreover, the control strategies of these methods are very complicated.

Lai et al (2001), Lascu et al (2000) proposed proportional integral controllers for the stator flux and torque regulations, but dynamic response is limited by the PI controllers. Kadjouds et al (2001) proposed a fuzzy algorithm for speed control of PMSM drive. The proposed FLC algorithm comprises of a classical fuzzy controller and if then rules and is defined by gradually varying symmetrical triangular membership function, adaptive FLC is also included in this work. Dariusz et al (2002) implemented the space vector modulation by using a DSP and achieved the direct torque control.


Luukko et al (2007) presented the different rotor and load angle estimation methods for the direct torque control. They directly calculated the load angle form the IM equations. In these calculations, they used the tangent function. When the results of the DSP controlled inverter and the motor test setup are investigated, it is seen that the rotor angle estimation has oscillations.
Noriega et al (2007) designed a fuzzy logic controller for the DTC. They used the torque error and the stator current for the fuzzy logic membership functions. In addition to the simulation studies, they used an AC motor setup called platform III by implementing fuzzy logic functions to the software of this setup. Both simulation and the experimental results show that the stator current is not in a waveform and it has some uncertain and random shapes.

Chan et al (2007) designed an output filter for a direct torque controlled inverter. The filter is composed of an RLC filter and an isolation transformer. This study is interesting since it includes both the transformer design and the soft switching techniques in power electronics. Furthermore, it is true that the transformer and RLC based filter will add significant cost to the system instead as compared to the developments in the generation of inverter switching signals in terms of controls.

Jilong et al (2008) proposed an improved Kalman filter in order to sensor-less estimation of the rotor’s initial position in DTC. For this reason they employed high frequency signal injection method. Since the high frequency signal is weak, it would not help the rotor’s motion. Therefore, the rotor speed is assumed to be zero. The computation intensity is very high due to the fact that the current and voltage quantities are obtained through differential inequalities depending on the speed.

Liu et al (2009) tried to use the predictive control method in direct torque control. Experimental results were obtained by using a DSP. However, in the experimental results, they implemented complicated trigonometric functions. In the experimental results, much more flux drop can be observed as compared to their simulation results. They could apply the proposed application by reducing the flux reference.
Geyer et al (2010) achieved the direct torque control of the PMSM by implementing a model predictive control algorithm that reduces the switching frequency and hence the switching losses. Guo et al (2009) applied the space vector modulation in a matrix converter for DTC. In this study, the signals for the matrix converter are generated by a DSP where the dual space modulation was used. However, it is seen that the current drawn by the matrix converter has very high total harmonic distortion.

Zhang and Gui (2008) introduced adaptive sliding mode variable structure control to improve the robustness of the system. Some schemes have managed to maintain constant switching frequency and low torque and flux ripples by utilizing space vector modulation with deadbeat torque and flux control (Habetler et al 1992), multilevel inverter (Kuro et al 2007), matrix converter (Cai-bin-jun et al 2010), adaptive flux observer (Zhifang Zhang et al 2010) and eighteen sector switching strategy (Gupta et al 2011). All of these techniques however increase the complexity of the drive systems. Thus, the inherent simple control structure of the conventional DTC drive is lost.

Marcin Zelechowski (2005) presented DSP based Space vector modulated - Direct torque controlled (DTC-SVM) inverter fed induction motor drive system. But, the flux estimator for the sensorless mode is based on the Voltage model with Reference Flux (VM-RF). Thus the algorithm is sensitive on accuracy of inverter output voltage calculation and dead-time effect. The dead-time compensation increases the complexity of flux estimator algorithm.

Vamsidhar and Fernandes (2004) proposed a method for designing and implementing direct torque control of induction motor based on Hardware - in - the loop simulation (HIL simulation). Two different strategies, conventional direct torque control and space vector PWM based direct torque
control are tested and implemented. The entire simulation is performed in real time using TMS320F240 digital signal processor. But the proposed SVPWM based DTC is with closed loop torque and flux control loops. The drawbacks of having closed loop torque and flux control are (i) Require coordinate transformation (ii) Interaction between torque and flux loop (iii) Must have decoupling circuit (iv) Require fast digital signal processor.

Mir et al (1998), Hu et al (1998), Kuo-Kai Shoyu et al (2004), a predictive controller was used to generate the voltage command for inverter control using SVM technique. However, the predictive controller consists of a deadbeat controller, a feed forward controller and two integrators and the implementation of pure integrator is difficult because of dc drift and initial value problems (Casadei et al 2001). The alternate method, which eliminates with initial conditions and dc drift, which appear in pure integrator, is a method with low pass filter (LPF) (Kazmierkowski et al 2002).

Nowadays, the embedded electrical systems are playing an increasingly important role in industrial control applications in different domains such as automotive, space and aircraft domains. The rising industrial demands in terms of performance and reliability require the use of complex and efficient control algorithms associated with high performance digital technologies.

Along this trend and when focusing on AC drive applications, the sensorless controllers are becoming an interesting alternative to standard controllers. Therefore, many researchers have been focused on the embedded electrical systems thanks to their attractive cost and size reduction associated to high reliability. Such sensorless controllers are well known for their complex computation which represents a real design challenge for implementing these strategies for embedded systems. Consequently, the use
of efficient digital technologies became primordial since they allow the implementation of such complex controllers (Matsuse 2001, Casadei 2001).

In general, power electronics controllers can be classified as analog controller and digital controller. The main advantages of analog solution are low price and ease of use. With the development of the control techniques and algorithms, the control becomes more and more complex. Although there are still several commercial ICs for solving this type of control problems, the cost reduction and improving performance of a digital controller have made it an ideal solution for the power converter control applications. The digital controller can also reduce the designing time. More and more research on power converter control using digital controller has been done in recent years (Shih-Liang Jung et al 1999, Dinavahi et al 2001, De Castro 2003).

There are different kinds of digital controllers. The first generation of digital controller is Microcontroller. Since the early 1980s, Microprocessors, Microcontrollers and Microcomputers have started and tended to present tremendous impact on power electronics (Sen 1990). Different from the existing analog controllers, they can enable the implementation of sophisticated and complex control techniques with computer programs in a much easier way.

A digital signal processor (DSP) is a specialized microprocessor. It has the following characteristics.

- A DSP has faster program execution due to its hardware architecture that permits the overlap of instruction fetch and execution of consecutive instructions.

- A DSP chip also uses a dedicated hardware multiplier and barrel shifter and permits these functions in one instruction cycle time.
• DSPs can exploit use of C language or assembly code for optimized performance.

• DSPs well suited for extremely complex mathematical-intensive tasks. DSPs operate in step by step manner and hence can provide the ability for the simple re-use of the processing units (Bose 1992).

Due to the sequential operations, that is, instructions are executed one after the other, and shared resources like memory buses, DSPs are not very common in high switching frequency applications or applications that require massively parallel calculations.

In contrast, field programmable gate array (FPGA) performs entire procedure with concurrent operation (parallel processing via hardware) using reconfigurable hardware. For its powerful computation ability and flexibility, the FPGA may be the best solution to achieve excellent performance in ac drive system. Employing FPGA in implementing vector control strategies provides advantages such as rapid prototyping, simpler hardware and software design, high speed computation and hence fast switching frequency (Idkhajine 2009, Tole Sutikno, Azuani Jidin 2010, Nekoei 2011).

FPGA offers the most preferred way of designing electric drives and control applications. They are basically interconnection between different logic blocks. When design is implemented on FPGA they are designed in such a way that they can easily modified if any need arise in future. This feature of reprogramming capability of FPGA makes it suittbale to make the design using FPGA. Also implementation of FPGA based digital control schemes proves less costly and hence they are economically suitable for electric drives and control designs (Naouar 2007, Monmasson 2007). Hence in this thesis FPGA based SVM-DTC is discussed.
1.4 THESIS OBJECTIVE AND CONTRIBUTIONS

The objective of this thesis is to study, implement and improve the performance of the FOC and DTC of induction motor drives. The thesis proposes a simple method to improve the torque response and reduce torque ripple and current distortion. The simple control structure of the DTC is preserved. The contributions of this thesis are as follows:

- It utilizes SVM to achieve fixed switching frequency, which considerably reduce switching losses as well as torque and current ripples.
- It proposes voltage model based flux and torque estimator with low pass filter which overcomes the problem in pure integrator based estimator.
- It improves the response of the torque produced by implementing the SVM and proposed LPF based estimator.
- It performs simulations to compare and analyze the performance of FOC, conventional DTC and proposed SVM-DTC using MATLAB/SIMULINK R2009b simulation package.
- It performs FPGA modeling using Xilinx System Generator 12.3 in MATLAB/SIMULINK environment and performs simulation using Xilinx’s inbuilt Integrated Synthesis Environment Simulator (ISim).
- It develops an experimental set-up to verify the proposed SVM-DTC drive utilizing Xilinx Spartan 3E FPGA.
1.5  THESIS ORGANIZATIONS

A brief review of the contents of this thesis is given as follows:

Chapter 2 presents mathematical model of induction motor, voltage source inverter construction and comparison of SPWM and SVPWM are presented.

Chapter 3 presents principle of FOC, conventional DTC and proposed SVM-DTC schemes. The proposed scheme consists of SVM and LPF based torque and flux estimator.

Chapter 4 evaluates the performance of the FOC, conventional DTC and proposed SVM-DTC via simulation using MATLAB/SIMULINK package, gives analysis and advantages and disadvantages of all methods.

Chapter 5 is devoted to architectural overview of FPGA, modeling and simulation of proposed scheme using Xilinx System Generator in MATLAB/SIMULINK environment and describes the experimental set-up in this research.

Lastly, Chapter 6 gives the conclusion of the thesis and possible directions of further research.