Chapter – I

CHAPTER 1
INTRODUCTION

1.1. INTRODUCTION

Although machines were introduced more than hundred years ago, the research and development in this area appears to be never ending. For machine drive applications, multiphase induction motor could potentially meet the demand for high power electric drive systems which are both rugged and energy efficient. High phase number drives possess several advantages over conventional three phase drives such as reducing the amplitude and increasing the frequency of torque pulsation, reducing rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, lowering the dc link current harmonics, higher reliability and increased power. Multiphase induction motors have found many applications such as electric/hybrid vehicles, aerospace applications, ship propulsion etc.

1.1.1 Status of Variable Speed Drive

The electrical machine that converts electrical energy into mechanical energy and vice versa, is the workhorse in a drive system [56]. The basic function of a variable speed drive is to control the flow of energy from the mains supply to the mechanical system process. Energy is supplied to the mechanical system through the motor shaft. Two physical quantities are associated with the shaft namely torque and speed, in practice either one of them is controlled and referred to as torque control or speed control.

Apart from flexibility of operation at various frequencies, variable frequency drives have an added advantage of energy conservation. Figure 1 show how the power consumption reduces in variable frequency drives as compared to constant speed drives [55] - [59].

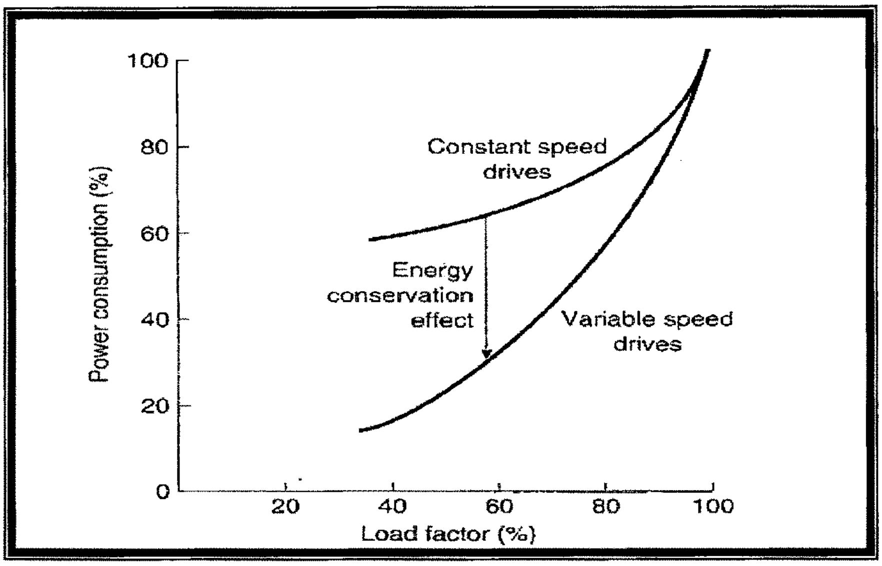

Fig.1.1. Energy Saving Characteristics of Variable Frequency Drives

In the past ac motor drives were mainly used in fixed speed applications. Variable speed applications were dominated by dc drives. Direct current (dc) motor drives were used for speed control because the flux and torque of dc motors can be controlled independently and the electromagnetic torque is linearly proportional to the armature current. Thus desirable speed and position control can be achieved.

But dc motors have disadvantages due to existence of commutator and brushes. Firstly Brushes require periodical maintenance secondly owing to the sparks created by the commutators; dc motors cannot be used in potentially explosive environment. Finally mechanical contacts of commutator and brushes limit high speed operation [55] - [59].

These problems can be overcome by ac motors which have simple and rugged structures. Their small dimensions as compared to dc motors allow ac motors to be designed with substantially higher output rating, low weight and low rotating mass.

Although squirrel cage induction motor was cheaper than dc motor, the converter and control circuit of an induction motor drive was very expensive compared to those for a dc drive. Therefore the total cost of an induction motor drive was significantly higher than that of a dc drive.

The fast progress in the development of ac motor drives in the past two decades was mainly due to development of power electronic devices, powerful and inexpensive microprocessors and modern ac motor control technologies. This resulted in reduction in cost of ac drive [59].

The ac variable speed drive has experienced two major control strategies namely scalar control and vector control.

Scalar control is used in low cost, low performance variable speed drives. This method does not guarantee good dynamic performance because transient states of motor are not considered in the control algorithm. Though some efforts were made to improve the scalar-control performance, the result is still unsatisfactory. So the vector control was introduced by Hasse and Blashke in order to achieve performance comparable to dc drives. Main advantage of vector control is that good dynamic performance of the drive is obtained. [55].

1.2 MULTIPHASE INDUCTION MOTOR DRIVE

Amongst many types of electrical motors, induction motors still enjoy the same popularity as they did a century ago. Several factors which include robustness, low cost and low maintenance have made them popular for industrial applications when compared to dc and other ac motors. Another aspect in induction motor drives which has been researched recently is the use of multiphase induction motors where the number of stator phases is more than three. Here, a multi-phase system is a system with more than three stator phases.

Among the different multi-phase induction motor drives being researched, following important advantages are derived for the dual-3-phase induction motor having two stator winding sets spatially shifted by 30 electrical degrees with separated neutral.

1. The current stress of each semiconductor power device is reduced by one half compared with the same power 3-phase conventional induction motor [1].

2. The dual-3-phase solution can generate higher torque as compared to conventional three phase motor. This characteristic makes them convenient in high power and/or high current applications, such as ship propulsion, aerospace applications, and electric / hybrid vehicles (EV). [5]

So when high power levels are required, the use of six-phase induction motor is one of the alternatives in industry. Six phase synchronous motor may also be used for high power applications, but weight of six phase induction motor is less as compared to six phase Synchronous motor of same rating [13]-[49].

1.3 LITERATURE SURVEY

In order to frame research problem, extensive study of the Multiphase induction motors and their related problems was carried out.

Three-phase induction machines are today a standard for industrial electrical drives. Cost, reliability, robustness and maintenance free operation are among the reasons these machines are replacing dc drive systems. The development of power electronics and signal processing systems has eliminated one of the greatest disadvantages of such ac systems, which is the issue of control. With modern techniques of field oriented vector control, the task of variable speed control of induction machines is no longer a disadvantage, [18, 19, 36] the need to increase system performance, particularly when facing limits on the power ratings of power supplies and semiconductors, motivates the use of increased phase number, and encourages new PWM techniques, new machine design criteria and the use of harmonic current and flux components. In a multi-phase system, assumed to be a system that comprises more than the conventional three phases, the machine output power can be divided into two or more solid state inverters that could each be kept within prescribed power limits, also, having additional phases to control mean additional degrees of freedom available for further improvements in the drive system [42].

Variable-speed AC motor drives with more than three phases (multi-phase drives) have several advantages when compared to the standard three-phase realizations. The current stress of the semiconductor devices decreases proportionally with the phase number, torque ripple is reduced, rotor harmonic currents are smaller, power per rms ampere ratio is higher for the same machine volume and harmonic content of the DC link current for VSI fed drives is reduced [29]. Other advantages include an improvement in the noise characteristics and a reduction in the stator copper loss, leading to improved efficiency. Further advantages are related to the higher reliability at the system level, since a multi-phase drive can operate with an asymmetrical winding structure in the case of loss of one or more inverter legs/machine phase. Applications of multi-phase induction motor drives are mainly related to the high-power/high-current applications [1].

The choice of asymmetrical (30° displacement between two three-phase windings) rather than symmetrical (60° displacement between two three-phase windings) six phase configuration was in the early days of the multiphase induction motor drives dictated by the need to eliminate the 6th harmonic of the torque ripple, caused by the 5th and the 7th harmonics of the stator current [1, 7]

Output Torque of multiphase induction motors is much higher than that of conventional three phase Induction Motor. Emil Levi [1] provides a review of the recent developments in the area of multiphase induction motor control. In this paper Vector control and direct torque control (DTC) are addressed and utilization of the additional degrees of freedom that exist in multiphase machines for differing purposes is described (higher stator current harmonic injection for torque enhancement and control of a group of series-connected multiphase motors supplied from a single multiphase VSI).

The experimental results of vector control and Direct Torque control (DTC) of multiphase induction motor are also discussed in the paper. The problem of 3^{rd} and 7^{th} harmonics has not been solved so far for any phase number higher than three, the exception being asymmetrical six-phase induction machine. Also series connected multiphase induction motors both five phase and six phase are discussed. Asymmetrical six phase induction motors are found to be more suitable [1]. Lipo and Nelson [2] have carried out stability analysis of symmetrical induction motors. Various methods for electric drives are described in detail by L. Romeral [3]. Samir Hamdani presented a generalized two axis model of squirrel cage induction motor [4], d-q axis model of squirrel cage induction motor is used for rotor faults diagnosis.

K. Gopakumar and Mahopatra [5] presented a novel scheme of six phase induction motor control with open end. The conclusion drawn is, substantial generation of the 5^{th} and 7^{th} current harmonics is one of the main drawbacks of multiphase Induction motor. These harmonics cause additional losses in the motor. This will lead to increased size and cost of motor and inverter [5]. Concept of multiphase multi motor drives control when fed from single voltage source inverter is given by Mahopatra [6] and Hamid Toliyat [7]. Sensor less Field oriented control of six phase induction motor is explained in detail and it is more economical for high power applications [9], [10], [13]. Kazutoshi Kaneyuki and Dr. Masato Koyama [14] presented application of multiphase motors in electric vehicles in a Mitsubishi Electric Advance - Technical report on electric drives for electric vehicles. Vector control of induction motor is explained in detail [16]-[19].

Split-phase induction motor consists of two similar stator windings sharing the same magnetic circuit. These motors help in extending the power range of solid-state based drives. [45]. A direct control method for five phase voltage source inverter (VSI) Induction Motor drives investigation leads to conclusion that fast torque response with low ripple torque can be obtained [11]. G.K. Singh [20] has given extended research on multiphase machines. Using two current sensors the torque can be improved in six phase induction motor [28] also six phase induction motor torque can be improved by injecting third harmonic current externally [29].

Torque Density Improvement in a Six-Phase Induction Motor is carried out with Third Harmonic Current Injection. The conclusion, drawn from the research done so far, is by injecting third harmonic currents the production of electromagnetic torque can be improved. [41]. Most of the researchers have used multiphase inverter for multiphase motor, i.e. six phase inverter for six phase induction motor [10].

All the control methods developed were for 30 degree displacement only [46].

1.3.1 Motivation:

In a multiphase induction motor, more than three phase windings are housed in same stator and the current per phase in the motor is thereby reduced. In the more common of such structures two sets of three phase windings are spatially phase shifted by 30^0 electrical. In such motors each set of three phase stator winding is excited by a three phase inverter, therefore total power rating of the system is theoretically doubled. It is also believed that drive system with multiphase induction motors will improve the system reliability [20].

Ward and Harner for the first time in 1969 have presented the preliminary investigation of an inverter fed five phase induction motor and suggested that the amplitude of torque pulsation can be reduced by increasing the number of stator phases [20]. Very few examples of design of multiphase induction motors can be found in the literature. Hamid Toliyat [7] [57] has reported the test results on five phase motors. The reason given for using five phases was to reduce the current such that it would match the ratings of available thyristors, for inverter source. However, the third harmonic current was found to be excessive when it was supplied by inverter. Motors with many phases have been proposed for high degree of reliability. These few attempts to develop multiphase induction motors show that they have some advantages over conventional three phase induction motors.

Recent surveys of the state-of-the art in this area [1, 20] indicate an ever increasing interest in multiphase machines within the scientific community world-wide.

After extensive literature surveys it is observed that very little research efforts are applied in the direction of practical design, development and control of multiphase induction motors.

So the goal of this research is to design and develop a six phase prototype induction motor. To reduce the operational complications, this novel design should be free from third harmonic current injection for torque improvement. Aim of this research is also to control the speed of developed prototype six phase induction motor with arbitrary phase displacement using vector control technique.

1.4 RESEARCH OBJECTIVE:

To achieve these goals, following research objectives are set:

1. To design practicable, techno economically competent, six phase, star connected Induction motor.
2. To avoid complexity of design and control, this innovative design should not need any third harmonic current injection and Special current waveforms for torque improvement.
3. To carry out mathematical modeling of the designed six phase induction motor for vector control.
4. To carry out simulation of Multi-motor vector control in Matlab and compare the same with three phase induction motor.
5. To carry out simulation of vector control of six phase induction motor in Matlab. Compare the same with three phase induction motor.
6. To test the developed prototype six phase induction motor first with three phase supply and then with six phase supply.
7. To use two three phase Space Vector Pulse Width Modulation (SVPWM) inverters for six phase supply after thorough study.

8. To run the developed prototype motor using two numbers of three phase SVPWM inverters suitable as per the motor rating.
9. To develop control algorithm, Sensor less vector control is to be studied in detail and then implemented for control.
10. Field Protected Gate Array (FPGA) technique of sensor less vector control is to be studied and implemented. FPGA is a silicon chip containing an array of configurable logic. A system of FPGA chip is more reliable as they do not need any control software [22].
11. To carry out speed control of six phase IM using:
    a) Scalar Control (Volts per Hertz) and
    b) Vector Control using Sensor-less control mode.
12. To compare motor performance with other high power available motor technologies and equivalent three phase Induction Motor.

Thus the research work is divided into following major parts:

1. Design of six phase Induction motor.
2. Development of prototype six phase Induction motor
3. Testing of six phase induction motor.
4. Simulation of Multi motor drive control and its comparison with three phase IM

5. Simulation for vector control of six phase IM.
6. Vector control of prototype motor when fed from two voltage source SVPWM inverters.

1.4.1 Scope of Research:

From the above research objectives the scope of the research is derived as

- To design practicable, techno economically competent, six phase, star connected Induction motor. To avoid complexity of design and control, this innovative design should not need any third harmonic current injection and Special current waveforms for torque improvement.
- To carry out mathematical modeling of the designed six phase induction motor for vector control. To carry out simulation of Multi-motor vector control in Matlab and compare the same with three phase induction motor. And to carry out simulation of vector control of six phase induction motor in Matlab. Compare the same with three phase induction motor.
- To test the developed prototype six phase induction motor first with three phase supply and then with six phase supply.
- To use two three phase Space Vector Pulse Width Modulation (SVPWM) inverters for six phase supply and to run the

developed prototype motor using two numbers of three phase SVPWM inverters suitable as per the motor rating.

- To develop control algorithm, Sensor less vector control is to be studied in detail and then implemented for control. Field Protected Gate Array (FPGA) technique of sensor less vector control is to be studied and implemented. FPGA is a silicon chip containing an array of configurable logic. A system of FPGA chip is more reliable as they do not need any control software [22].
- To carry out speed control of six phase Induction motor using:

a) Scalar Control (Volts per Hertz) and

b) Vector Control using Sensor-less control mode. And to compare motor

performance with other high power available motor technologies and equivalent three phase Induction Motor.

1.5 ORGANIZATION OF THE THESIS

The layout of the thesis is as follows:

Chapter 1 discusses about advantages of ac motor drives over dc motor. Literature survey of the research topic is discussed in detail. Background knowledge of multiphase induction motor is given in brief and then problem statement with detailed literature survey and problem approach is discussed.

Chapter 2 discusses multiphase induction motors in detail. The equivalent circuit of six phase induction motor is drawn and described. The advantages of six phase induction motor over conventional three phase induction motor are discussed.

Chapter 3 is devoted to design, development and testing of prototype six phase induction motor starting from basic design of three phase induction motor. Testing of prototype six phase induction motor is discussed with waveforms. It focuses on problems faced while actual development and how the solution is obtained to overcome these difficulties.

Chapter 4 is devoted to various control methods like scalar control and vector control of induction motor and gives details of vector control. Also Matlab simulation of three phase multi motor drive control is compared with single, three phase induction motor control. Chapter is ended with overview of sensor less vector control.

Chapter 5 is devoted to control of six phase induction motor. It includes mathematical modeling of six phase induction motor and matlab simulation of vector control of six phase induction motor. Finally it focuses on comparison of three phase multi motor drive with six phase Motor drive.

Chapter 6 analyses Experimental implementations for control of six phase induction motor .It also discusses the scalar control and vector control of six phase induction motor.

Chapter 7 concludes the research work with thorough analysis of various results derived during the course of work. It compares conventional design and control methods with novel method. Also future research scopes are presented.