DESIGN, DEVELOPMENT AND CONTROL OF MULTIPHASE INDUCTION MOTOR

A THESIS SUBMITTED
FOR AWARD OF
THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ELECTRICAL ENGINEERING.

By

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Vadodara

March 2012

Dedicated to One & All Who Have

Inspired, Encouraged & Helped Me

to Make This Thesis

A Reality.

CERTIFICATE

This is to certify that the thesis entitled "Design, Development and Control of Multiphase Induction Motor**" submitted by** Ms. A.S. Nanoty **in fulfilment of the requirements of the degree of "**Doctor of Philosophy**" in Electrical Engineering is a bonafide record of investigations carried out by her in the Department of Electrical Engineering, Faculty of Technology and Engineering, M.S. University of Baroda, Vadodara under my guidance and supervision. In my opinion, this has attained the standard fulfilling the requirements of the Ph.D. degree as prescribed in the regulation of the University.**

March 2012

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DECLARATION

I, **Archana S. Nanoty,** hereby declare that the work reported in this thesis entitled "**Design, Development and control of Multiphase Induction Motor**" submitted for the award of the degree of.

DOCTOR OF PHILOSOPHY

(Electrical Engineering)

is original and was carried out by me in Department of Electrical Engineering, Faculty of Technology & Engineering, M.S. University of Baroda, Vadodara. I further declare that the work reported in this thesis is original and not submitted elsewhere for the award of any degree of this University or any other institution in India or abroad.

March 2012

Archana S. Nanoty.

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ABSTRACT

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.

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).

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].

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. Control of same motor when fed from two voltage source SVPWM inverters.

ACKNOWLEDGEMENT

AUM SRI SAINATHAY NAMAHA

I heartily acknowledge my deep sense of gratitude to almighty God to give me wisdom, knowledge, intelligence and strength to carry out and complete this research work successfully. It is only because of His kindness, wish and blessings this thesis is a reality.

I express my deep sense of gratitude towards my respected parents and my in-laws, who have, with love and care, inducted the habits of honesty and hard work by setting the example through their own deeds. This thesis is a result of their blessings.

I have no words to express my heartily deep sense of gratitude to my respected guide Professor Dr.A.R.Chudasama. I have no hesitation to write that it is only because of my highly inspiring guide's patient, encouragement, active support, constructive suggestions and extensive help; I am able to carry out this research work successfully.

I take this opportunity to express my most sincere gratitude to Dr. K.K.Thakkar, director (JSL, Mogar) for sparing his valuable time for extensive discussion on this research topic,for providing facilities for Motor design and testing at JSL, Mogar. I also wish to acknowledge all his support and encouragement.

I am thankful to the Motor section staff of JSL, Mogar, for their support.
I also wish to heartily thank Mr.S.Salvi, Managing Director, VACON, Chennai, for his technical support in carrying out control circuit design and using facilities at VACON, Chennai. Mr.Venkatesh and Mr.Anil and all the staff at R&D and testing at VACON Chennai for their invaluable assistance and support.

I am thankful to Dr. Jayesh Patel Chairman and Dr.Devanshu Patel, Management trustee, Parul Arogya Seva Mandal(PASM) for kind support and encouragement. I am thankful to Mr. Jagdish Patel, Chairman, Babaria Institute of Technology for their kind support.

I also wish to thank Dr. Kelkar, Prof.MSU, and Dr. M.V. Aware, VNIT, Nagpur for providing all type of literature for my research work and for fruitful discussion and valuable suggestions during course of research work.

I am also thankful to Prof.S.P.Muley , Head, Electrical department, Priyadarshini college of Engineering, Nagpur, for her kind support and help in Matlab software simulation.

I am also heartily thankful to Mr.M.R.Tilwalli, Gururaj Engineers, GIDC, Makarpura, Vadodara for his kind help and co-operation.

I am grateful to IEEE, especially IEEE Industry Association Society and IEEE Power & Energy Society for making available all the literature and very rich quality papers in my area.

I also express my deep sense of gratitude towards Dean Faculty of Technology & Engineering for his active support and time to time encouragement.

I wish to thank Prof.Mrs.S.A.Kanitkar and Prof.S.K.Shah past and present, Head of the Electrical Engineering Department for their kind co-operation. Special thanks to Prof. Mrs. S. A. Kanitkar for her timely help and invaluable suggestions.

I am thankful to Ex-Principal of Parul Institute of Engg. & Technology, Dr. Rupesh Vasani, my friends and colleagues at Parul Institute of Engineering and Technology, Limda for their support and timely help. All the faculty of Parul Institute of Engineering & Technology-Diploma Studies working under me for their kind support and timely help.

I am thankful to Shri. Shailesh Shah, Chairman Sigma Group of Institutes and all the staff and faculty working under me at Sigma Institute of Engineering for their kind support and help.

This thesis is a result of prayers and well wishes of my husband and lovely daughter Sampada. So I heartily thank both of them for their moral support and encouragement.

I am also thankful to my younger brothers and their families for their moral support and encouragement.

I sincerely thank all those who have helped me directly or indirectly in my research program.

Once again I wish to express my very sincere feeling of respect and gratitude for my guide Professor Dr. A.R.Chudasama who has guided me with perfection throughout the different stages of the research program and made it a memorable learning experience for me as always …….

(Archana S. Nanoty)
March 2012

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LIST OF SYMBOLS

I_{S1} , I_{S2}	Stator Currents
V_{S1}, V_{S2}	Stator Voltages
$\mathbf{V}_{DC}$	dc link voltage
θ	Rotor angular position
R_s	Stator Resistance
R_r	Rotor Resistance
i_r	Rotor Current
λ^{-}_{s}	Stator Flux Linkages
λ^{-}_{r}	Rotor Flux Linkages
ω_r	Rotor Angular Speed
L_s	Stator Inductance
L_r	Rotor Inductance
X_{l1}	Stator Leakage Reactance
X_{lm}	Mutual Reactance
X_{lr}	Rotor Leakage Reactance
λ_s	Stator Flux Linkages
λ_r	Rotor Flux Linkages
L_{ss}	Stator Self Inductance
L_{rr}	Rotor Self Inductance
L_{sr}	Mutual Inductance between Stator and Rotor
δ_r	Rotor Angle
M	Operator
M	Number of phases

S_s	No. of Stator Slots
p	No. of machine poles
i_d , v_d	Direct Axis current, Voltage
i_q , v_q	Quadrature Axis current, Voltage
T_e	Electromagnetic Torque
J	Moment of Inertia

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].

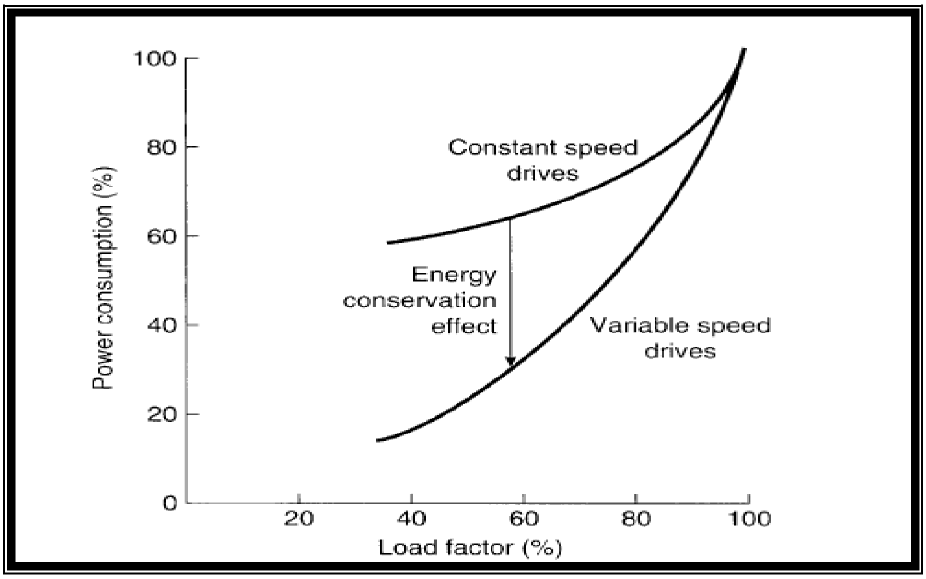


Fig.1.1. Energy Saving Characteristics of Variable Frequency Drives

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 3rd and 7th 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 5th and 7th 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 Induction motor 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.

CHAPTER 2

MULTIPHASE INDUCTION MOTORS

2.1. INTRODUCTION

Three phase motors have been in use more frequently for last century. However, there has been a growing interest in multiphase motors in application areas where high power, high torque and reliability is a prime target. Development of application areas like traction, aerospace, hybrid electric vehicles, ship propulsion have provided the motivation for research in multiphase motors [1, 20]. In this section multiphase induction motors are discussed in detail with equivalent circuit of six phase induction motor.

2.1.1 Multiphase Induction motor

In traditional electric machine applications a three-phase stator winding is selected, since the three-phase supply is readily available. However, when an AC machine is supplied from an inverter, the need for a predefined number of phases on stator, such as three, disappears and other phase numbers can be chosen. [51]

Probably the first proposal of a multiphase variable speed electric drive dates back to 1969 [20]. While [12, 33] proposed a five phase induction motor drive, a six-phase (double star) induction machine supplied from a six-phase inverter was examined in [28, 29]. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed drives, when compared to the three-phase case. Another advantage of a multiphase motor drive over a three-phase motor drive is an improved reliability due to fault tolerance features, this being one of the main reasons behind the application of six-phase (double-star) and nine-phase (triple-star) induction motor drives in locomotives [48]. The other main reason is that for a given motor rating, an increase of the number of phases enables reduction of the power per phase, which translates into a reduction of the power per inverter leg (that is, a semiconductor rating). Multiphase machines are therefore often considered for and applied in high power applications [1, 5, 7]. Other advantages of multiphase machines over their three-phase counterparts include an improvement in the noise characteristics and a possibility of reduction in the stator copper loss, leading to an improvement in the efficiency. Vector control principles can be extended from a three-phase to a multiphase motor in a simple manner when the machine torque is produced by the fundamental stator current component only. For example, vector control of a five-phase induction motor is elaborated in [12]. In principle, there is not any difference with regard to the vector control scheme between a three-phase and an *m*-phase machine.

Multiphase motor drives have been proposed for different applications where some specific advantages (lower torque pulsations, less DC link current harmonics, higher overall system reliability, etc) can be better exploited justifying the higher complexity in contrast to the three-phase solution [2]. Some of the most suitable applications are the high current ones (ship propulsion, aircraft applications, locomotive traction, electrical vehicles), where the main advantage of multi-phase drives is the splitting of the controlled power (current) on more inverter legs, reducing the single switch current stress compared to the three-phase converters. Since the power switches rated current is reduced proportionally with the phase number, the increased number of power switches does not represent an additional cost; on the contrary, in some cases the cost is reduced by the "non-linearity" of the component prices. However, the system cost (and complexity) is penalized by the increased number of the current sensors, gate drive circuits, additional circuitry power supply, etc. Among the different multi-phase induction drives solutions, the dual-3-phase induction machine having two stator winding sets spatially shifted by 30 electrical degrees with separated neutral has important advantages [3-4]:

1. The current stress of each semiconductor power device is reduced by one half compared with the same power 3-phase machine counterpart.

2. The dual-3-phase solution can benefit of the wide availability of components dedicated to 3-phase systems.

3. These electrical machines are convenient in high power and/or high current applications, such as ship propulsion, aerospace applications, and electric/hybrid vehicles (EV). In applications like EV, often the low available DC-link voltage imposes high phase current for a 3-phase machine. In this case, the dual-3-phase induction machine is an interesting alternative to the conventional 3-phase counterpart.

2.1.1 (A) Split Phase Induction Motors

Split-phase electrical machines consist of two similar stator windings sharing the same magnetic circuit. Such a construction made it possible to extend the power range of solid-state based drives by sharing the total power between two drives [8]. Usually a split-phase machine is built by splitting the phase belt of a conventional three-phase machine into two equal parts with spatial phase separation of 30 electrical degrees. By using this arrangement, for the same air gap flux, the inverter dc bus voltage can be reduced by approximately a half, compared to a three-phase system, since the number of turns per phase is reduced [29]. Such structure has a disadvantage of the need for two or more inverters to drive the machine.

Another advantage of using this kind of winding arrangement is harmonic cancellation. The sixth harmonic torque pulsation, which is common in a six-step three-phase drive, can be eliminated by using split-phase arrangement.

As in split-phase machines, the dual-stator machines consist basically of two independent stator windings sharing the same magnetic frame. Differently, a dual stator machine does not necessarily have similar winding groups. For example, a 6 different voltage rating or a different number of phases could be used for each winding group.

For instance, two independent stator windings may be used for an induction generator system [30]. One set of windings may be responsible for the electromechanical power conversion (i.e. driving the load) while the second one is used for excitation purposes. This eliminates the need of a converter rated to full load power in a vector controlled induction generator [30, 35]. The same idea can be used for power factor correction in induction motors. One of the two different sets of three-phase windings may be connected to the main power and carry the active power responsible for the torque production while the second winding carries the reactive power.

2.1.1 (B) Dual Stator Motor

Using a dual-stator machine which is a particular case of a multi-phase machine, the power ratings may be extended without the need to use multi-level converters. Instead of increasing the power rating of a three-phase converter using multi levels for the converter, additional phases are added and the current is shared by additional inverter legs.

The six-phase machine is a particular case of split-phase or dual-stator machine. It can be built by splitting a three-phase winding into two groups. These three-phase groups are shifted by thirty electrical degrees from each other. This composes an asymmetrical six-phase machine since the angular distance between phases is not the same. Figure 2.1 shows the representation of the machine stator windings for Y connection and a simplified construction diagram for a concentrated-winding, a method which is similar to that of a three-phase machine can be adopted in analyzing a six-phase induction machine.

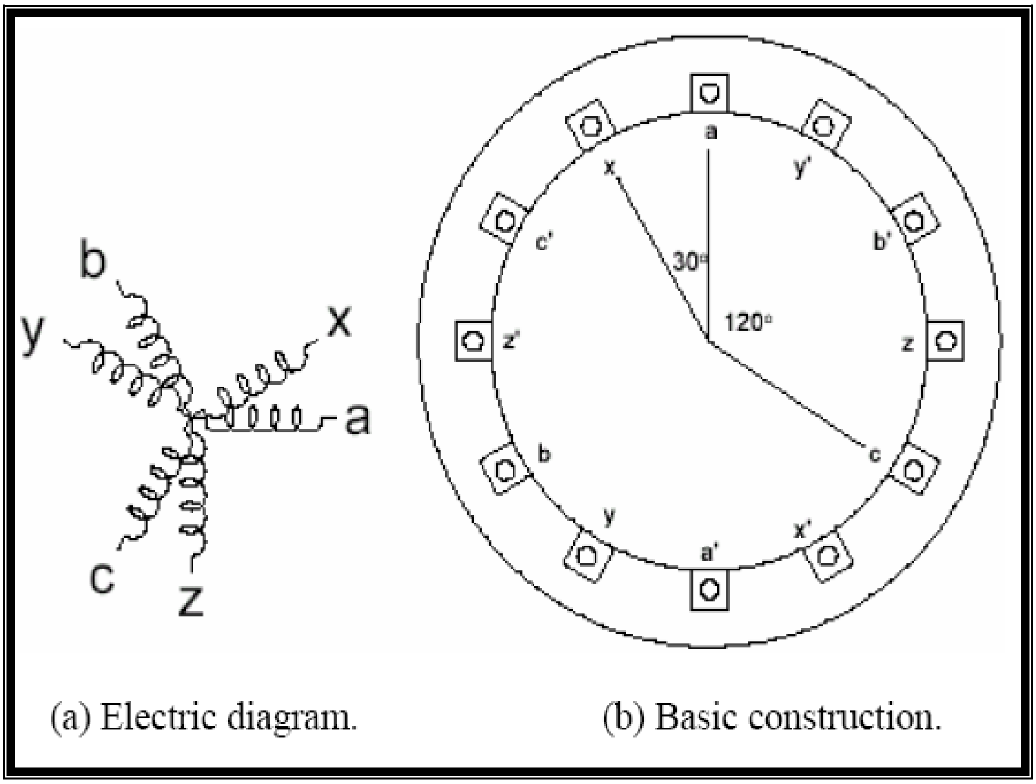


Figure 2.1 Six phase Machine

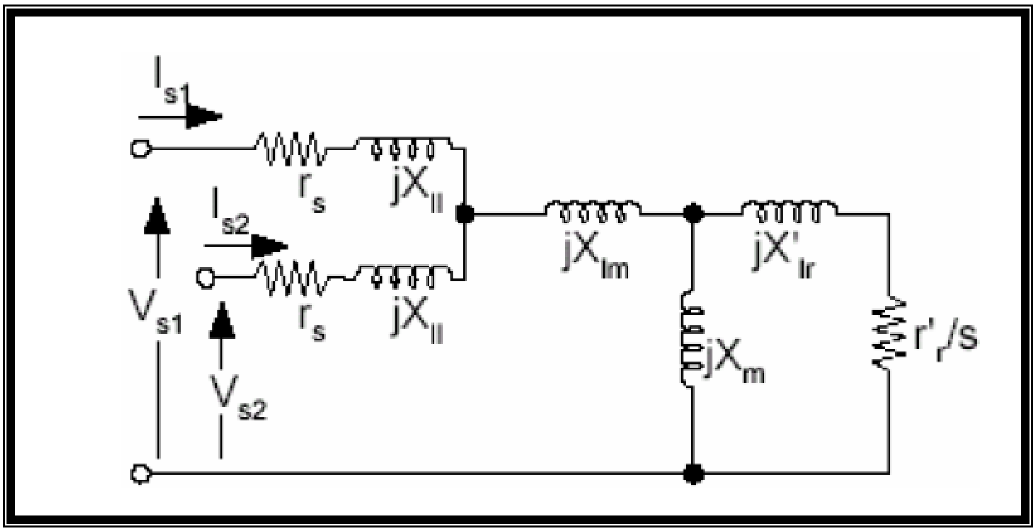
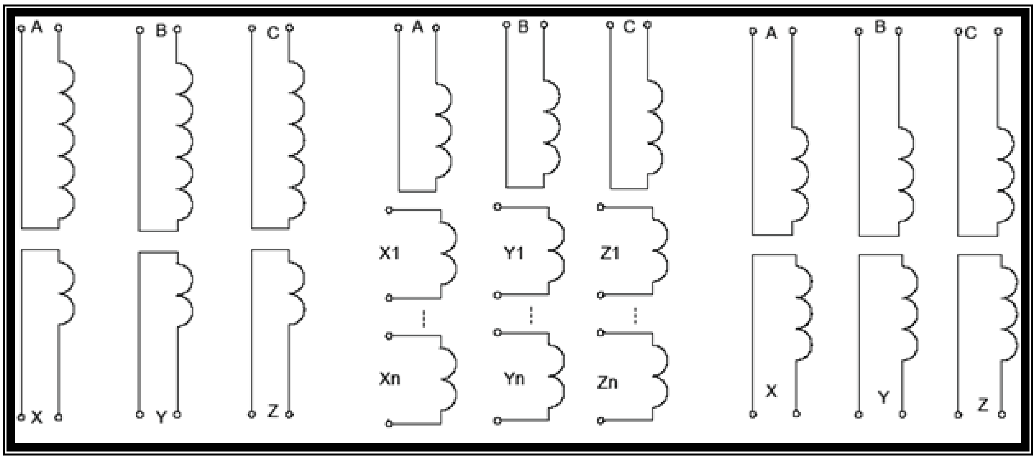


Figure 2.2 Equivalent Circuit of Six phase IM for sinusoidal steady state

In Figure 2.2, the steady-state equivalent circuit for sinusoidal excitation which is similar to the one of a conventional three-phase machine with the addition of an extra stator circuit is shown. When compared to three phase induction motor equivalent circuit, the six phase motor has two stator currents as shown, i.e. I_{S1} and I_{S2} . Also voltages across stator 1 and 2 are V_{S1} and V_{S2} respectively. Two stators are identical so that I_{S1} = I_{S2} and $V_{S1} = V_{S2}$. Similarly stator resistance and reactance for both the stators are same. Thus six phase induction motor can be considered as, two identical three phase motors sharing same magnetic circuit, electrically separate and common shaft.

Basically, the six-phase induction motor was introduced with two objectives. First, the opportunity to divide the output power into two three-phase groups allows the increase in the drive system power ratings. Secondly, for use with six step inverters, the pulsating torque in a six-phase machine is lower than in a three phase machine. Another reason for using six-phase systems is reliability. When a failure happens in one of the phases, in the machine or in the power converter, the system can still operate at a lower power rating since each three-phase group can be made independent from each other. In the case of losing one phase, the six-phase machine can be operated as a five-phase machine as described in [41].



(a) Split Phase (b) Dual Stator (c) Six Phase

Figure 2.3 Illustration of Six phase windings

Dual-stator machines are similar to split-phase machines with the difference that the stator groups are not necessarily equal. As a particular case of split-phase or dual-stator machine, the six-phase machine can be built by splitting a three-phase winding into two groups. Usually these three-phase groups are displaced by thirty electrical degrees from each other. This arrangement composes an asymmetrical six-phase machine since the angular distance between phases is not all the same [41].

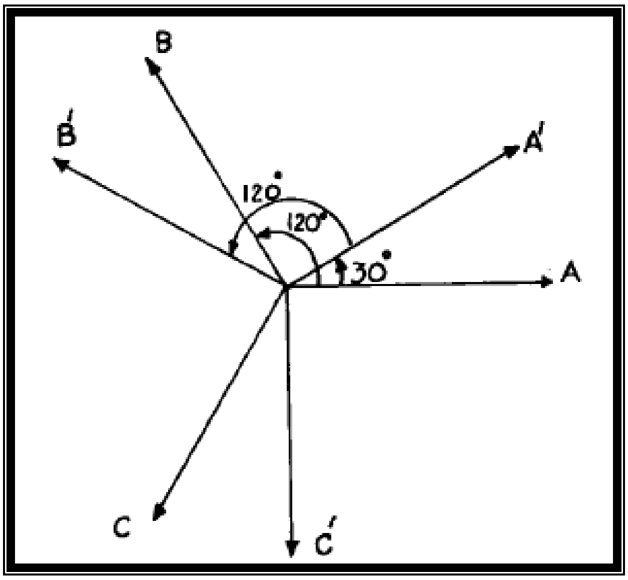


Figure 2.4 Phasor diagram for split phase IM

The split-phase motor configuration is achieved by splitting the phase belt of a conventional three-phase motor into two equal halves with a phase separation of **30”** between the two (Fig. 2.4). The split phase groups, namely *ABC* and *A’B’C’* (Fig. 2.5) are controlled by two inverters with a dc link voltage of $\mathbf{V}_{DC}$ / (2 cosl5) each. In figure 2.5, the n sets of three-phase windings are spatially phase shifted by 60^0/n electrical degrees.

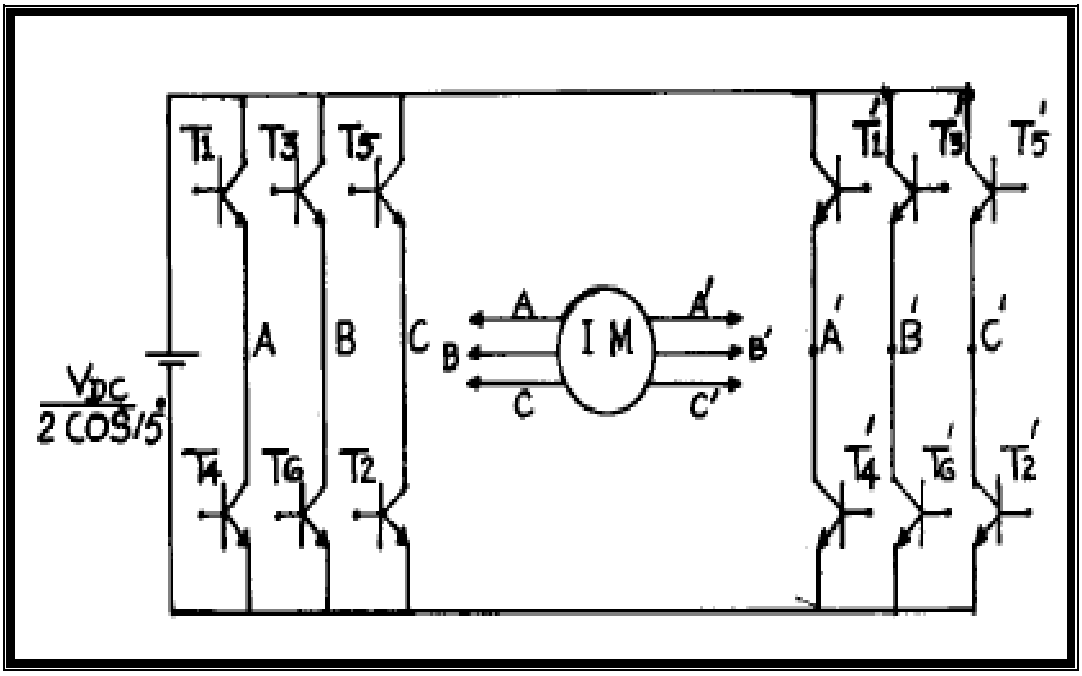


Figure 2.5 Split Phase Induction motor drive

2.2. MODELING OF SIX PHASE INDUCTION MOTOR

The dual three-phase induction machine is a six dimensional system. Therefore, modeling and control of this machine in the original reference frame would be very difficult. For this reason, it is necessary to obtain a simplified model to control it. To derive this model, some assumptions must be made like the sinusoidal distribution of the stator and rotor windings.

Moreover, the magnetic saturation, the mutual leakage inductances and the core losses must be neglected. If so, the voltage equations in the original phase coordinates can be expressed as:

$$[V_s] = [R_s][i_s] + p[\lambda_s]$$

$$= [R_s].[i_s] + p([L_{ss}].[i_s] + [L_{sr}(\delta_r)].[i_r]) \qquad [2.1]$$

$$[\theta] = [R_r].[i_r] + p[\lambda_r]$$

$$= [R_r].[i_r] + p([L_{rr}].[i_r] + [L_{rs}(\delta_r)].[i_s]) \qquad [2.2]$$

Where **θ** is the rotor angular position and *p=d/dt*

For analysis and control purposes, the original six dimensional machine systems can be decomposed into three two-dimensional orthogonal subspaces (α, β),

(μ_1 ,μ_2) and (z_1, z_2) by using the transformation matrix T6

$$\mathbf{T_6} = \mathbf{K} \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & -1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \qquad \mathbf{[2.3]}$$

, K =1/3

Thus, applying the matrix (2.3) to the voltage equations (2.1), (2.2) yields:

As shown in [6]-[7], the machine model can be divided into three sets of decoupled equations, corresponding to the three subspaces (α, β), (μ_1 , μ_2) and (z_1, z_2).

$$[\mathbf{T_6}] = [T_6].[R_s].[T_6^{-1}].[T_6].[i_s] + p.\begin{pmatrix}[T_6].[L_{ss}].[T_6^{-1}].[T_6].[i_s] \\ + [T_6][L_{ss}][T_6^{-1}][T_6][i_r]\end{pmatrix} \quad \textbf{[2.4]}$$

$$[\theta] = [T_6][R_s][T_6^{-1}][T_6][i_r] + p.\begin{pmatrix}[T_6].[L_{rr}].[T_6^{-1}].[T_6].[i_r] \\ + [T_6].[L_{rs}].[T_6^{-1}].[T_6].[i_s]\end{pmatrix} \quad \textbf{[2.5]}$$

$$\begin{bmatrix} Vs\alpha \\ Vs\beta \\ 0 \\ 0 \end{bmatrix} =$$

$$\begin{bmatrix} Rs + Ls.p & 0 & M.p & 0 \\ 0 & Rs + Ls.p & 0 & M.p \\ M.p & \omega r.M & Rr + Lr.p & \omega r.Lr \\ -\omega r.M & M.p & -\omega r.Lr & Rr + Lr.p \end{bmatrix}.[\mathbf{i_{s\alpha}}\ \mathbf{i_{s\beta}}\ \mathbf{i_{r\alpha}}\ \mathbf{i_{r\beta}}]^{\mathbf{t}}$$

[2.6]

The (α, β) machine model is similar to the three-phase machine model in the stationary reference frame. Thus, equation (6) can be rewritten using the space vectors mapped in the (α, β) subspace.

$$\overline{v}_s = R_s \, . \, \overline{i}_s + p \, . \, \overline{\lambda}_s$$

$$0 = R_r \, . \, \overline{i}_r + p. \, \overline{\lambda}_r - j \, .\omega_r \, . \, \overline{\lambda}_r \qquad \textbf{[2.7]}$$

Where the flux linkage vectors are expressed as:

$$\overline{\lambda}_s = L_s \, . \, \overline{i}_s + M \, . \, \overline{i}_r$$

$$\overline{\lambda}_s = L_r \, . \, \overline{i}_r + M \, . \, \overline{i}_s \qquad \textbf{[2.8]}$$

The machine model in (μ_1 , μ_2) subspace can be expressed by equations (2.9), and in (z_1, z_2) subspace by equations (2.10).

$$\begin{bmatrix} v_{su1} \\ v_{su2} \end{bmatrix} = \begin{bmatrix} R_s + L_{ls}.p & 0 \\ 0 & R_s + L_{ls}.p \end{bmatrix} . \begin{bmatrix} i_{su1} \\ i_{su2} \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_r + L_{lr}.p & 0 \\ 0 & R_r + L_{lr}.p \end{bmatrix} . \begin{bmatrix} i_{ru1} \\ i_{ru2} \end{bmatrix} \qquad \textbf{[2.9]}$$

$$\begin{bmatrix} v_{sz1} \\ v_{sz2} \end{bmatrix} = \begin{bmatrix} R_s + L_{ls}.p & 0 \\ 0 & R_s + L_{ls}.p \end{bmatrix} . \begin{bmatrix} i_{sz1} \\ i_{sz2} \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_r + L_{lr}.p & 0 \\ 0 & R_r + L_{lr}.p \end{bmatrix} . \begin{bmatrix} i_{rz1} \\ i_{rz2} \end{bmatrix} \qquad \textbf{[2.10]}$$

The following can be noted:

1) The electromechanical energy conversion variables are mapped in the

   (α, β) subspace, while the non electromechanical energy conversion variables can be found in the two other subspaces.

2) The current components in the (μ_1, μ_2) and (z_1, z_2) subspaces do not contribute to the air-gap flux and are limited only by the stator resistance and stator leakage inductance, which is usually small. These currents will only produce losses and consequently should be controlled to be as small as possible.

3) The control of the dual three-phase machine is greatly simplified since it can be solved with the equivalent circuit in the (α, β) subspace, being similar to the equivalent circuit of a three-phase machine. Finally we get two phase equivalent of six phase.

2.3. ADVANTAGES OF SIX PHASE IM OVER THREE PHASE IM

Variable-speed AC motor drives with more than three phases (multi-phase drives) have several advantages when compared to the standard three-phase realizations [20, 21]: 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. Other advantages include an improvement in the noise characteristics [30, 39] 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 phases, the operation is maintained though at reduced rating. [41].

2.4. CONCLUSION

This chapter is devoted to theory of multiphase induction motor, modeling of six phase motor and its comparison with three phase motors. The advantages of six phase induction motor over three phase are discussed.

Applications of multi-phase induction motor drives are mainly related to the high-power/high-current applications, such as for example in electric ship propulsion in locomotive traction and in electric/hybrid electric vehicles.

CHAPTER 3

DESIGN, DEVELOPMENT AND TESTING OF PROTOTYPE SIX PHASE INDUCTION MOTOR

3.1. INTRODUCTION

This chapter focuses on complete design, development and testing of prototype six phase induction motor. The design of six phase induction motor is done as per three phase induction motor initially. The problems faced with existing three phase motor specifications are discussed in detail. Actual design and development of six phase induction motor at a manufacturing unit is discussed in detail.

As per the area of application, i.e. high power-high current, multiphase motors are of very high rating. So to design a techno economical motor, moderate and economical size which can very well show the characteristics of multiphase motor is chosen. Thus a 3 HP, 4 pole, 200 V, six phase induction motor specifications are calculated for prototype six phase motor. As per novel calculations, reasonable size of stampings is selected which also eliminated the need of third harmonic current injection. How torque improvement is achieved without any harmonic injection or current sensor is proved at the end.

3.2 ACTUAL DESIGN OF PROTOTYPE SIX PHASE INDUCTION MOTOR:

To begin with, an m-phase symmetrical induction machine, such that the spatial displacement between any two consecutive stator phases equals $\alpha = 2\pi/m$, is considered. Stator winding is treated as m–phase and it is assumed that the windings are sinusoidally distributed, so that all higher spatial harmonics of the magneto-motive force can be neglected. The phase number m can be either odd or even. When the number of phases is six, i.e. m = 6, there are two, three phase windings. The two, three phase windings are displaced by 60^0 in symmetrical design but there is a problem of magnetic circulating currents. So asymmetrical design is implemented in which two, three phase windings are displaced by 30^0, which eliminates ($6n \pm 1$) order harmonics, where n = 1,3,5………. [1].

A six phase machine can be easily constructed by splitting the 60^0 phase belt into two portions each spanning 30^0.The winding distribution factor increases from 0.965 for three phase to 1.0 for six phase for split phase belt connection.[20] A true six phase that retains the same winding pitch and distribution factor is shown in the table below. The last column represents six phase asymmetrical winding which is implemented for prototype motor.

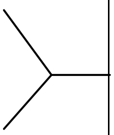
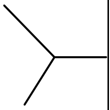
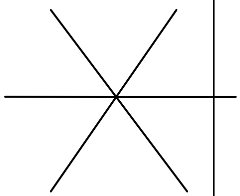
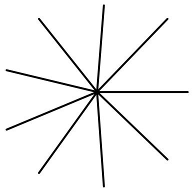
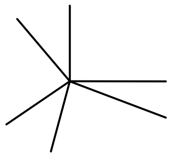
Phase belt angle (degrees)	120	60	60	40	30
No. Of phase belt per pole	1.5	3	3	4.5	6
Number of stator terminals	3	3	6	9	6
Connection name	THREE PHASE	SEMI SIX PHASE	SIX PHASE SYMMETRICAL	NINE PHASE SYMMETRICAL	SIX PHASE ASYMMETRICAL
Schematic diagram of star connection & voltage phasor diagram					

Table 3.1:- Multiphase Winding configuration

The six-phase machine uses the same magnetic frame with the baseline machine. So initially the stator dimensions, stator size, rotor size etc. were kept same as 3 phase, 3 HP induction motor. And the same stator is rewound for making six phase.

Stator design depends upon number of stator slots. General expression for number of stator slots is given by,

$$S_s = m/2.p\ [2+K]\ \text{Slots} \qquad [3.1]$$

Where, S_s = No. of Stator Slots

m = No. of machine phases

p = No. of machine poles

K = 0,1,2…..

For Symmetrical ac winding: K = 0,2,4…..

For Asymmetrical ac winding: K = 1,3,5….

In this case no. of poles = 4, so putting the values of m, p, K in equation [3.1] we get,

$$S_s = (6/2).4[2+1] = 36 \quad [3.2]$$

Thus it is a 4-pole machine with 36 stator slots. In order to keep the leakage distribution balanced, the phases are displaced among the two stator layers. The six-phases are constructed such that one three-phase group is displaced from the other one by 30 electrical degrees.

Thus it is an asymmetrical six phase machine

where;

$$\theta m = 2.\ \theta e / p \quad [3.3]$$

$$\theta m = 2\ .30° / 4 = 15° \text{ mechanical} \quad [3.4]$$

$$\text{Slot pitch} = 360° / 36 = 10° \text{ mechanical} \quad [3.5]$$

Hence, the 30 electrical degrees displacement corresponds to 15°/10° = 1.5 slots.

It is not possible to implement such a configuration and an approximation has to be used. This is done as shown below:

One of the three-phase groups has the same structure of the baseline machine with half of the circuits and winding distributed in 3 slots per pole per phase ($q_A = 3$)

The second group is distributed into 4 slots per pole per phase ($q_X = 4$) but keeping the same number of conductors per pole per phase.

Initially the same dimensions as per 3 phase, 3 HP, induction motor have been used. And stator is divided into two parts and winding is carried out as discussed above.

Prototype six phase induction motor is developed in such a way that, first three phase set say, “ABC” has two pole pitches viz. 9 for outer layer and 7 for inner layer. While the second three phase set say “XYZ” has two pole pitches viz.8 for outer layer and 6 for inner layer. The number of poles is kept same for both the windings. Also wire gauge and number of turns are same for both the windings. The neutrals of two three phase sets are kept open. The motor is star connected.

The initial design parameters, which are implemented for developing a prototype 3 HP, 4 pole 3 phase squirrel cage induction motor, are having 36 stator slots with stator bore diameter 105 mm and 33 rotor slots.

There are 96 conductors per slot of 24 SWG with number of turns equal to 144 with insulation class B (130^{o} C).

The specifications are listed below:

Stator Dimensions:-

● Number of slots	36
● Inner diameter	105mm
● Stack length	110mm

Rotor Dimensions:-

● Number of slots	33
● Outer diameter	105mm
● Inner diameter	33.5mm
● Stack length	110mm

Winding Details:-

● conductors per slot	96
● No. of turns	144
● Conductor Size	24 SWG
● Insulation	Class B

3.3 PROBLEMS FACED IN DEVELOPMENT OF MOTOR

Motor developed with these parameters (used same dimensions as per three phase motor) have very compact winding.

Initially two three phase sets of developed motor are tested alternatively one by one from three phase supply and following points are noted:

1. Over heating is experienced even under no load condition.
2. Over heating has also lead to failure of insulation.
3. With these specifications, when one of the three phase sets was fed with three phase AC supply, the motor started vibrating.
4. Also because of high input voltage i.e. 415 V to one of the three phase sets say ABC, after sometime motor started burning.
5. Also there was a problem of Body earth because of complicated winding and proper insulation not done at the time of actual winding.

3.3.1 Solution to the Problem:-

To overcome above said problems following steps are taken:

1. Over heating is caused due to I^2R losses. If the heat dissipating area can be increased and at the same time number of conductors and conductor size changed, it will

affect the current. Thus the frame size of the motor is increased as per the calculations shown in next section. Also number of conductors is increased as per the slot. And conductor size is changed from 24 SWG to 22 SWG.

2. To avoid insulation failure due to overheating, the insulation class is changed from class B (130^0) to class F (155^0).
3. Vibration is experienced because of high torque. To overcome vibration, frame size is increased. This increases the mechanical strength of motor and eliminates third harmonic current injection.
4. The motor voltage is increased gradually up to 200 Volts, to overcome burning problem.
5. As frame size is increased slot area is increased thus there is no compact winding.

3.4 **RE DEVELOPMENT WITH NEW SPECIFICATIONS**: (Novel Design)

The practical problems faced at the time of actual development of prototype were overcome by using next higher standard stator stamping. As per the calculations for six phase motor the main dimensions are not same as three phases. But the stator slots, pole pitches are kept same.

3.4.1 Calculations:

To design main dimensions of 3 HP (2.238 KW), 200 Volts, 6phase, 4 pole induction motor (assuming efficiency η= 85%, power factor $\cos\Phi$ = 0.8 lagging

Q = Output in KW / $\eta \times \cos\Phi$ [3.6]

$Q = 2.238 / 0.85 \times 0.8 = 3.3$ KVA [3.7]

Also $Q = C_0 D^2 L n_s$ [3.8]

(Appendix-I)

And $C_0 = 11\ B_{av}\ ac\ Kw\ 10^{-3}$ [3.9]

(Appendix-I)

Kw = Window space factor for 6 phase = 1

Assuming Specific magnetic loadings B_{av} = 0.65 wb/m^2 , Specific electric loading, ac = 12000 Ampere conductors

$C_0 = 11 \times 0.65 \times 12000 \times 1 \times 10^{-3} = 85.8$ [3.10]

Putting the value of C_0 from [3.10] in [3.8]

We get, D = 0.124 m = 124 mm [3.11]

Taking overall good design condition, i.e. $L / \Gamma = 1$ [3.12]

Where, Γ = pole pitch = $\pi D / p$ [3.13]

Thus L = 0.102 m = 102 mm [3.14]

Similarly turns per phase,

$T_{ph} = E_{ph} / 4.44\ f\varphi\ Kw = 312$ [3.15]

[Appendix-I]

Total conductors = $Z_{ss} = 2mT_{ph}$ [3.16]

Stator slots S_s =36, no. of phases m =6

Thus Total conductors = 3744

Conductors per slot $Z_s = Z_{ss} / S_s = 3744 / 36 = 104$ [3.17]

The next higher standard dimension stamping available at the manufacturing unit near to the calculated value are selected. Standard Stator bore diameter available is 125 mm, nearest to the calculated value 124 mm. And stack length as per standard is selected as 100mm nearest to 102 mm.

Thus the motor is redesigned and developed with stator bore diameter increased from 105mm to 125mm. As per stator frame size, rotor slots changed from 33 to 28 as per standard. Instead of 96 conductors per slot of 24 SWG, 104 conductors per slot with 22 SWG conductors are used. And total number of turns is increased from 144 to 312. Insulation class is also changed from Class B (130^o C) to Class F (155^oC). These changes have reduced the stator resistance from 3.17 Ohms to 2.34 Ohms.

Stator Dimensions:-	
● **Stator Bore or Inner Diameter**	**125 mm**
● **Stator Slots**	**36**
● **Stack length**	**100 mm**
Rotor Dimensions:-	
● **Outer Diameter**	**125 mm**
● **Rotor Slots**	**28**
● **Stack length**	**100 mm**
● **Conductor size**	**22 SWG**
● **Conductors per slot**	**104**
● **No. of Turns per phase**	**312**
● **Insulation**	**Class F**

The winding layout as per new design is developed as shown below,

Figure 3.1 to figure 3.6 shows the complete winding of six phases.

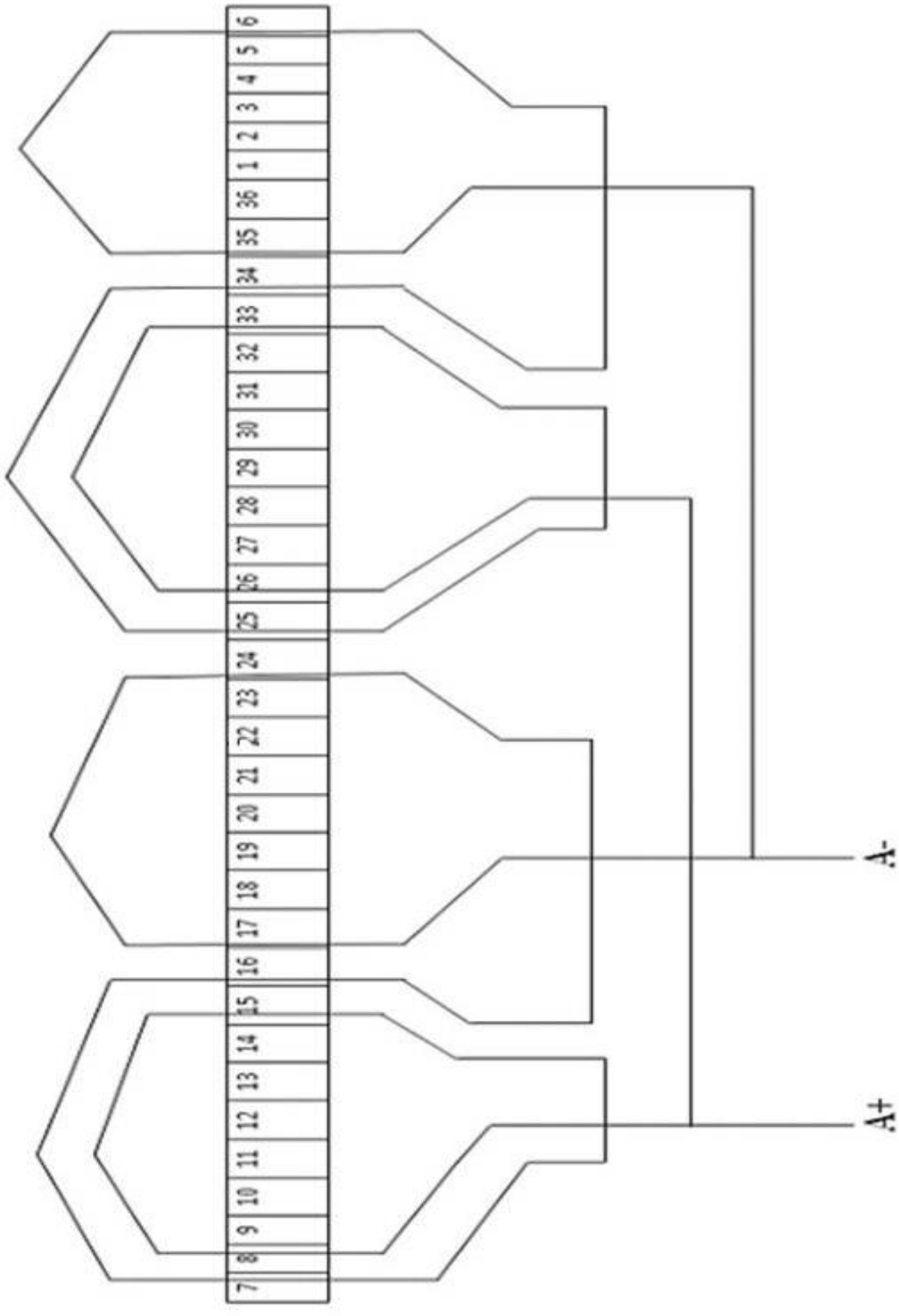


Figure 3.1 Winding Design of Phase A

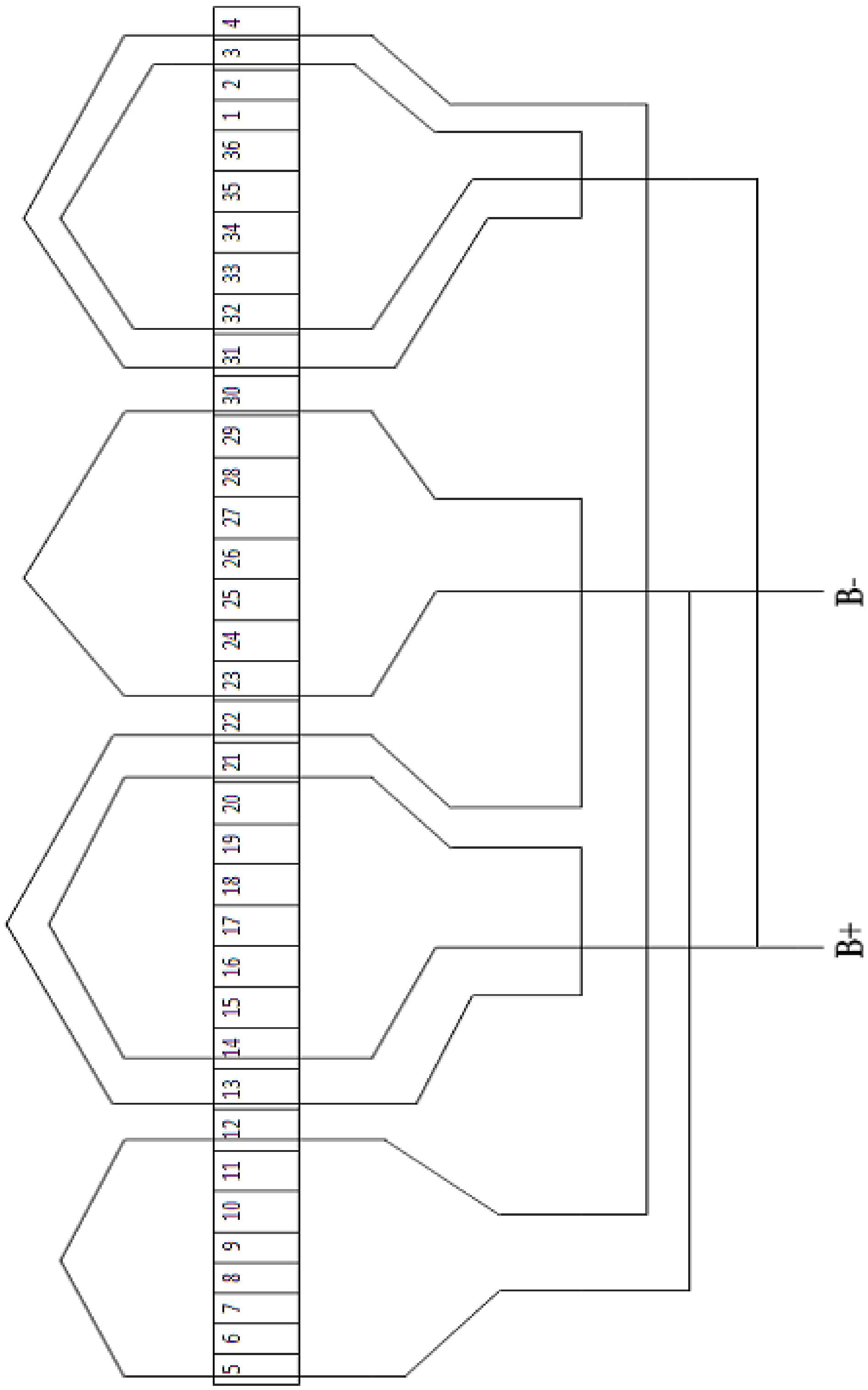


Figure 3.2 Winding Design of Phase B

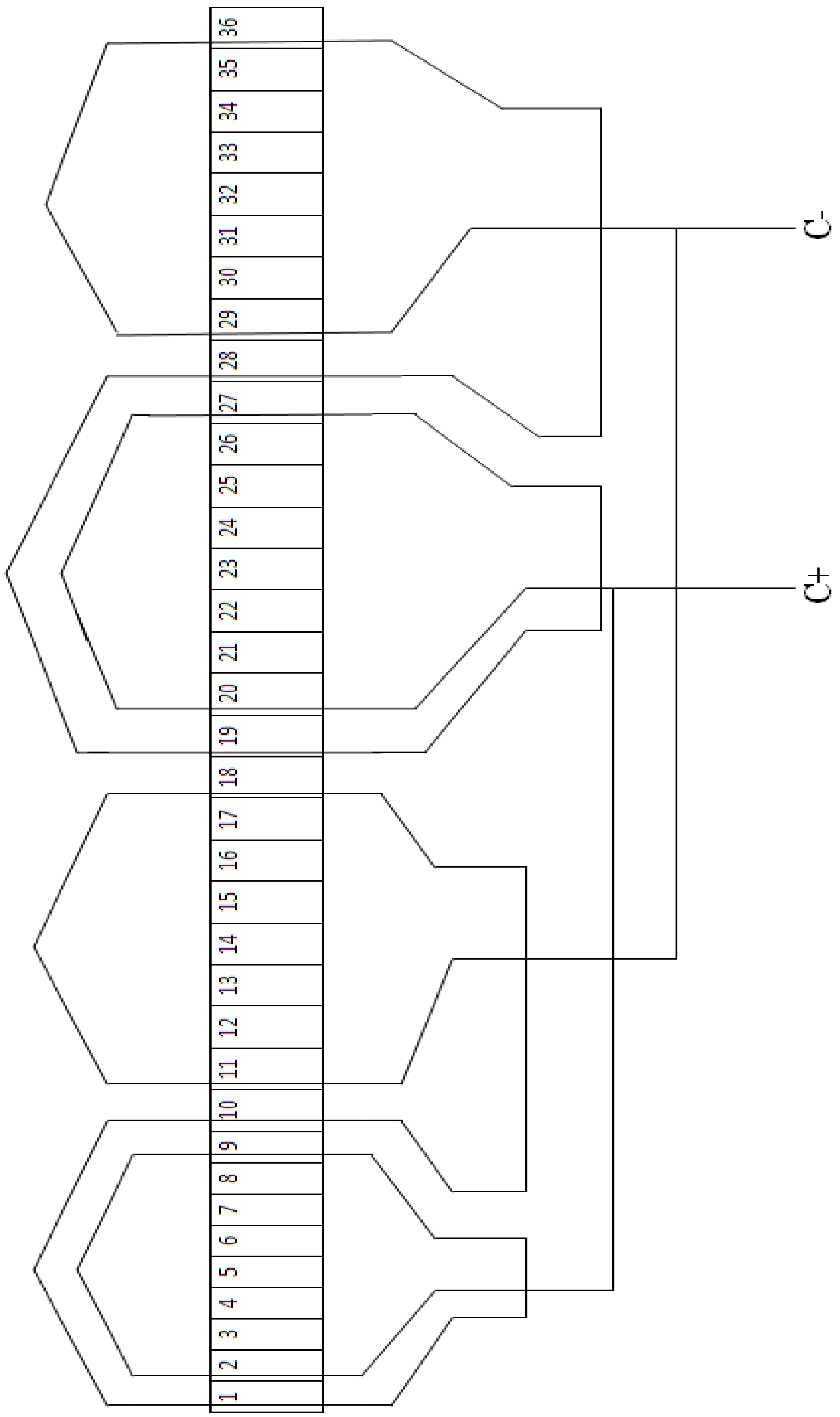


Figure 3.3 Winding Design of Phase C

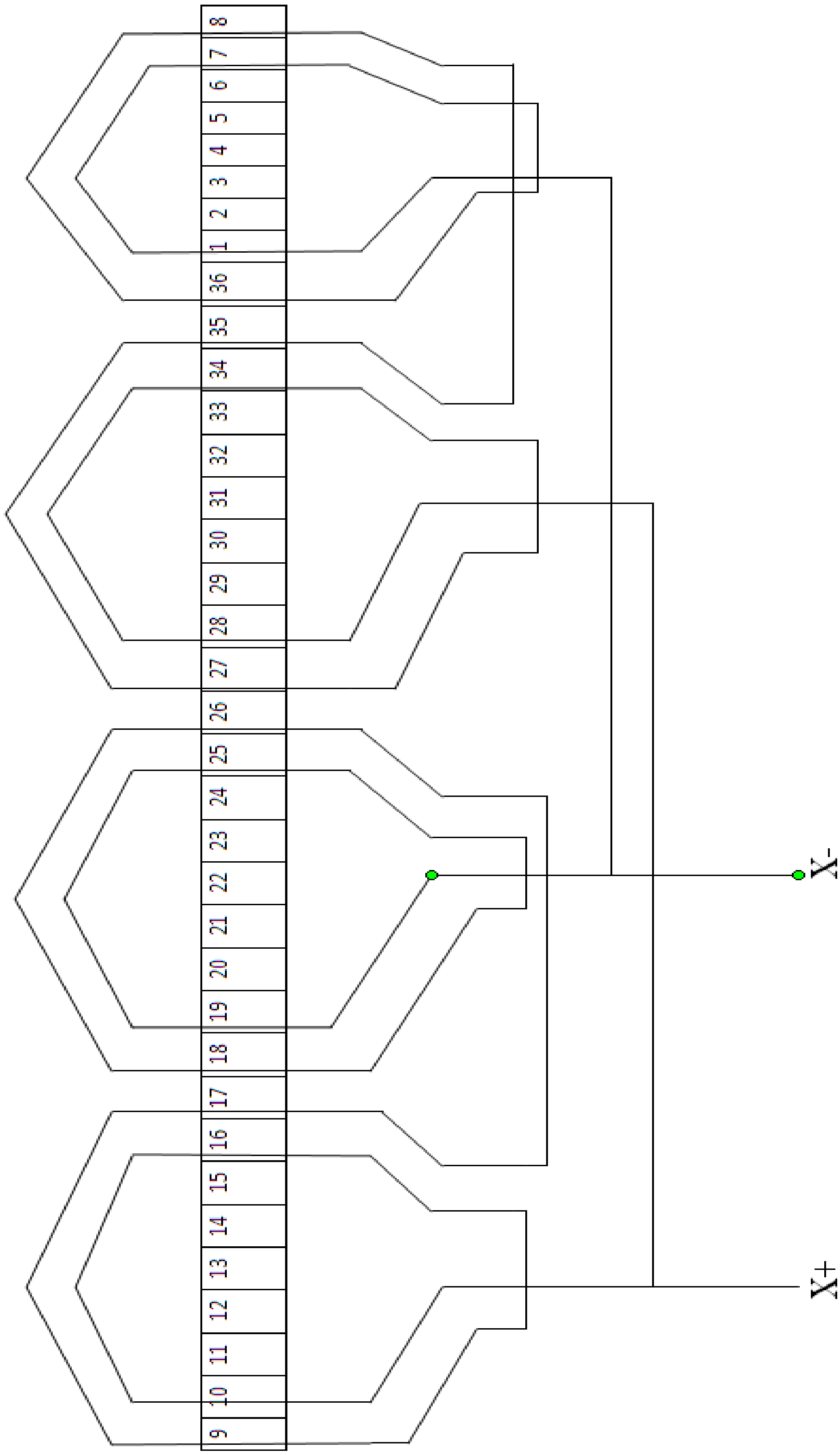


Figure 3.4 Winding Design of Phase X

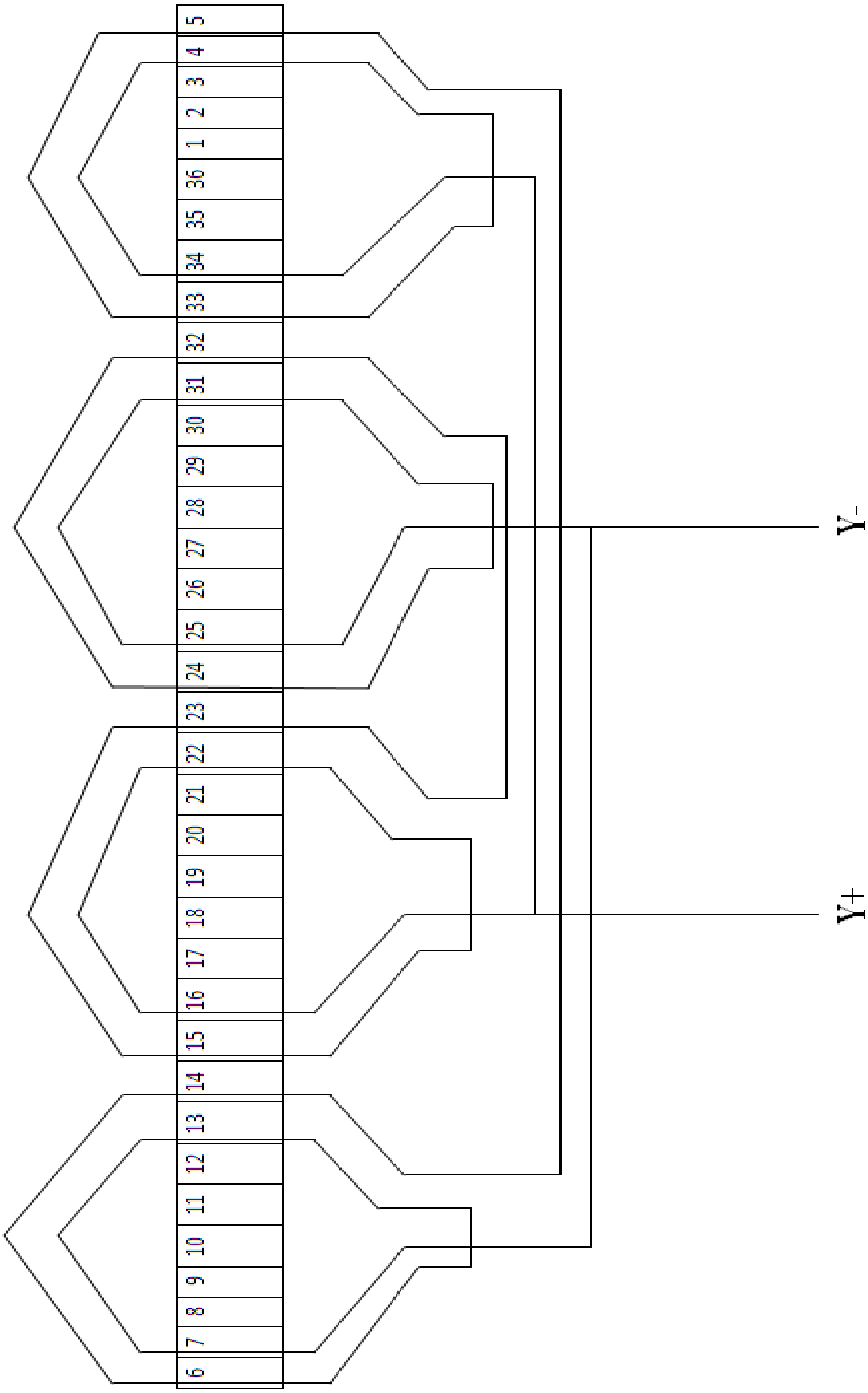


Figure 3.5 Winding Design of Phase Y

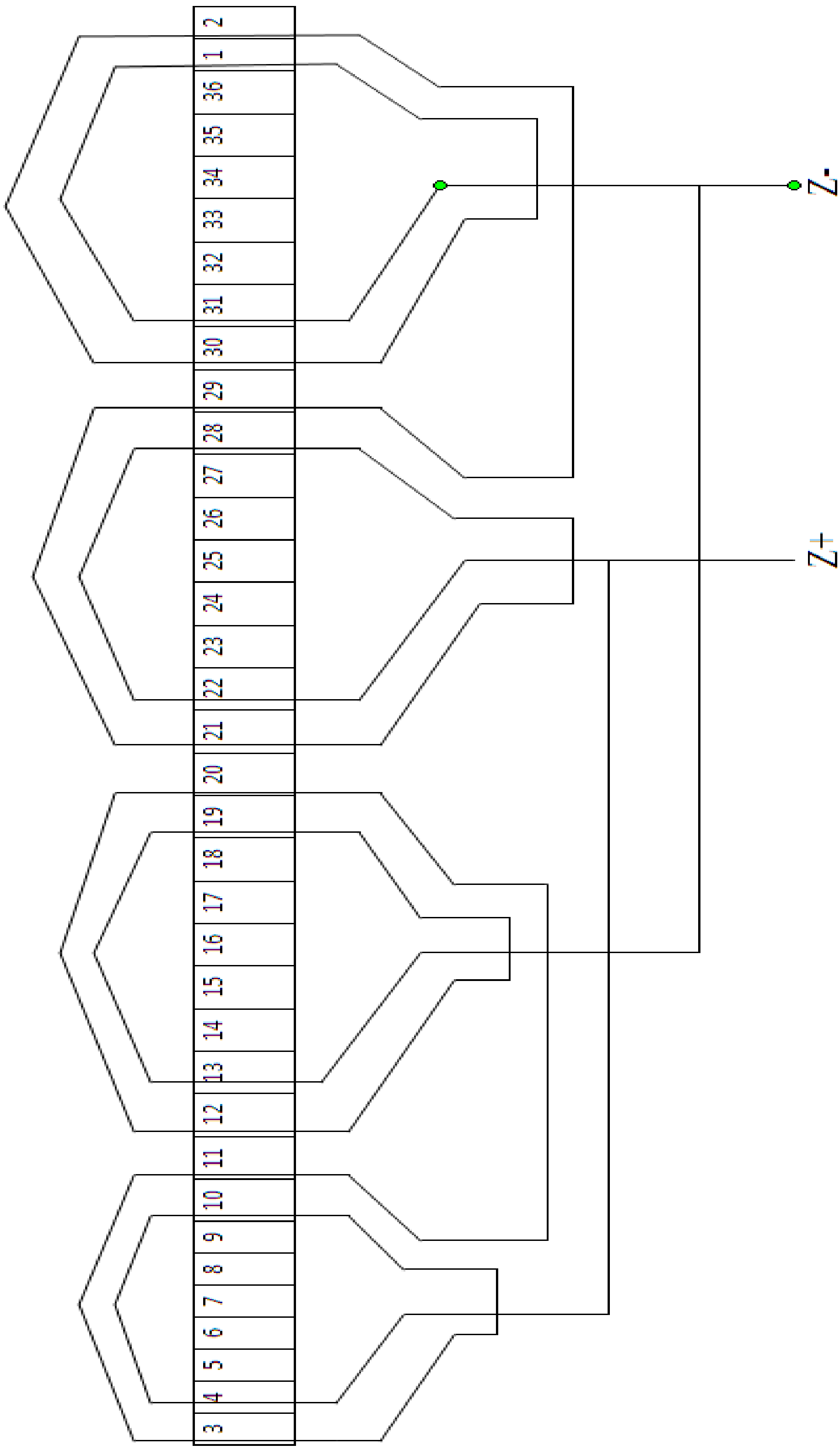


Figure 3.6 Winding Design of Phase Z

3. 5 ACTUAL DEVELOPMENT OF PROTOTYPE SIX PHASE INDUCTION MOTOR

1. A stator lamination having diameter 125 mm is pressed into a cylindrical frame as per the stack length of 100 mm.

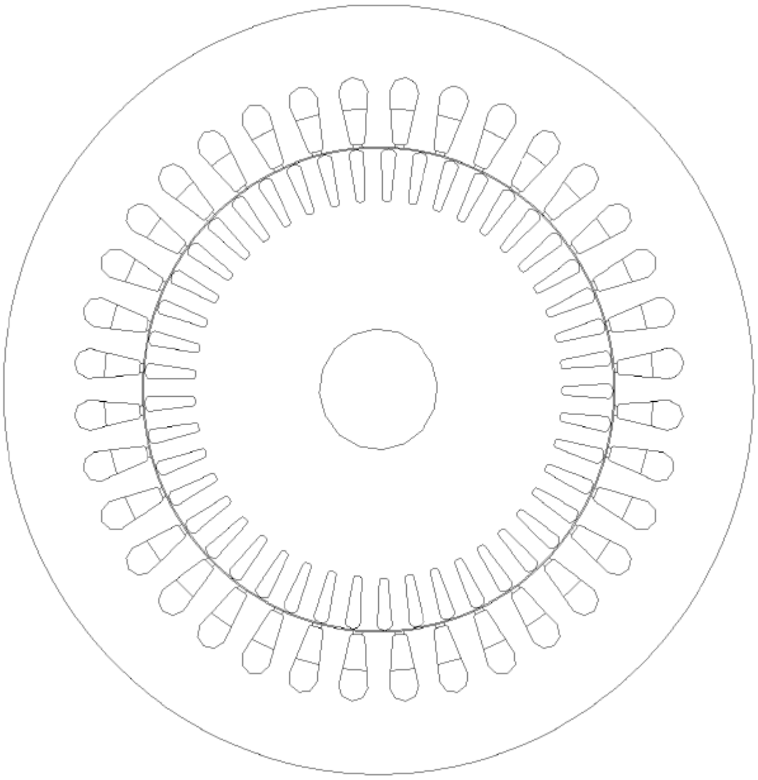
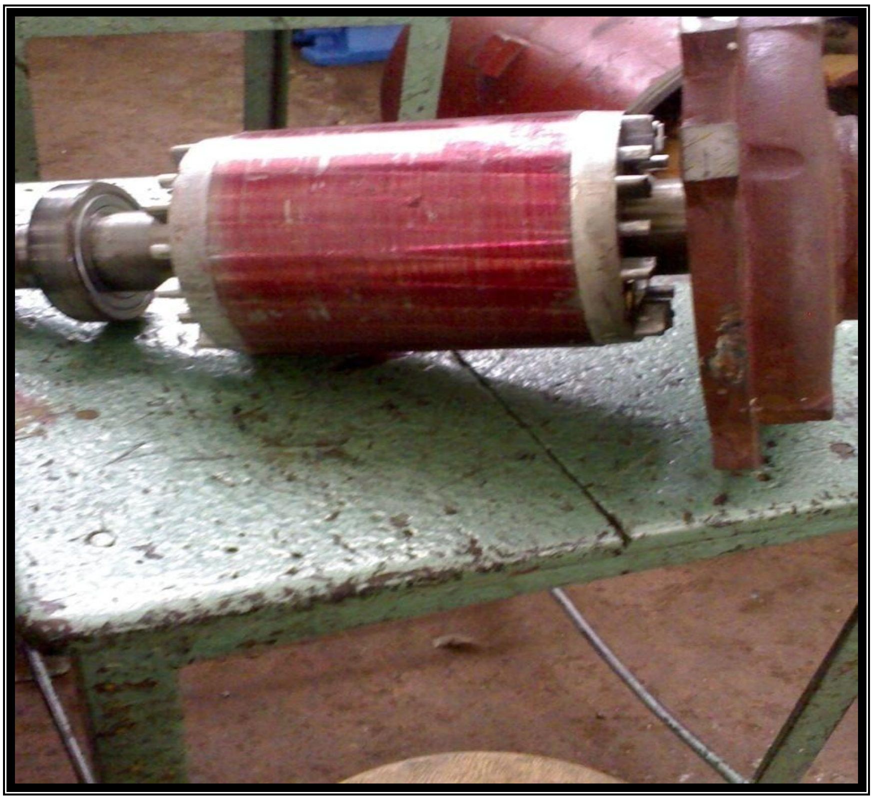


Figure 3.7 A stator lamination for 36 stator slots

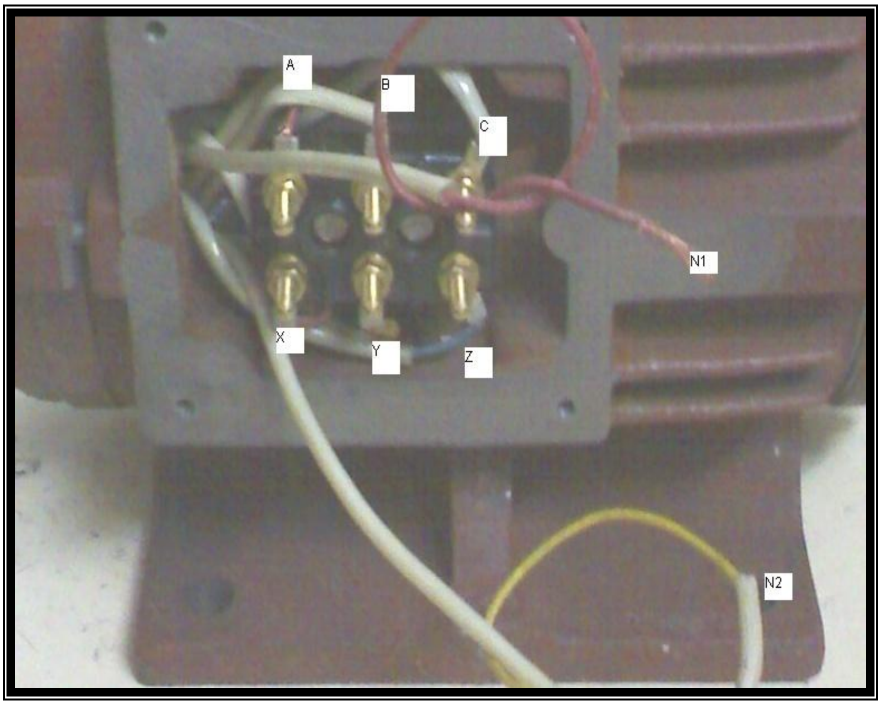
2. Rotor laminations as per the dimension are also pressed for 28 rotor slots.
3. Then windings are formed as per the number of turns per phase shown in the figure (3.1-3.6).
4. 22 SWG Copper conductors is used for winding.
5. Class F insulation is used.

Photograph 3.1. Actual winding

Photograph 3.2. Six phase stator after winding



Photograph 3.3. Rotor for prototype motor



Photograph 3.4. Prototype Six phase IM

3.6 TESTING

There is no standard separately for six phase induction motor. Thus the routine tests which are carried out for three phase motor , the same tests are carried out on prototype. It is considered like two, three phase induction motors sharing the same magnetic circuit and same shaft but electrically separated. Thus routine tests as per IS standards are carried out, by taking ABC and XYZ one by one.

A. HV Test:- A 2 KV voltage is given to the terminal box between phase to phase and phase to earth for one minute and there should be no sparking. If there is sparking, there may be inter turn fault.

Prototype six phase induction motor is tested like, two three phase stators sharing same shaft and same magnetic circuit and electrically separate. Prototype six phase induction motor satisfies this test, i.e. there is no sparking for both the three phase sets (ABC and XYZ).

B. Insulation Resistance (IR) Test: - Insulation resistance as per IS-325, should be 1 Mega Ohm.

Prototype six phase induction motor has insulation resistance 1MΩ for both three phase sets.

C. No load Test: - Motor is run at rated voltage at no load and rated speed. No load test results with waveform are shown below.

Supply Voltage	Current In Amp in ABC	Speed In RPM
60 V	**0.9**	**1475**
105 V	**1.27**	**1489**
152 V	**1.77**	**1491**
202 V	**2.33**	**1492**

Table 3.2 No load test results when ABC terminals energized

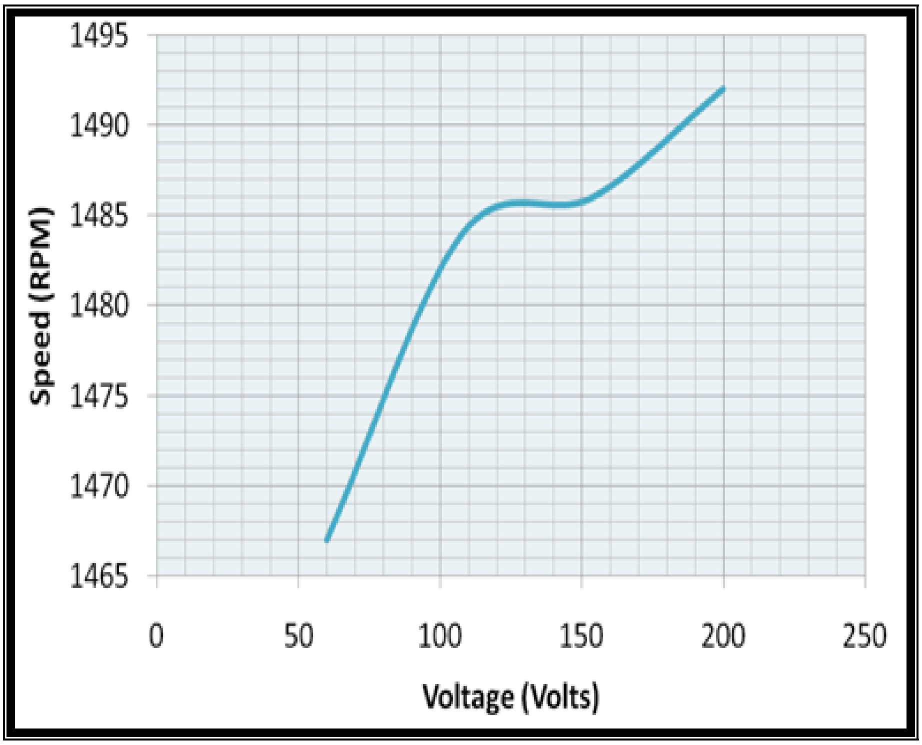


Figure 3.8 Speed Vs Voltage when ABC energized at No load

D. Blocked rotor test:- Full load current is passed when the rotor is locked. Test results are shown below

V_{sc} = 64 V, I_{sc} = 9.44 A

W_{sc} = 0.56 Kw

Speed N = 1460 rpm

E. Temperature rise Test:- Motor is run continuously for about a day and its temperature rise is noted, if it is getting overheated, winding and insulation is to be checked.

F. Load test:- Motor is loaded gradually at 50%, 75%, and 100%. Test results are shown below.

Photograph 3.5. Load test when ABC energized

Photograph 3.6. Load test when XYZ energized.

Supply Voltage	Current In Amp in XYZ	Speed In RPM
60 V	**0.84**	**1467**
108 V	**1.36**	**1484**
154 V	**1.8**	**1486**
200 V	**2.38**	**1492**

Table 3.3 No Load test results when XYZ Energized

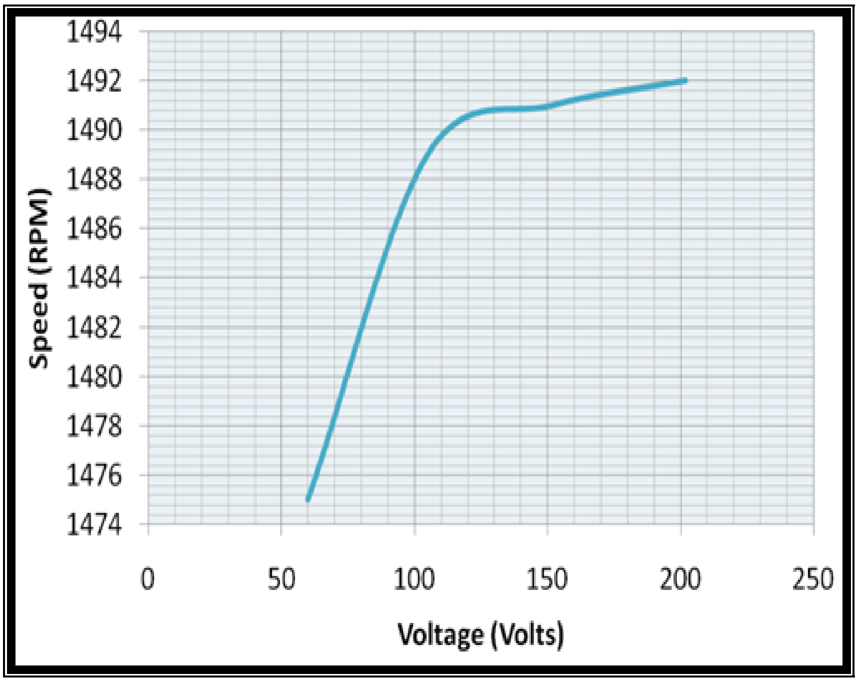


Figure 3.9 Speed Vs Voltage at No load when XYZ energized

Supply Voltage	Current in ABC (Amp)	Speed In RPM	Load in Kw
200 V	**3 Amp each**	**1460**	**0.78**
200 V	**3.5 Amp each**	**1450**	**1**
200V	**4.2 Amp each**	**1438**	**1.5**
200 V	**7.8 Amp each**	**1425**	**2.0**

Table 3.4 Load Test Results when ABC terminals energized

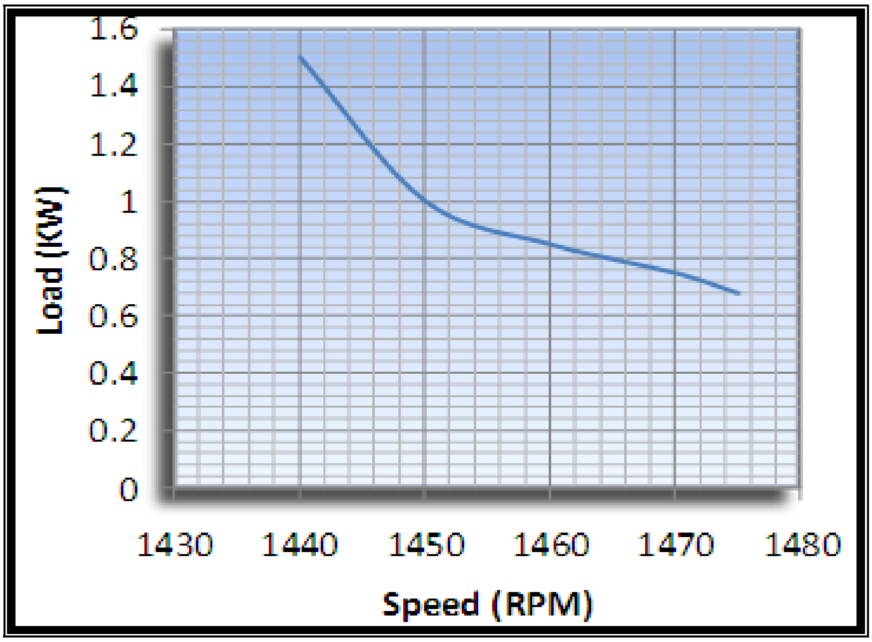


Figure 3.10 Speed Vs Load Characteristics when ABC terminals energized

Supply Voltage	Current In Amp in XYZ	Speed In RPM	Load in Kw
200 V	2.95 Amp each	1468	0.72
200 V	3.46 Amp each	1452	1
200V	4. 1 Amp each	1438	1.5
200 V	7.5 Amp each	1425	2.0

Table 3.5 Load test results when XYZ terminals energized

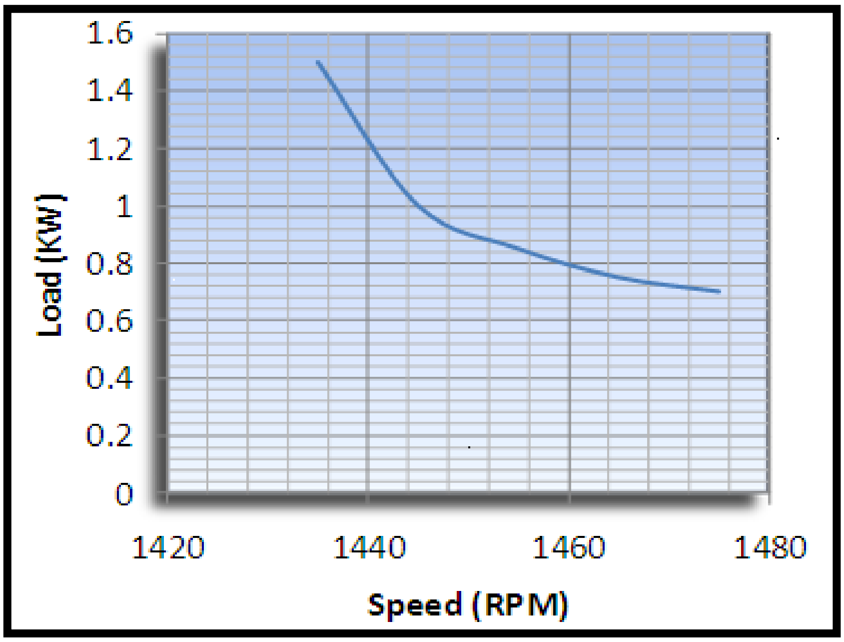


Figure 3.11 Speed Vs Load Characteristics when XYZ terminals energized

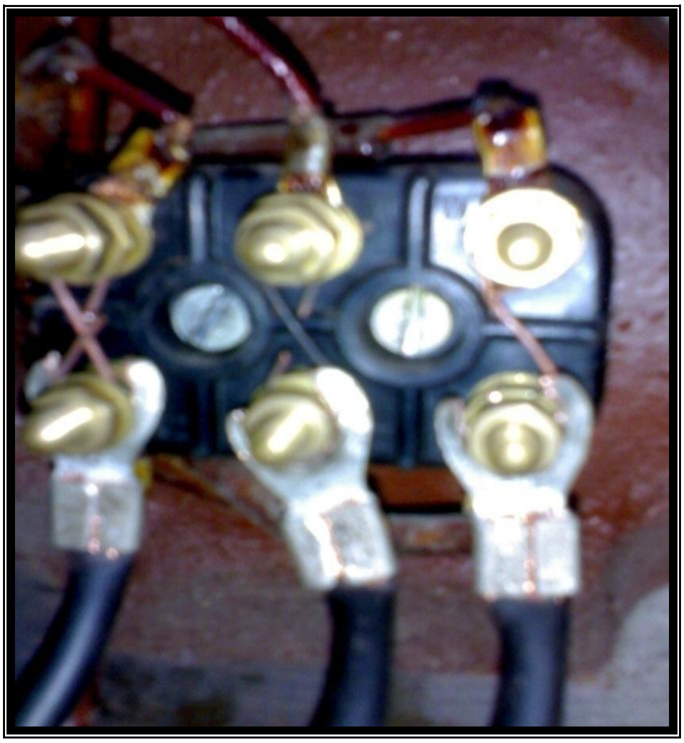
In no-load test, increasing voltage, increases the current and speed. While in load test, increasing current through load, reduces speed.

Apart from these tests, following tests are carried out as per customer requirement:-

G. Noise level test:- As per IS standards it should be less than 85 db. Prototype six phase induction motor satisfies this condition. Its noise level is below 85 db.

H. Vibration test:- Vibration should be minimum so as motor should not move. Prototype six phase induction motor vibration is minimum.

I. Momentary overload test:-Motor may be overloaded for 50% overload for few minutes. Prototype motor satisfies this test. Before supplying the motor from two, three phase inverters, the no load and blocked rotor tests are carried out with two, three phase sets shorted. The six phase motor is supplied through three phase, 200 V, 50 Hz supply when A shorted to X, B to Y, C to Z. the same set up is supplied through single three phase inverter for variable frequency operation.



Photograph3.7 ABC terminals shorted to XYZ terminals respectively

Photograph 3.8 Testing with shorted terminals

No Load test results when ABC and XYZ shorted: (Six phase star connected 3 HP, 4 pole IM)

No Load voltage, V_0 = 200 V

No Load Current, I_0 = 4.19 A

No Load Speed N = 1475 rpm

No Load Loss W_0 = 0.36 Kw

In general,

$$W = mV_{ph} I_{ph} \text{Cos } \Phi \qquad [3.18]$$

For three phase IM, m=3

$$W = 3 V_{ph} I_{ph} \text{Cos } \Phi = \sqrt{3}\, V_L I_L \text{Cos } \Phi \qquad [3.19]$$

For six phase IM, m= 6

$$W = 6 V_{ph} I_{ph} \text{Cos } \Phi = 2\sqrt{3}\, V_L I_L \text{Cos } \Phi \qquad [3.20]$$

$$W_0 = 2\sqrt{3}\, V_0 I_0 \text{Cos } \Phi_0 \qquad [3.21]$$

$$\Phi_0 = W_0 / 2\sqrt{3}\, V_0 I_0 = 82.87^o \qquad [3.22]$$

Blocked rotor test results

$V_{sc} = 64$ V

$I_{sc} = 9.44$ A

$W_{sc} = 0.56$ Kw

Speed N = 1460 rpm

$W_{sc} = 2\sqrt{3}\, V_{sc} I_{sc} \cos \Phi_{sc}$ [3.23]

$\Phi_{sc} = W_{sc} / 2\sqrt{3}\, V_{sc} I_{sc}$ [3.24]

$\Phi_{sc} = 74.47^{o}$

With this knowledge, the circle diagrams for three phase, 3 HP and six phase ,3 HP (shown in figure 3.19 and figure 3.20 respectively) are drawn to calculate torque and efficiency, etc. For three phase, 3 HP, 4 pole, 200V induction motor, choosing the scale of 1cm = 1 Amp the circle diagram as shown in the figure 3.19 is drawn. Power scale is 1 cm =340 Watt (Power scale: √3 x voltage)

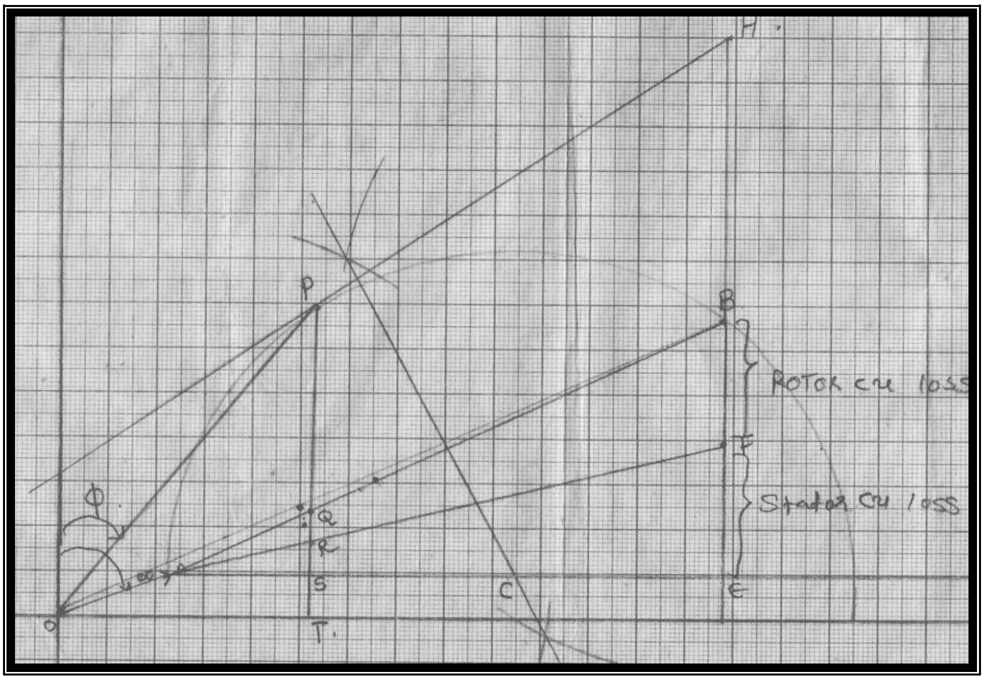


Figure 3.12 Circle diagram of three phase, 3 HP IM

From figure 3.12

Full Load line current OP = 8.4 cm

As per current scale, 1 cm = 1 Amp

Hence full load current = 8.4 Amp

Full load p.f. CosΦ = PT / OP = 6.8 / 8.4 = 0.8 lag [3.25]

Full load torque = Rotor input = PR = 5 cm

As per power scale 1 cm = 340 W

Hence full load torque = 5 x 340 = 1700 N-m [3.26]

Full Load Efficiency = PQ / PT = 4.5/6.8 = 66 % [3.27]

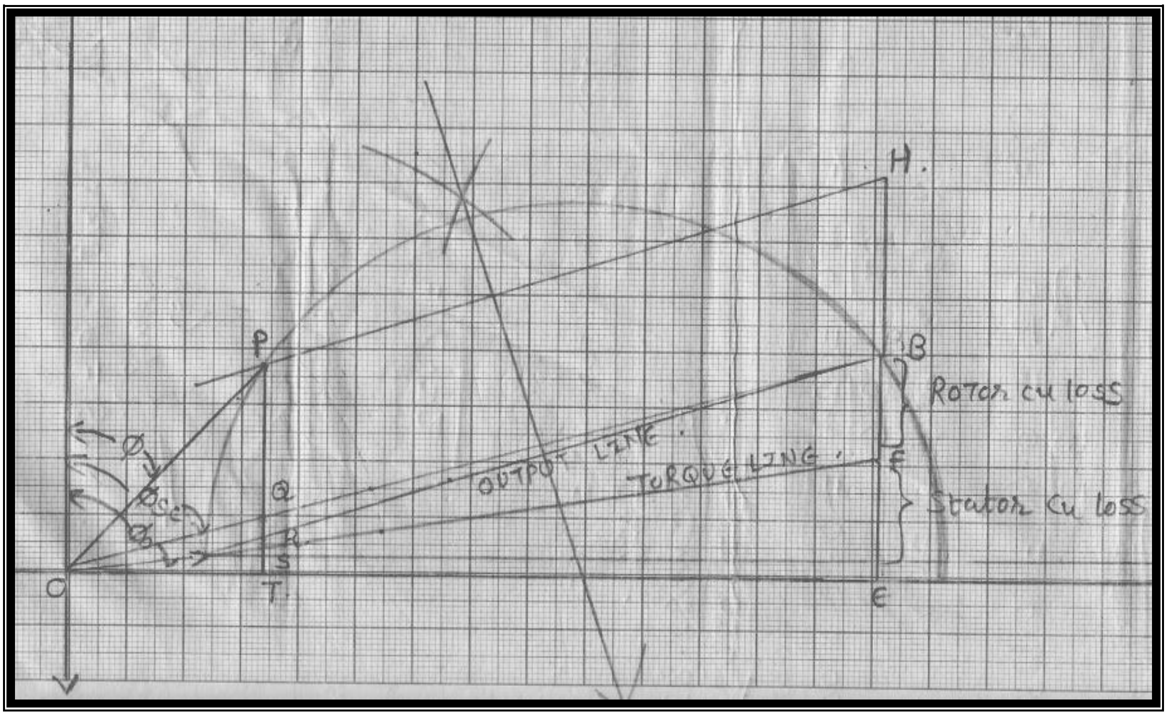


Figure 3.13 Circle Diagram of 6 phase 3 HP Motor

For six phase, 3 HP, 4 pole, 200 Volts Induction motor the

current scale is

1 cm = 2 Amp and power scale is 1 cm = 695 W, ($2\sqrt{3}$ x voltage)

From figure 3.13,

Full Load line current OP = 5 cm

As per current scale 1 cm = 2 Amp

Hence Full load line current = 10 Amp

Full Load P.f. $\cos\Phi$ = PT/ OP = 4/5 = 0.8 [3.28]

Full Load torque = Rotor input = PR = 3.9 cm [3.29]

As per power scale 1 cm = 695 W

Hence Full load torque = 3.9 x 695 = 2710.5 N-m [3.30]

Full Load Efficiency = PQ / PT = 3.5 / 4 = 88 % [3.31]

3.7 DISCUSSION:

From equations (3.26) and (3.30)

The full load torque of 3 HP, 4 pole, 200 volts, 3 phase induction motor is 1700 N-m and full load torque of 3 HP, 4 pole, 200 volts, 6 phase induction motor is 2710.5 N-m.

Thus

Full Load torque of 6 phase IM / Full Load torque of 3 phase IM = 2710.5/1700 = 1.6.

Also efficiency of 6 phase IM = 88% ; From equation [3.31]

While efficiency of 3 phase IM = 66%; From equation [3.27]

From the circle diagram and calculations it is clear that the torque of six phase induction motor is more and found to be approximately 1.6 times more than equivalent three phase motor. Also Efficiency of six phase induction motor is 1.4 times more than that of equivalent three phase induction motor.

3.8 CONCLUSION

Three phase induction motor design and then six phase induction motor design, development and testing is discussed in detail in this chapter. Following points are noted:

1. The torque of six phase induction motor is much higher than equivalent three phase induction motor. Prototype six phase induction motor torque is 1.6 times that of equivalent three phase

motor. In [1]-[41] torque improvement is obtained by third harmonic current injection. Third harmonic current injection needs large inductors. The application of multiphase induction motor is mainly in high power-high current applications so the use of inductor for current injection is uneconomical. Though the initial cost of six phase induction motor is increased as compared to three phase induction motor but at the same time efficiency and torque are significantly improved. Also torque improvement with third harmonic current injection is 1.4 times that of equivalent three phase induction motor [1]-[41] while the developed prototype six phase induction motor torque is 1.6 times that of equivalent three phase induction motor. As the motor rating increases it is tedious to arrange third harmonic current injection externally and also uneconomical.

2. From the no load and load tests conducted separately on ABC and XYZ, it is obvious that the prototype motor is highly reliable: If one of the three phase sets is not supplied the motor will continue to run as three phase and continuity of operation is maintained as the neutrals are separate.
3. Instead of copper conductors, aluminum conductors may be used to reduce the cost, thus making it more economical.

4. When both the three phase sets will be supplied simultaneously through inverters may get better results.

CHAPTER 4

CONTROL OF INDUCTION MOTORS

4.1 INTRODUCTION:

Poly-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 [55-59]. This chapter focuses on various control methods for speed control of induction motor. Vector control is discussed in detail and sensor less vector control is explained. Space vector Pulse width modulated inverter (SVPWM) is discussed in detail. Matlab simulation of vector control of Multi motor is discussed with output waveform and finally compared with three phase motor.

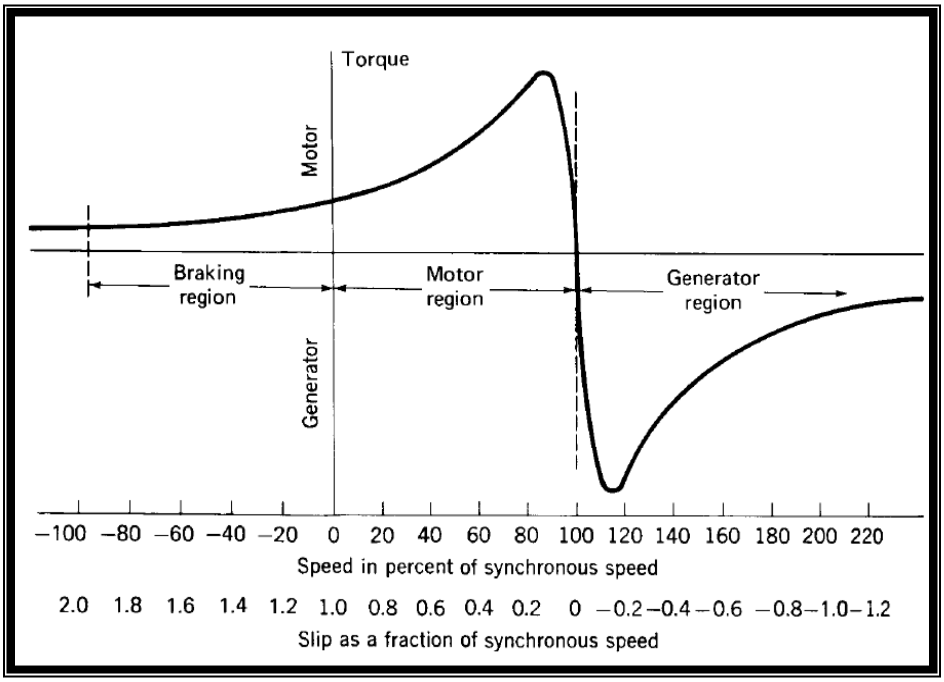


Figure 4.1 A typical speed-torque curve of induction motor

4.1.1 Speed control of three phase induction motor

Controlling a DC machine is much easier because of the fact that the main flux and the armature current distribution are fixed in space and can be controlled independently while with an AC machine these quantities are strongly interacting and move with respect to the stator as well as the rotor. They are, in a complex way determined by the amplitudes, frequency and phases of the stator currents. The three stator currents can be reduced to two independent control variables. And Field oriented control can be achieved.

4.2 VECTOR CONTROL

The control and estimation of ac drives is complex than those of dc drives. The main reason for this complexity is the need for variable frequency. Now-a-days the vector control overcomes the drawbacks of scalar control improving the transient performance of motor and hence ac induction motor is the winner in industry. Application of induction motors in continuous duty variable speed drives calls for static inverters of adequate power, generating three phase voltages of variable amplitude and frequency. In that case, indirect frequency conversion methods are appropriate. The indirect frequency changer consists of rectification and inversion. There is a large variety of solution for the inverter and control problem.[55-56]

In vector or field oriented control both the magnitude and phase alignment of vector variables are controlled. The invention of vector control in the beginning of 1970s and the demonstration that an induction motor can be controlled like a separately excited dc motor brought renaissance in the high performance of control of ac drives. Because of dc like performance vector control is also known as “decoupling” orthogonal or trans-vector control.

Field orientation is a technique that provides a method of decoupling the two components of stator current: one producing the air-gap flux and the other producing the torque. The principle of field orientation originated in the former West Germany through the work of Blaschke and Hasse (Blaschke 1972; Hasse 1969). A variety of implementation methods have now been developed but these techniques can be broadly classified into two groups: direct control and indirect control [55].

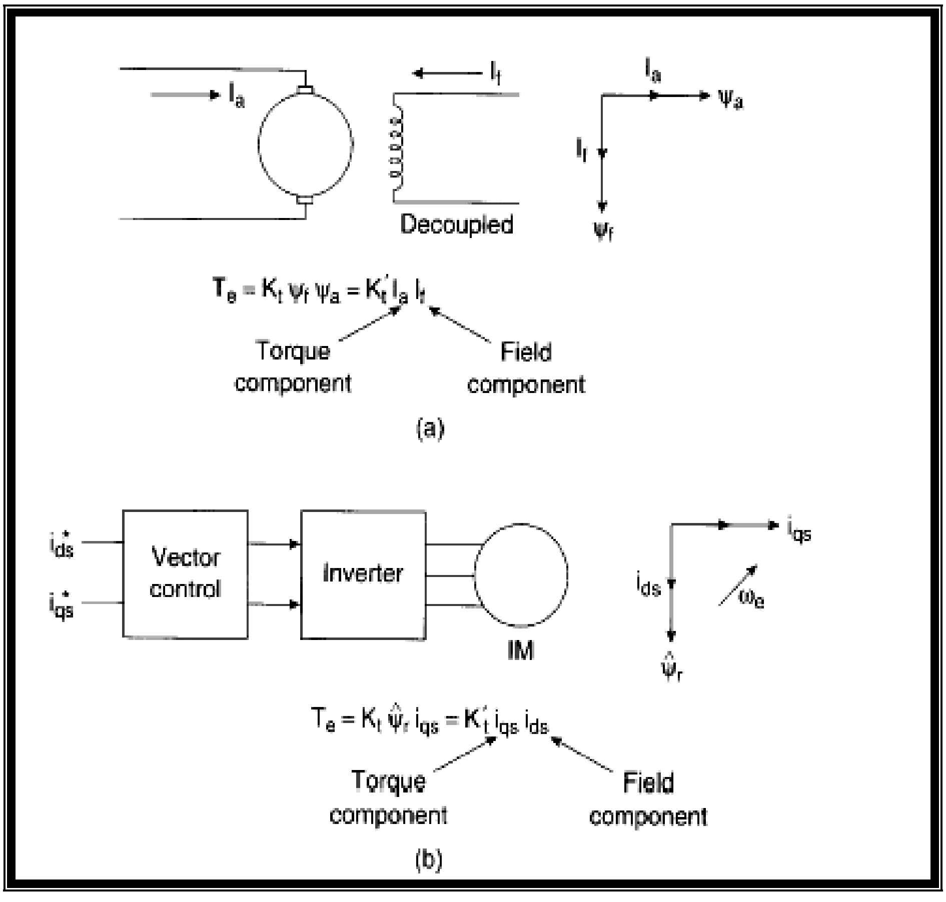


Figure 4.2 Principle of field oriented control

Figure 4.2 explains the principle of vector control. Here analogy of three phase induction motor with separately excited dc motor is shown. For field oriented control, three phase induction motor is run like a separately excited dc motor. For this a d-q axis model of induction motor is must.

In vector or field oriented control both the magnitude and phase alignment of vector variables are controlled. Induction motor can be controlled like a separately excited dc motor. Because of dc like performance vector control is also known as "decoupling" or Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine.

In the case of induction motor, the control is usually performed in the reference frame d-q (d- direct axis, q- quadrature axis) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis (d) is aligned with the rotor flux space vector. Orthogonal or Trans - vector control.

4.2.1 Sensor less vector control

AC drives often need mechanical sensors (tachometers, position encoders) for field orientation. In many applications these sensors reduce robustness and increase costs of a drive considerably. Sensor-less control schemes using motor terminal voltages and currents, works very well at high speeds of operation.

Consequently, this has opened a new interesting area for research and during the last few years a variety of different solutions has reached the market. Neural networks, artificial intelligence and sensor less control are names that might sound familiar. The last one is a method that consists, as indicated by the name, of different ways of controlling the induction motor without using a speed sensor. Even though the induction motor is cheap and simple in its construction, this is not the case when it comes to its mathematics. The machine is represented by a nonlinear model with unknown variables and external inputs, which with its complexity makes sensor less control a challenging theoretical problem.

Sensorless vector control of an induction motor drive essentially means vector control without any speed sensor. An incremental shaft-mounted speed encoder (usually an optical type) is required for close loop speed or position control in both vector- and scalar-controlled drives. A speed signal is also required in indirect vector control in the whole speed range and in direct vector control for low speed range, including the zero speed start up operation.

A speed encoder is undesirable in a drive because it adds cost and reliability problems, besides the need for shaft extension and mounting arrangement. It is possible to estimate the speed signal from machine terminal voltages and currents with the help of DSP (Digital Signal Processor) [55].

4.3 SIMULATION OF VECTOR CONTROL OF MULTI-MOTOR DRIVES IN MATLAB SOFTWARE:

The classic vector-control scheme consists of the torque and flux control loops, and motor 1 is supplied from a voltage source inverter (VSI) and motor 2 is supplied from current source inverter (CSI). Although most of the power absorbed by the motor is supplied by the CSI, from the control point of view it is the VSI that constitutes the actuator, and, consequently, the motor can be considered as voltage-controlled. The voltage source characteristic of the tandem converter is decisive with respect to the structure of a vector-control scheme. For the vector control of induction motors, the rotor-field orientation has the advantage of easy decoupling of the torque and flux controls. The two motors are controlled using Tandem converter i.e. One motor fed by Voltage source inverter, VSI and the other fed by current source inverter, CSI.

Three phase sinusoidal voltage is converted to dc voltage with the help of universal diode bridge rectifier. Rectified voltage is fed to Voltage source inverter & Current source inverter. Inverter pulses are regulated through Bang- Bang current controller. Two three phase Induction motors are modeled in a synchronously rotating reference frame. Stator currents, Speed & Torque of the induction motor 1 are seen in figure 4.4 to figure 4.6 Stator currents; Speed & Torque of the induction motor 2 are seen in figure 4.7 to figure 4.9 Speed controller used is PI controller. Flux is calculated in flux calculator & there from theta is calculated. A Bang-Bang current controller is used**.** Stator current**,** Speed & Torque characteristics of motor 1 for change in reference speed can be seen in figure 4.10 to 4.12. Stator current**,** Speed & Torque characteristics of motor 2 for change in reference speed can be seen in figure 4.13 to 4.15.

Computer simulations using Matlab/Simulink have been performed for assessment of operating features of the proposed scheme. The simulation involved a start-up of an unloaded, 5.5-kW, 380-V, 50-Hz motor and 4.5 Kw, 380-V, 50 Hz motor, followed by a step torque command at the rated-torque level and reversal of the drive with the same rated torque. All pertinent mathematical models have been developed individually, using Simulink's S-function blocks for the power electronic converters and the motor (the "Power System" block set could be used as well).

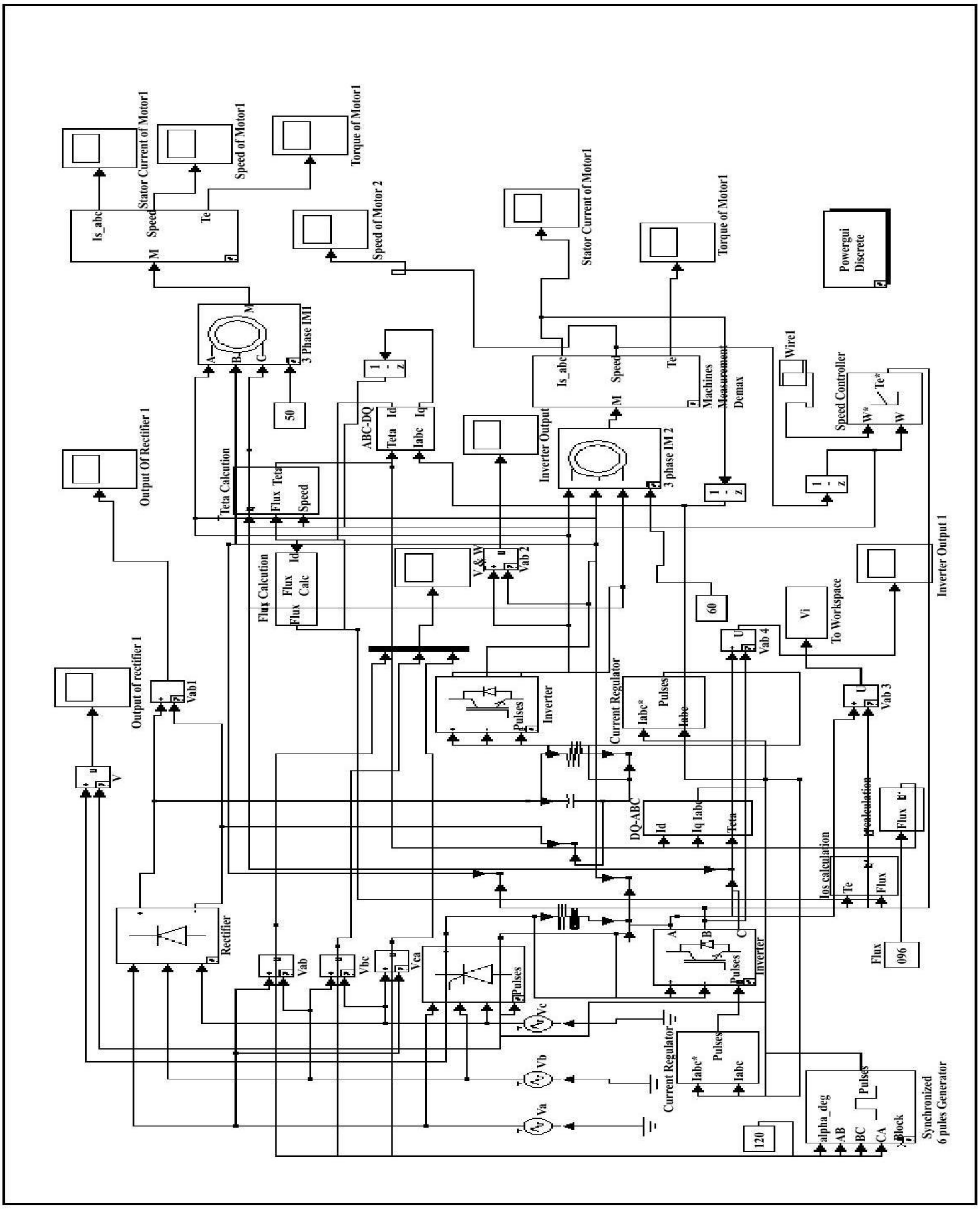


Figure 4.3 Simulated circuit for Vector Control of Two, Three phase Induction motor

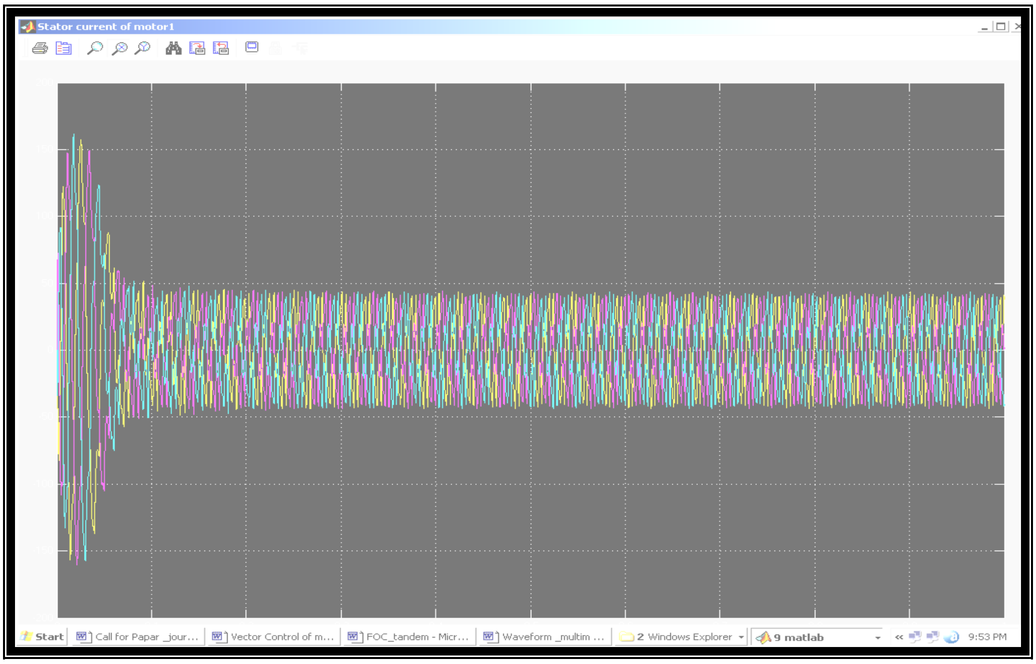


Figure 4.4 Stator current waveform of motor 1

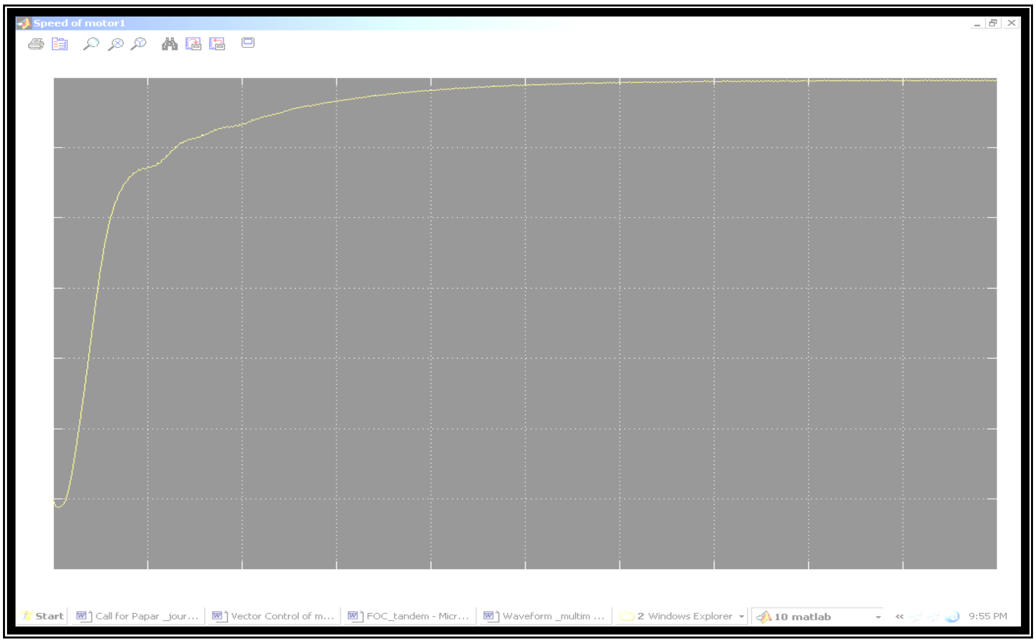


Figure 4.5 Speed of motor 1

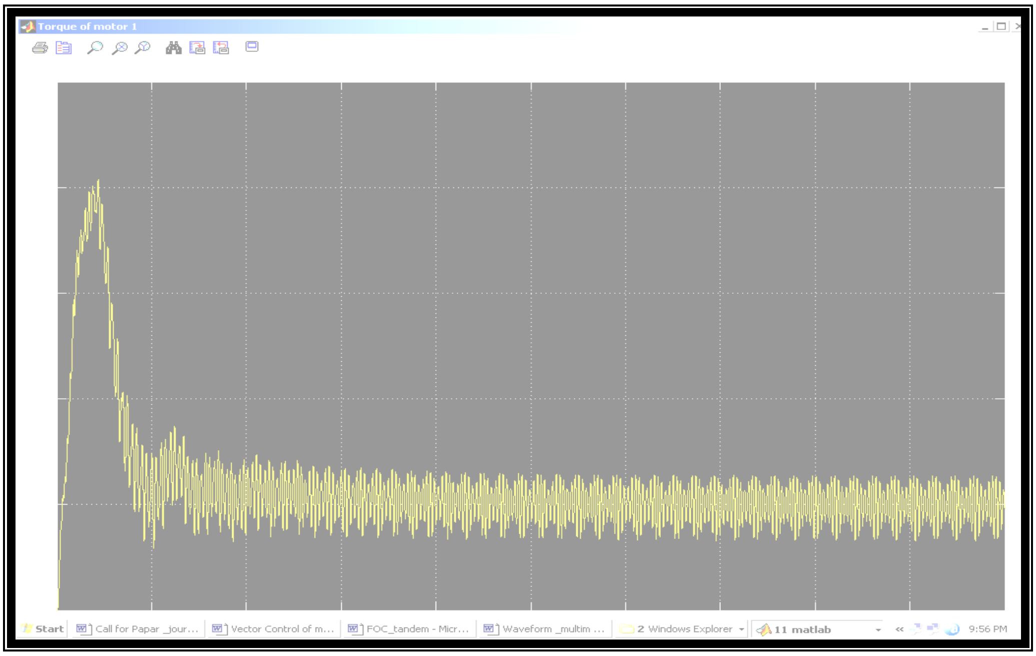


Figure 4.6 Torque of motor 1

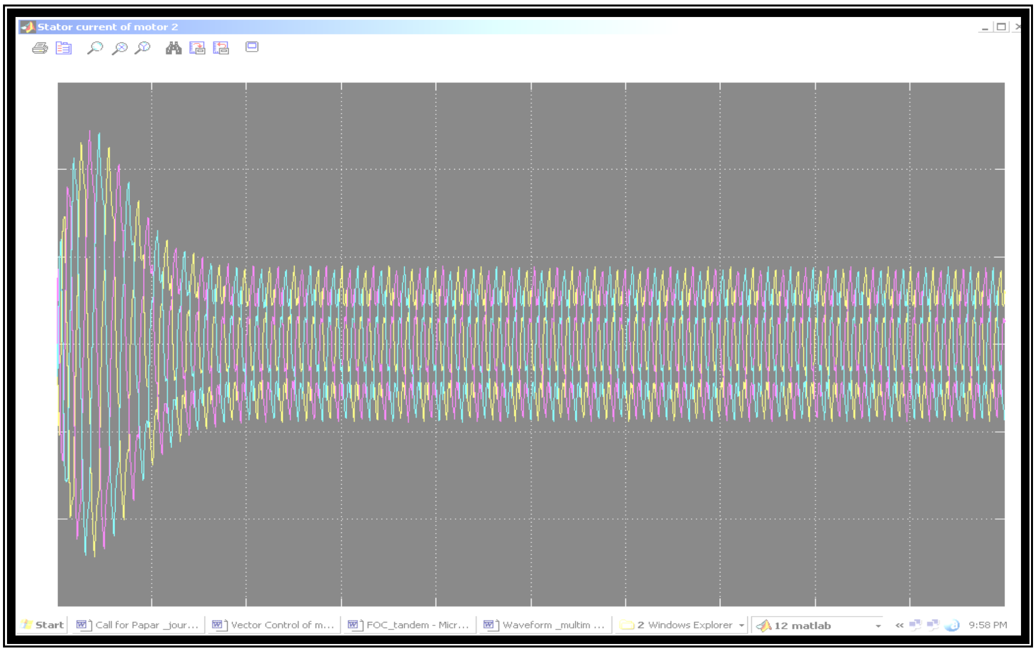


Figure 4.7 Stator current of motor 2

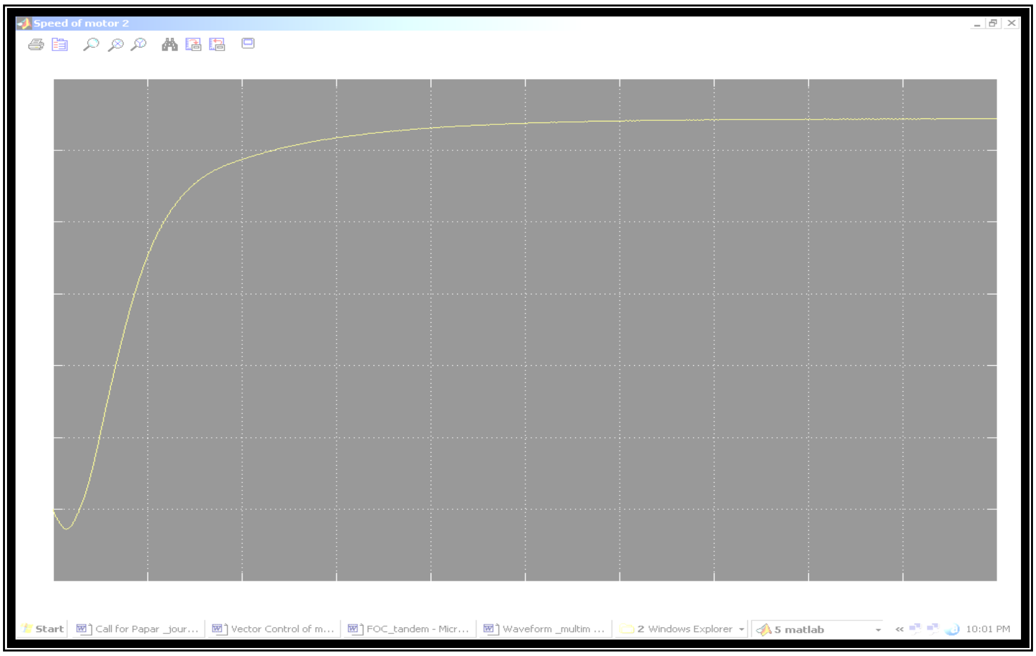


Figure 4.8 Speed of motor 2

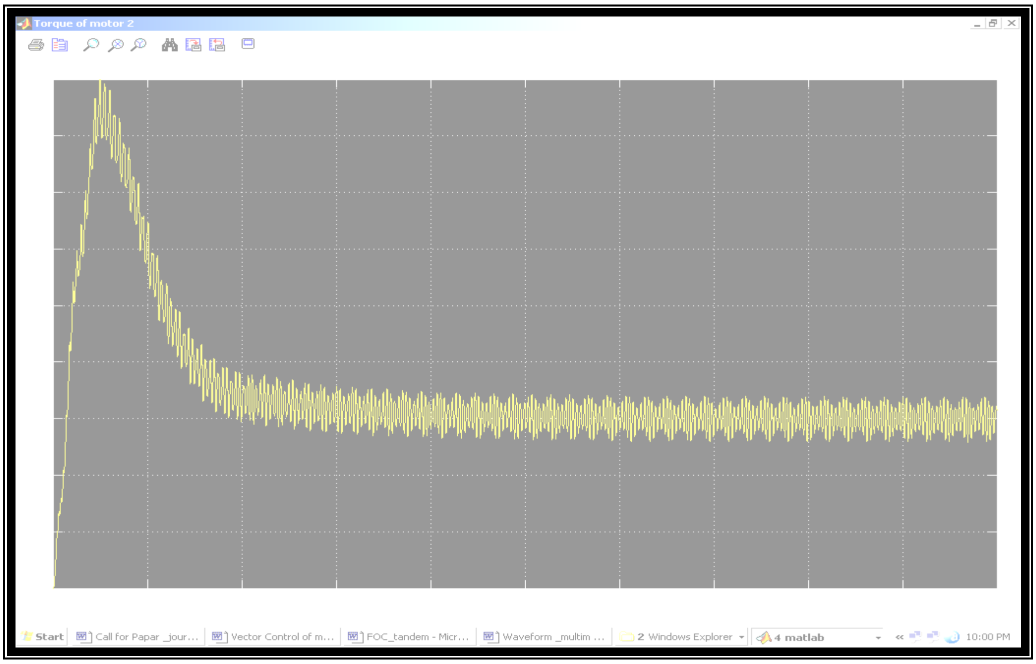


Figure 4.9 Torque of motor 2

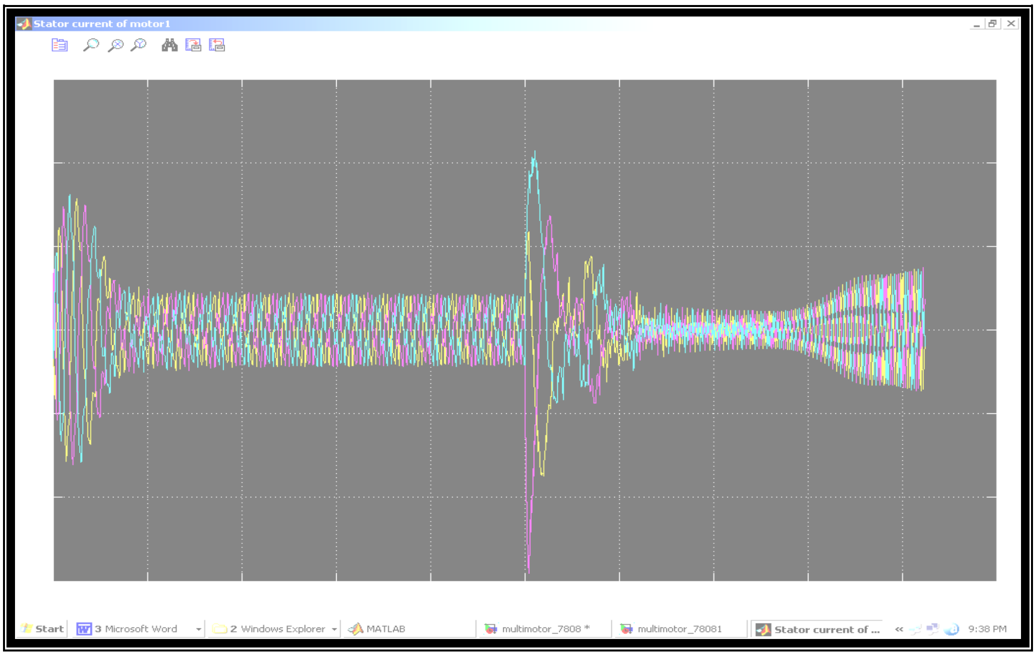


Figure 4.10 Waveform for Stator current of motor 1 for change in reference speed

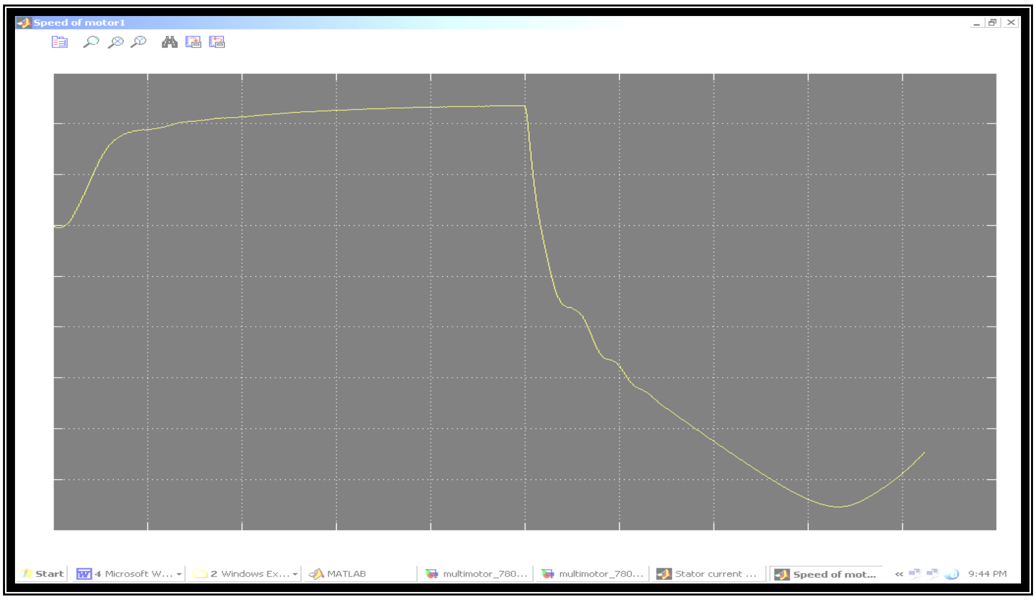


Figure 4.11 Waveform of speed of motor 1 for change in reference speed

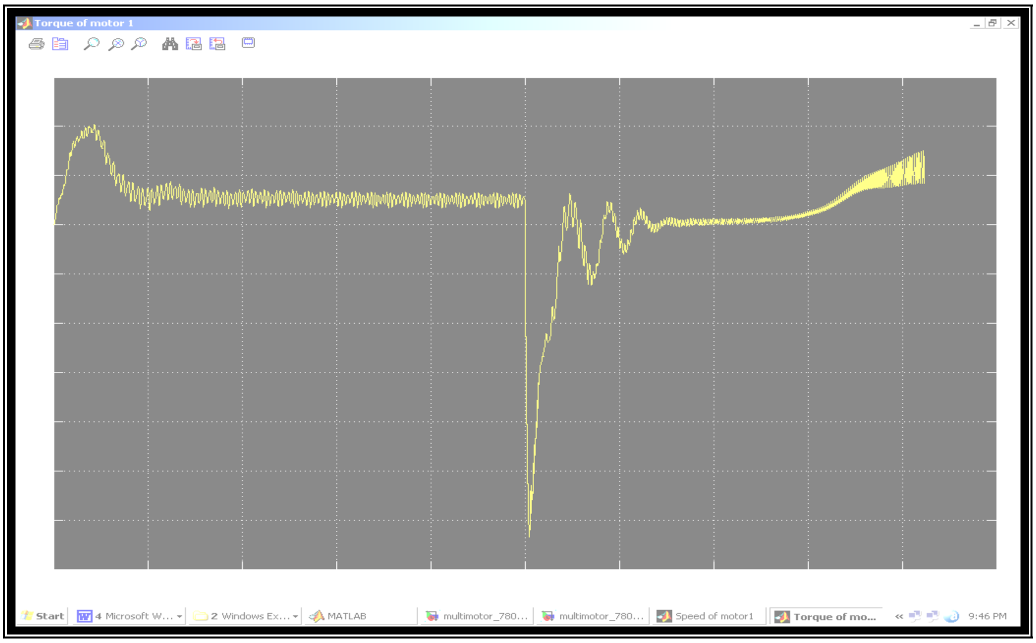


Figure 4.12 Waveform for torque of motor 1 for change in reference speed.

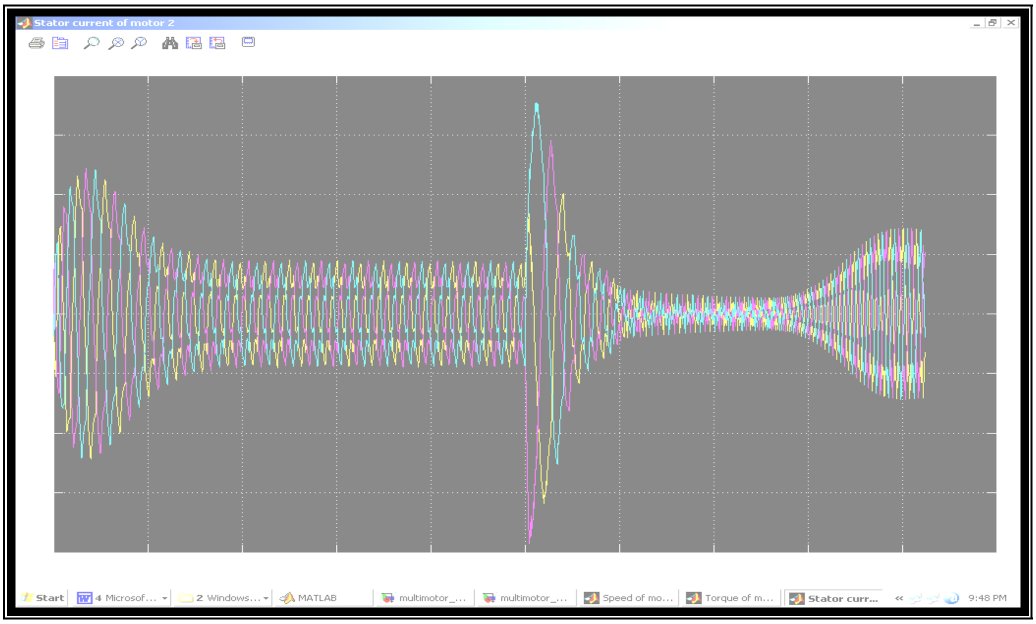


Figure 4.13 Waveform for Stator current of motor 2 for change in reference speed

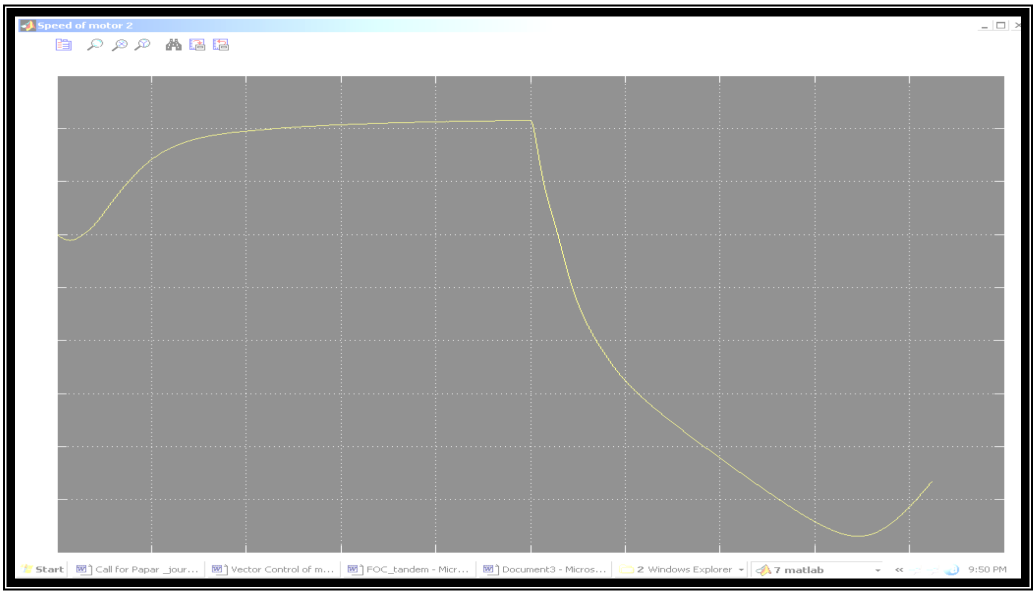


Figure 4.14 Waveform of speed of motor 2 for change in reference speed

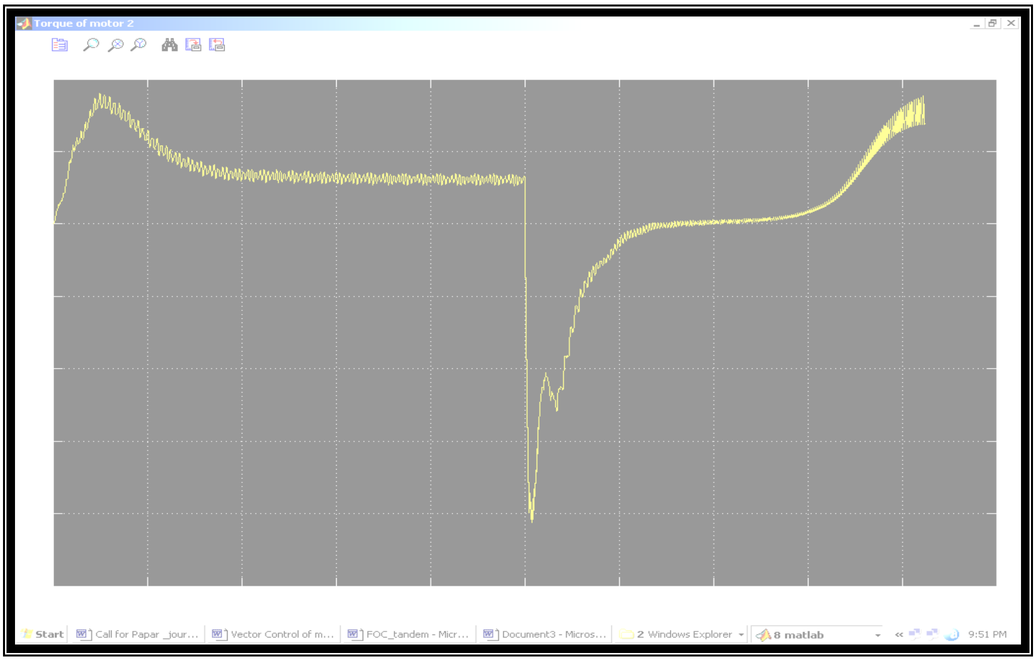


Figure 4.15 Waveform for torque of motor 2 for a change in reference speed.

Motor Specifications:-

Motor 1:- 5.5 kw, 380-V, 50-Hz

Motor 2:- 4.5 Kw, 380-V, 50 Hz

4.3.1 Comparison with single, three phase induction motor:

Reliability is the main advantage of multi motor operation over single three phase motor. If one of the motor fails by any reason the continuity of operation is maintained.

4.4 CONCLUSION

Though there is an advantage of reliability there are no other advantages like torque and efficiency improvement. Thus instead of using two, three phase motors if a single, six phase motor is used, torque and efficiency can be improved. The Matlab simulation for vector control of six phase induction motor is discussed in next chapter.

CHAPTER 5

MATLAB SIMULATION FOR VECTOR CONTROL OF PROTOTYPE SIX PHASE INDUCTION MOTOR

5.1 INTRODUCTION

As discussed in previous chapter vector control demands two axis (d-q) model of three phase induction motor. This is required because the motor is run like separately excited dc motor. In the case of induction motor, the control is usually performed in the reference frame d-q (d- direct axis, q- quadrature axis) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector [55, 56]. Before actual control of six phase induction motor, mathematical modeling of the prototype is carried out in Matlab software. Then simulation of vector control of six phase induction motor is carried out and the results are compared with equivalent three phase induction motor.

5.2 MODELING OF SIX PHASE INDUCTION MOTOR

The equations that describe the behavior of the six-phase induction motor when expressed in the arbitrary reference frame are listed in equations shown below:

$$V_{q1} = r_1 I_{q1} + p\lambda_{q1} + w_k \lambda_{d1} \tag{1}$$

$$V_{d1} = r_1 I_{d1} + p\lambda_{d1} - w_k \lambda_{q1} \tag{2}$$

$$V_{01} = r_1 I_{01} + p\lambda_{01} \tag{3}$$

$$V_{qr} = r_r I_{qr} + p\lambda_{qr} - (w_k - w_r)\lambda_{dr} \tag{4}$$

$$V_{dr} = r_r I_{dr} + p\lambda_{dr} - (w_k - w_r)\lambda_{qr} \tag{5}$$

$$V_{0r} = r_r I_{0r} + p\lambda_{0r} \tag{6}$$

$$V_{q2} = r_2 I_{q2} + p\lambda_{q2} + w\lambda_{d2} \tag{7}$$

$$V_{d2} = r_2 I_{d2} + p\lambda_{d2} - w\lambda_{q2} \tag{8}$$

$$V_{02} = r_2 I_{02} + p\lambda_{02} \tag{9}$$

where $\boldsymbol{\omega_k}$ is the speed of the reference frame,

and $\boldsymbol{\omega_r}$ is the rotor speed.

5.2.1 Expressions for rotor and stator flux linkages

$$\lambda_{q1} = (L_{l1} - L'_{lm})I_{q1} + L'_{lm}\left(I_{q1} + I_{q2}\right) + L_m(I_{q1} + I_{q2} + I'_{qr}) \tag{10}$$

$$\lambda_{d1} = (L_{l1} - L'_{lm})I_{d1} + L'_{lm}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I'_{dr}) \tag{11}$$

$$\lambda_{01} = L_{l1} I_{01} + L'_{lm}(I_{01} + I_{02}) \tag{12}$$

$$\lambda_{q2} = (L_{l2} - L'_{lm})I_{q2} + L'_{lm}\left(I_{q1} + I_{q2}\right) + L_m(I_{q1} + I_{q2} + I'_{qr}) \tag{13}$$

$$\lambda_{d2} = (L_{l2} - L'_{lm})I_{d2} + L'_{lm}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I'_{dr}) \tag{14}$$

$$\lambda_{02} = L_{l2} I_{02} + L'_{lm}(I_{01} + I_{02}) \tag{15}$$

$$\lambda_{qr} = L'_{lr} I_{qr} + L_m\left(I_{q1} + I_{q2} + I'_{q2}\right) \tag{16}$$

$$\lambda_{dr} = L'_{lr} I_{dr} + L_m(I_{d1} + I_{d2} + I'_{d2}) \tag{17}$$

$$\lambda_{0r} = L'_{lr} I_{0r} \quad (18)$$

5.2.2 Electromagnetic torque and mechanical model of motor

$$T_e = (\frac{3}{2}\frac{p}{2})\left[\lambda_{md}\left(I_{Q1} + I_{Q2}\right) - \lambda_{mq}\left(I_{d1} + I_{d2}\right)\right] \quad (19)$$

$$J\,\frac{2}{P}\frac{dWr}{dt} = T_{em} - T_L \quad (20)$$

5.2.3 Current expressions in terms of flux linkages

The equations that describe the electrical and mechanical behavior of the machines contain mixed variables (flux linkages and current). Above equations can be simplified by algebraic manipulations of equations (1)-(18). Thus, the currents when solved in terms of flux linkages are obtained as:

$$I_{d1} = \frac{1}{lx}\left[(L_{12}+L_{lm})\,\lambda_{d1} - L_{12}\lambda_{md} - L_{lm}\lambda_{d2} - L_{ldq}(\lambda_{q2} - \lambda_{q12})\right] \quad (21)$$

$$I_{q1} = \frac{1}{lx}\left[(L_{12}+L_{lm})\,\lambda_{q1} - L_{12}\lambda_{mq} - L_{lm}\lambda_{q2} + L_{ldq}(\lambda_{d2} - \lambda_{d12})\right] \quad (22)$$

$$I_{d2} = \frac{1}{lx}\left[(L_n+L_{lm})\,\lambda_{q2} - L_n\lambda_{md} - L_{lm}\lambda_{d1} + L_{ldq}(\lambda_{q1} - \lambda_{mq})\right] \quad (23)$$

$$I_{q2} = \frac{1}{lx}\left[(L_n+L_{lm})\,\lambda_{q2} - L_n\lambda_{mq} - L_{lm}\lambda_{q1} + L_{ldq}(\lambda_{q1} - \lambda_{md})\right] \quad (24)$$

$$I'_{qr} = \frac{\lambda_{qr} - \lambda_{mq}}{L'_{tr}} \quad (25)$$

$$I'_{dr} = \frac{\lambda_{dr} - \lambda_{md}}{L'_{tr}} \quad (26)$$

$$\lambda_{md} = L_D[\lambda_{d1}L12 + \lambda_{d2}L_{l1} - L_{idq}(\lambda_{q2} - \lambda_{q1}) \tag{27}$$

$$\lambda_{mq} = L_Q[\lambda_{q1}L12 + \lambda_{q2}L_{l1} + L_{idq}(\lambda_{d2} - \lambda_{d1}) \tag{28}$$

Where

$$L_D = [\frac{L_A}{L_m} + (L_{l1} + L_{l2})]^{-1} \tag{29}$$

$$L_A = L_{l1} L_{l2} + L_{lm}(L_{l1} + L_{l2}) \tag{30}$$

$$L_Q = [\frac{L_A}{L\_} + (L_{l1} + L_{l2})] \tag{31}$$

Substituting equations (21)-(28) into (1) – (8) and solving the equation in the rotor reference frame, (i.e. $\boldsymbol{\omega_k}$ becomes $\boldsymbol{\omega_r}$) the integral form of the machine voltage and torque equations with flux linkage as state variables is given as:

$$\lambda_{d1} = \int[V_{d1} + \omega\lambda_{q1} - \frac{R_1}{L_\lambda}\{(L_{l2}+L_m)\lambda_{d1} - L_{l2}\lambda_{md} - L_m\lambda_{d2} - L_{idq}(\lambda_{q2-}\lambda_{mq})\}] \tag{32}$$

$$\lambda_{q1} = \int[V_{q1} + \omega_r\lambda_{d1} - \frac{R_1}{L_\lambda}\{(L_{l2}+L_m)\lambda_{q1} - L_{l2}\lambda_{mq} - L_{lm}\lambda_{q2} - L_{idq}(\lambda_{d2-}\lambda_{md})\}] \tag{33}$$

$$\lambda_{d2} = \int[V_{d2} + \omega_r\lambda_{q2} - \frac{R_1}{L_\lambda}\{(L_{l1}+L_m)\lambda_{l2} - L_{l1}\lambda_{md} - L_{lm}\lambda_{d1} + L_{idq}(\lambda_{q1-}\lambda_{mq})\}] \tag{34}$$

$$\lambda_{q2} = \int[V_{q2} + \omega_r\lambda_{d2} - \frac{R_{12}}{L_\lambda}\{(L_{l1}+L_{lm})\lambda_{q2} - L_{l1}\lambda_{mq} - L_{lm}\lambda_{q1} - L_{idq}(\lambda_{d1-}\lambda_{md})\}] \tag{35}$$

$$\lambda_{dr} = \int\frac{r'_r}{L'_r}(\lambda_{dr-}\lambda_{md}) \tag{36}$$

$$\lambda'_{dr} = \int\frac{r'_r}{L'_r}(\lambda_{qr-}\lambda_{mq}) \tag{37}$$

$$\omega_r = \frac{P}{2J}\int[T_{em} - T_L]dt \tag{38}$$

$$\Theta_r = \int \omega_r \, dt \tag{39}$$

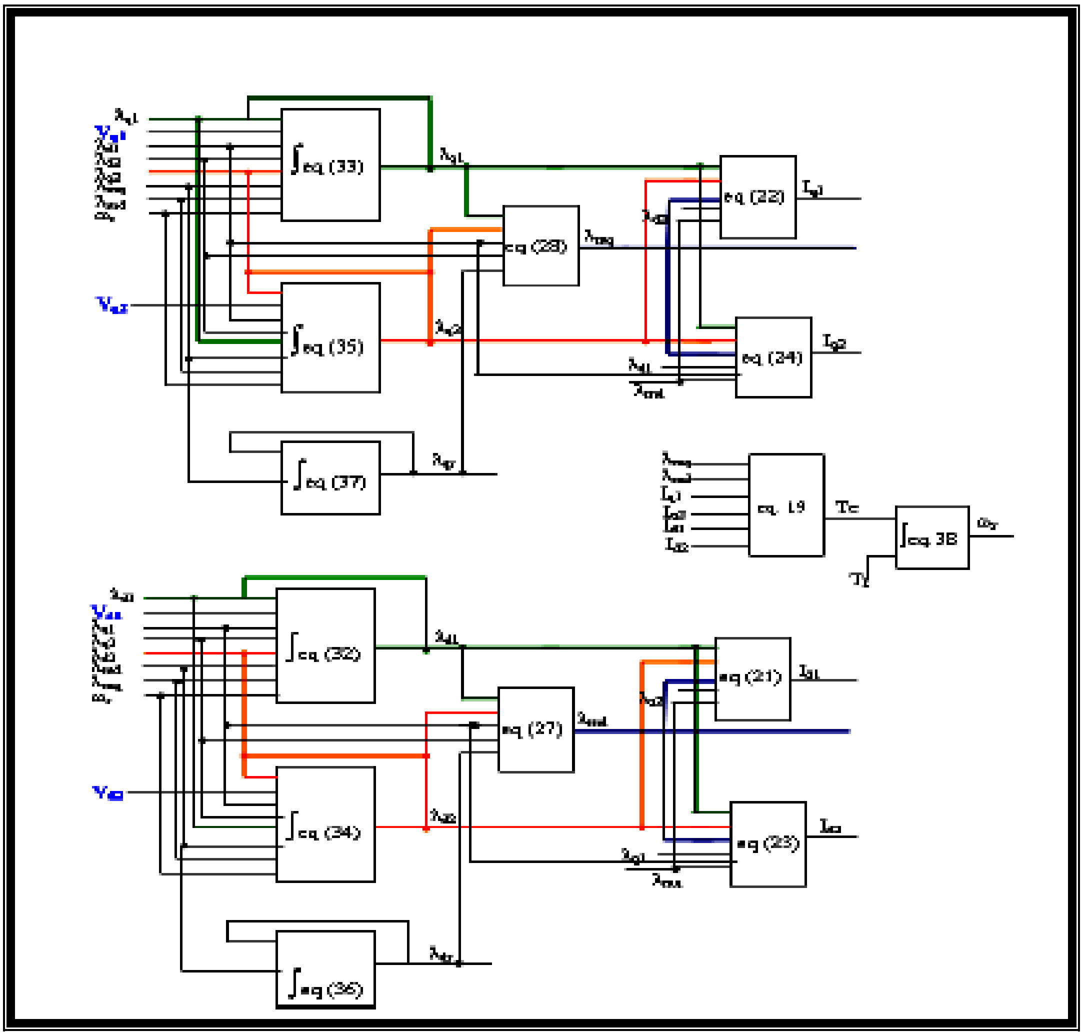


Figure 5.1Flow diagram of the electrical part for the simulation of the six-phase

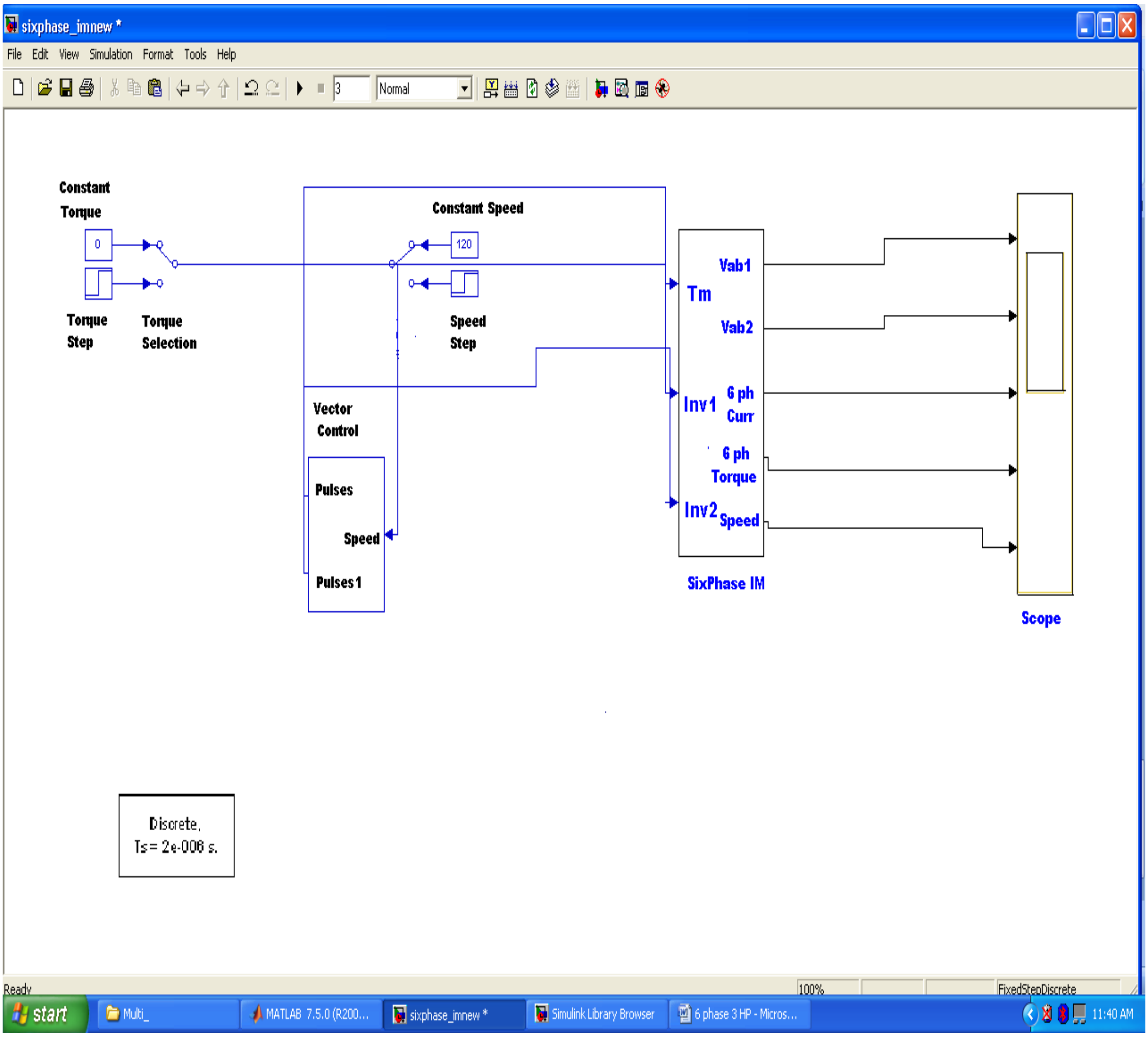


Figure 5.2 Simulated circuit of six phase 3 HP IM vector control

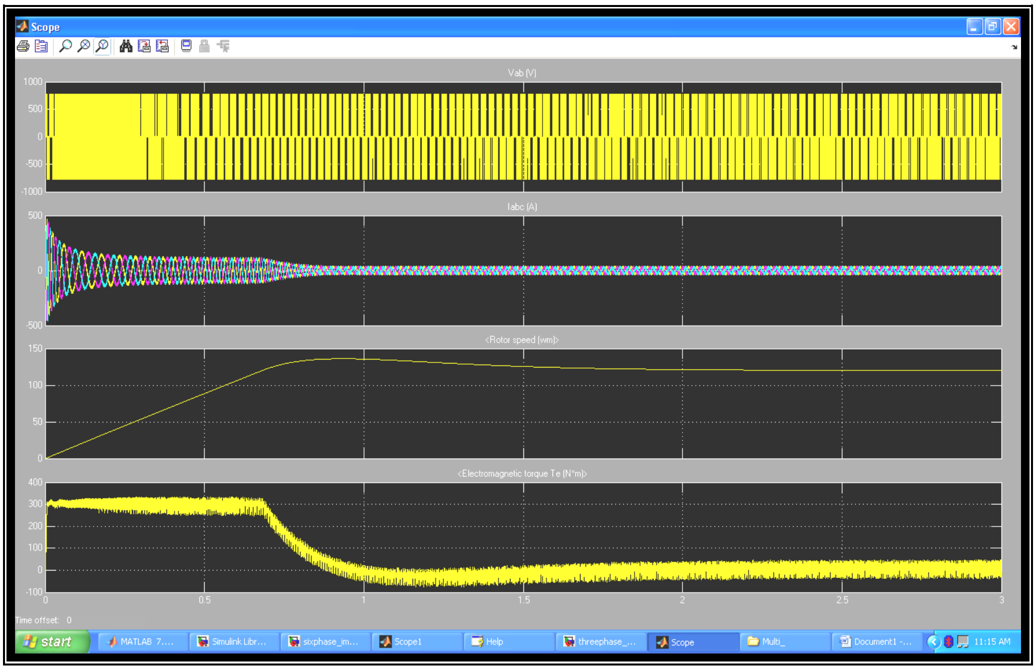


Figure 5.3 Simulation results of three phase, 3HP, 200V, 50 Hz IM

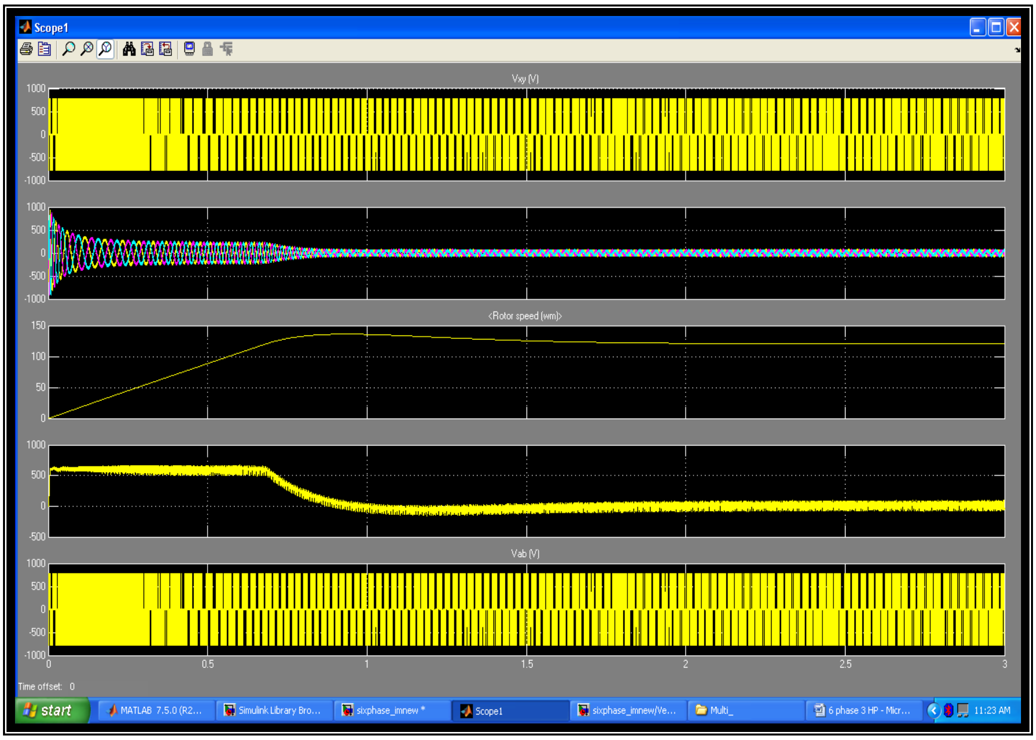


Figure 5.4 Simulation results of six phase,3HP,200V, 50Hz IM

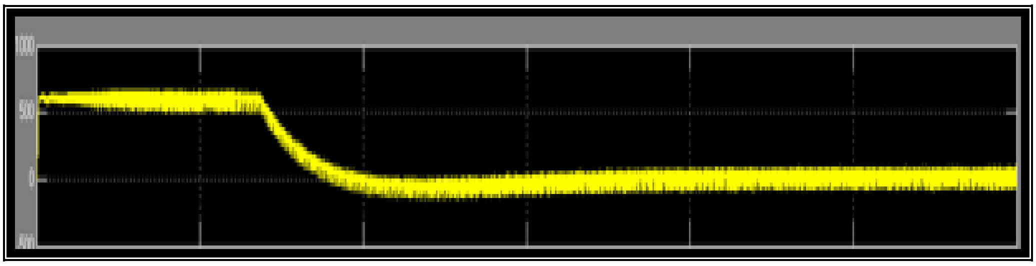


Figure 5.5 Six phase IM torque

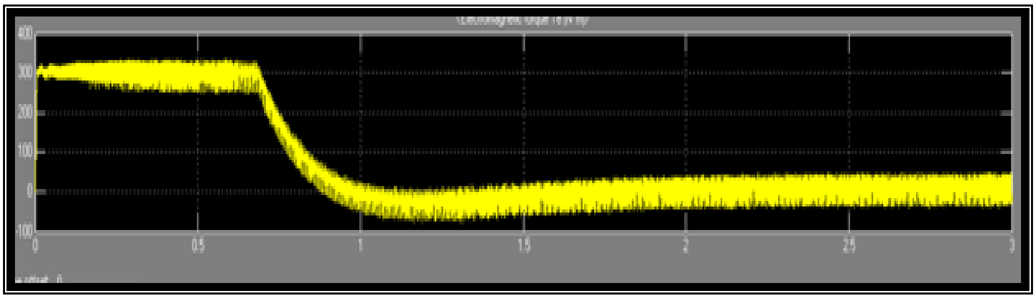


Figure 5.6 Three phase IM torque

5.3 DISCUSSION:

Rectified voltage is fed to the two voltage source inverters and then output of two inverters, is given to six phase induction motor. Six phase induction motor is modeled using above equations.

The figures 5.3 and 5.4 show the Simulation output of six phase and three phase induction motors respectively.

From the waveforms of torque of six phase and three phase induction motor (figures 5.5 and 5.6) it is clear that the starting torque of six phase induction motor is about 550 N-m for say from 0 to 0.8 sec., the speed is increasing from zero to 140 rps approximately. When rated speed is reached, the torque reduces to zero as seen from the waveform. Similarly the starting torque of three phase motor is about 350 N-m for 0 to 0.8 sec, when rated speed is reached the torque reduces to zero. Thus the six phase motor torque is almost 1.6 times more than three phase induction motor torque. Thus higher starting torque is obtained as compared to three phase motor. The rating of three phase and six phase motor are same.

Also figure 5.7 show the output of six phase induction motor for step change in speed and torque. With the step change of speed, at start, i.e at nearly zero speed the torque is highest and when rated speed is reached the torque reduces to zero. When again speed reduces to zero, torque increases.

It is clear from the output waveform that the torque of six phase IM is about 1.6 times more than that of three phase motor of same size. Also the torque pulsations are reduced in six phase IM due to elimination of $6n \pm 1$ harmonics.

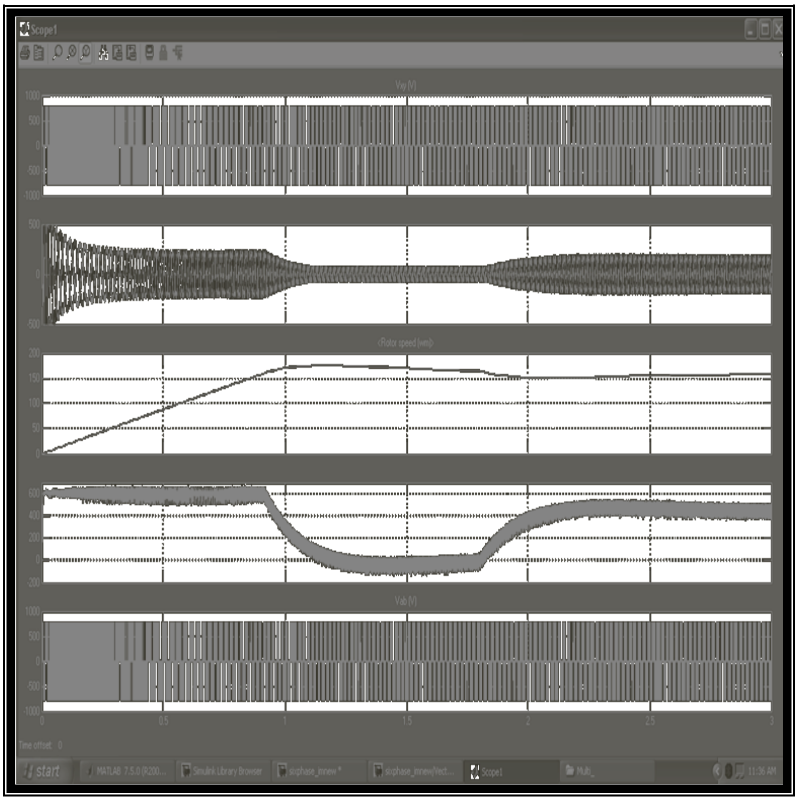


Figure 5.7 Six phase, 3 hp IM output waveform for change in step of torque

5.4 CONCLUSION:

In this chapter mathematical modeling and Matlab simulation of prototype six phase induction motor is discussed. Before actual control of six phase induction motor, which needs two separate three phase SVPWM inverters, software simulation helps in deciding parameters. Thus 1.6 times more torque of six phase induction motor as compared to equivalent three phase induction motor is obtained. Also torque pulsations are reduced in case of six phases.

Harmonics are reduced because all the harmonics of the order (6n$\pm$1) where n = 1, 3, 5, 7------- get cancelled because of 30 degrees phase displacement. Reduced torque pulsations are observed because of harmonic reduction. (Figure 5.7)

CHAPTER 6

EXPERIMENTAL IMPLEMENTATION OF VECTOR CONTROL OF PROTOTYPE SIX PHASE INDUCTION MOTOR

6.1 INTRODUCTION:

Basically speed of an induction motor can be controlled by two methods: 1.Pole changing, (not used now) 2.Frequency Control. For variable frequency control motor is to be supplied by inverter. Variable frequency control is carried out in two ways: 1. Scalar control where only magnitude of the quantity is controlled, and 2. Vector control where magnitude and direction of the quantity is controlled.

The scalar control method has been the most popular because it is the least complex. The scalar control method, also known as constant volts per hertz, is an open-loop control system, which maintains a constant ratio between applied voltage and frequency. Scalar control is the least robust control method of the two. During steady–state operation, if the load torque is increased, the slip will increase within the stability limit and a balance will be maintained between the developed torque and the load torque. If the desired output frequency exceeds the base frequency of the motor, the voltage is held at the rated value, ensuring less than rated flux flows through the core.

Vector control gives superior results over scalar control. The vector control method is also known as field–oriented control. In vector control, the d-axis of the stationary reference frame for the motor is maintained on top of the rotating rotor flux. The resulting dynamic behavior is similar to that of a DC machine. This allows the AC motor's stator current to be divided into a flux–producing component and an orthogonal torque–producing component, similar to a DC machine field current and armature current. The key to vector control is knowledge of the rotor flux position angle with respect to the stator. It allows the motor to be controlled like a separately–excited DC motor. Vector control allows for fast transient response due to decoupling the torque and flux-producing currents. It also eliminates the conventional stability problem of crossing the breakdown torque point. It requires the model of six phase induction motor in d-q axis. In case of three phase motor, three phase to two phase conversion is done and the motor is run like a separately excited dc motor. For six phase motor, it is run like, two three phase motors sharing same magnetic circuit and shaft but electrically separated.

Practical implementation of vector control is quite complicated. [55-56]

The various control strategies for the control of the inverter-fed induction motor have provided good steady-state but poor dynamic response. From the traces of the dynamic responses, the cause of such poor dynamic response is found to be that the air gap flux linkages deviate from their set values. The deviation is not only in magnitude but also in phase. The variations of the flux linkages have to be controlled by the magnitude and frequency of the stator and the rotor phase currents and their instantaneous phases. So far, the control strategies have utilized the stator phase current magnitude and frequency and not their phases. This resulted in the deviation of the phase and magnitudes of the air gap flux linkages from their set values. Separately excited dc drives are simpler in control because they independently control flux, which, when maintain constant, contributes to an independent control of torque. This is made possible with separate control of field or armature currents which, in turn, control the field flux and the torque independently. Moreover the dc motor control requires only the control of the field or armature current magnitude, providing simplicity not possible with ac machine control. By contrast, ac induction motor drives require a coordinated control of stator current magnitudes, frequencies, and their phases, making it a complex control. Like the dc drives, independent control of the flux and torque is possible in ac drives. The stator current phasor can be resolved, say, along the rotor flux linkages, and the component along the rotor flux linkages is the field producing current, but this requires the position of the rotor flux linkages at every instant; (note that this is dynamic, unlike in the dc machine). If this is available, the control of ac machines is very similar to that of separately-exited dc machines. The requirement of phase, frequency and magnitude control of the currents and hence of the flux phasor is made possible by inverter control. The control is achieved in field coordinates (hence the name of this control strategy, field-oriented control); sometimes it is known as vector control, because it relates to the phasor control of the rotor flux linkages [56].

Vector control schemes are classified according to how the field angle is acquired. If the field angle is calculated by using terminal voltages and currents or hall sensors or flux sensing windings, then it is known as direct vector control. The field angle can also be obtained by using rotor position measurement and partial estimation with only machine parameters but not any other variables, such as voltages or currents; using this field angle leads to a class of control schemes known as indirect vector control. Vector control is summarized by the following algorithm.

1) Obtain the field angle.
2) Calculate the flux producing component of current, i_f^*, for a required rotor flux linkage λ_r^*. By controlling only this field current, the rotor flux linkages are controlled. It is very similar to the separately-exited dc machine, in that the field current controls the field flux; the armature current has no impact on it.
3) From λ_r^* and required T_e^*, calculate the torque-producing component of stator current, i_T^*. Controlling the torque-producing component current when the rotor flux linkages phasor is constant gives an independent control of electromagnetic torque. It is very similar to the case of the armature current's controlling the electromagnetic torque in a separately-exited dc machine with the field current maintained constant. Steps (2) and (3) enable a complete decoupling of flux- from torque-producing channels in the induction machine.

4) Calculate the stator-current phasor magnitude i_s^*, from the vector sum of i_T^* and i_f^*.

5) Calculate torque angel from the flux- and torque-producing components of the stator-current commands are found by going through the *qdo* transformation to *abc* variables:

$$i_{as}^* = i_s^* \sin \theta_2$$

$$i_{bs}^* = i_s^* \sin (\theta_2 - \frac{2\pi}{3})$$

$$i_{cs}^* = i_s^* \sin (\theta_2 + \frac{2\pi}{3})$$

6) Synthesize these currents by using an inverter; when they are supplied to the stator of the induction motor, the commanded rotor flux linkages and torque are produced.

The correspondence between the separately-exited dc motor and the induction motor is complete; i_f and i_T correspond to the field and armature currents of the dc machine, respectively. Even though the induction motor does not have separate field and armature windings, finding equivalent field and armature currents as components of the stator-current phasor has resulted in the decoupling of flux- from torque-producing channels in a machine that is highly coupled. Unlike the scalar control involved in dc machines, phasor or vector control is employed in induction machines. In the dc machine, the field and armature are fixed in space by the commutator, whereas, in the induction machine, no such additional component exists to separate the field (to produce the flux) from the armature (to produce the torque). Thus the optimum space angel of 90 electrical degrees is obtained between them. In the place of the commuter, the induction machine (and for that matter any ac machine) acquires the functionality of the commuter with an inverter. The inverter controls both the magnitude of the commuter with an inverter. The inverter controls both the magnitude of the current and its phase, allowing the machine's flux and torque channels to be decoupled by controlling precisely and injecting the flux- and torque-producing currents in the induction machine to match the required rotor flux linkages and electromagnetic torque. The phasor control of current further adds to the complexity of computation involving phase and magnitude and of transformations to orient i_f and i_T with respect to rotor flux linkages. Note that the orientation need not be on rotor flux linkages; the computations can be carried out in stator or rotor or arbitrary reference frames. Synchronous reference frames are often used for the sake of freeing the signal-processing circuits from high bandwidth requirements [56].

Since Encoder and related circuitry required for high power applications sensor control is costlier, sensor-less control is developed and implemented for controlling prototype induction motor. This chapter focuses on practical control of prototype six phase induction motor.

6.2 CONTROL OF PROTOTYPE SIX PHASE INDUCTION MOTOR

After successful simulation using Matlab software, it is shown in previous chapter that the torque of six phase induction motor is 1.6 times that of three phase motor torque. The motor is also tested with single three phase Voltage source inverter. This is done to check the suitability of the developed six phase motor for variable frequency operation. The three phase and six phase current waveforms are obtained and compared. The six phase current is double than that of three phase current.

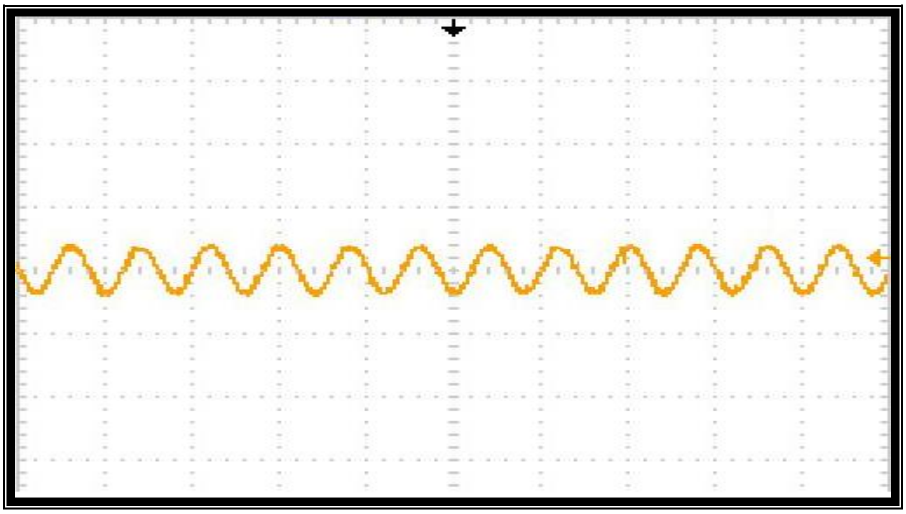


Figure 6.1 Three phase current when only one three phase set energized through inverter

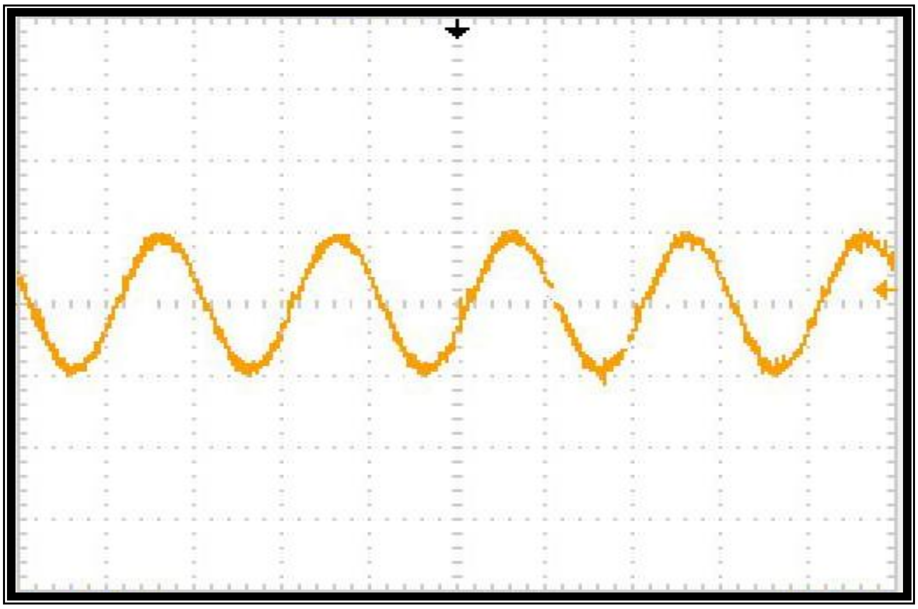


Figure 6.2 Six phase current when six phases energized through inverter

6.2.1 Experimental Implementation

To carry out control of prototype six phase induction motor, the two three phase SVPWM inverters with synch (Synchronization card for synchronization between two inverters) is essential. Synch is a card which is inserted in both the drives supplying two three phase sets. It adjusts the phase angle as per Master slave configuration of both inverters.The synch is an essential requirement when six phase induction motor is fed from two numbers of three phase inverters. It is decided to carry out innovative control of prototype six phase induction motor. The novel control is possible if the six phase prototype motor runs like two three phase induction motors having common shaft.

As shown in figure 6.3 each set of the three phase stator windings is fed by a six pulse voltage source inverter (VSI). These VSIs may operate according to trigger signals produced by the controller and generate voltages phase shifted by 60^0/n. The controller can be a digital signal processor (DSP)

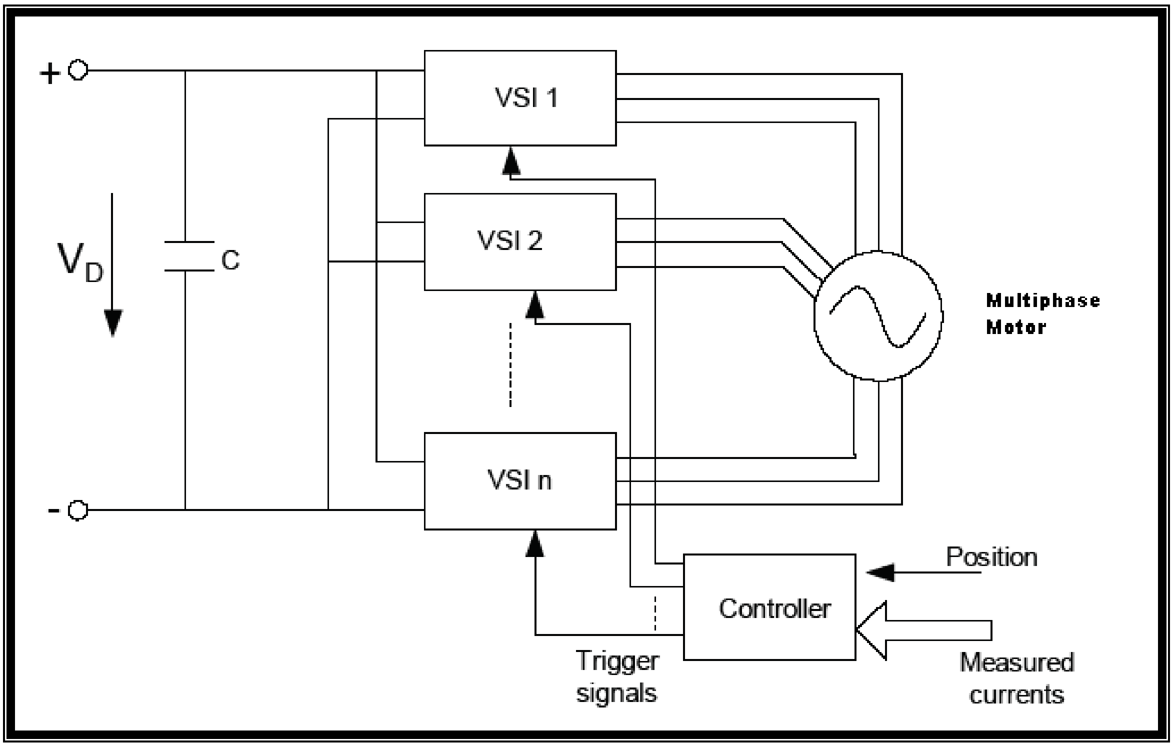


Figure 6.3 Multiphase Induction motor supplied from n number of inverters

Figure 6.4 presents the basic block diagram of the six phase induction motor fed from two, three phase drives. The frequency converter mechanically consists of two units, the Power Unit and the Control Unit.

The three phase drive consists of three-phase AC-choke at the mains end together with the DC-link capacitor form an LC-filter, which, again, together with the diode bridge produce the DC-voltage supply to the IGBT Inverter Bridge block. The AC-choke also functions as a filter against High Frequency disturbances from the mains as well as against those caused by the frequency converter to the mains. It, in addition, enhances the waveform of the input current to the frequency converter. The entire power drawn by the frequency converter from the mains is active power.

The IGBT Inverter Bridge produces a symmetrical, 3-phase PWM-modulated AC-voltage to the motor. The Motor and Application Control Block is based on microprocessor software. The microprocessor controls the motor on the basis of information it receives through measurements, parameter settings, control I/O and control keypad. The motor and application control block controls the motor control ASIC which, in turn, calculates the IGBT positions. Gate drivers amplify these signals for driving the IGBT inverter bridge.

The control keypad constitutes a link between the user and the frequency converter. The control keypad is used for parameter setting, reading status data and giving control commands. It is detachable and can be operated externally and connected via a cable to the frequency converter. Instead of the control keypad, also a PC can be used to control the frequency converter if connected through a similar cable. Frequency converter can be equipped with a control I/O board which is either isolated (OPT-A8) or not isolated (OPT-A1) from the ground.

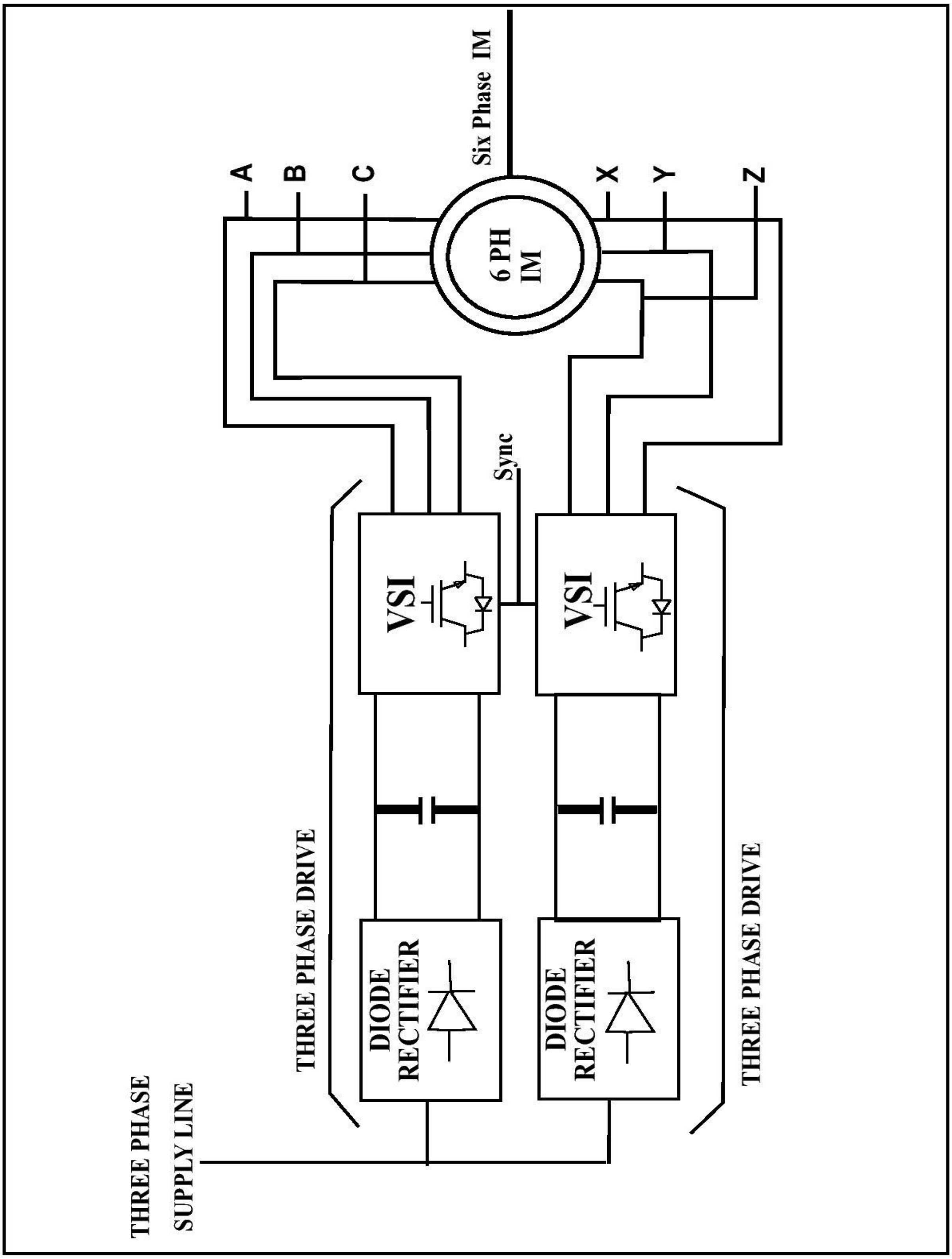


Figure 6.4 Block Diagram of six phase IM fed from two, three phase drives

Since Encoder and related circuitry required for high power applications sensor control is costlier, sensor-less control is developed and implemented for controlling prototype induction motor. For sensor-less control, the motor control algorithm and Space vector Pulse width Modulation (SVPWM) for inverter are implemented. The mathematical model of the motor and control algorithm is fed into the Field Protected Gate Array (FPGA), through Software. Matlab program is also loaded into FPGA.

6.2.2 Actual Control

Prototype six phase induction motor control is done as explained below:

3HP, 200V, 50 Hz four pole 36 stator slots, star connected, six phase , squirrel cage prototype induction motor is supplied from two PC based separate Drives as per the rating of prototype motor, i.e. 3 HP, 200 volts, 4 pole, star connected six phase induction motor. This is done at Ac drives industry at Chennai. The drives which were used in controlling two, three phase induction motors simultaneously; same drives were selected as per prototype six phase induction motor (50 Amp rating). The motor speed is controlled like two, three phase induction motors connected to the same shaft and sharing the same magnetic circuit but electrically separated.

The two inverters are synchronized properly with specially designed OPT-D2 card (Synch). The two inverters run in master-slave mode, i.e. one inverter acts as a Master and other as a slave or follower. Synchronization plays very important role in this control. If there is no proper synchronization then the motor cannot run.

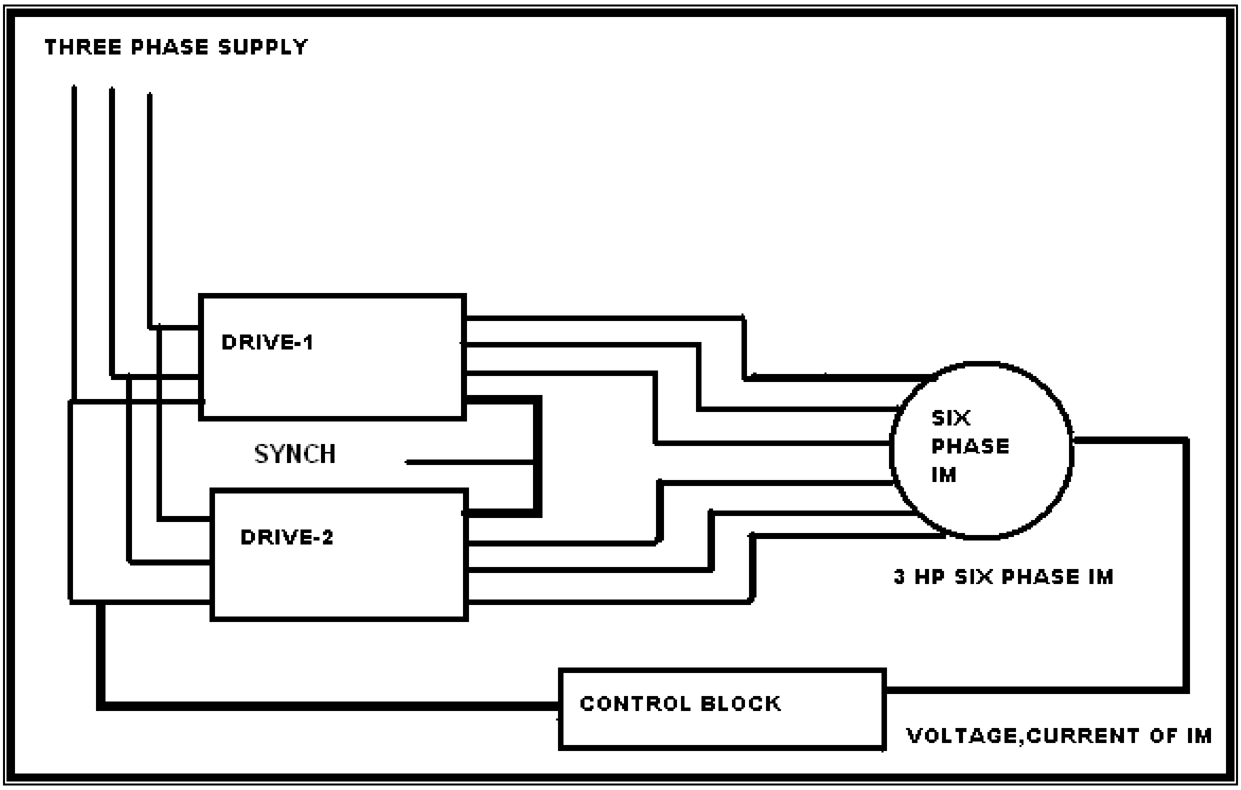


Figure 6.5 Multiphase Induction motor fed by two three phase drives with control block

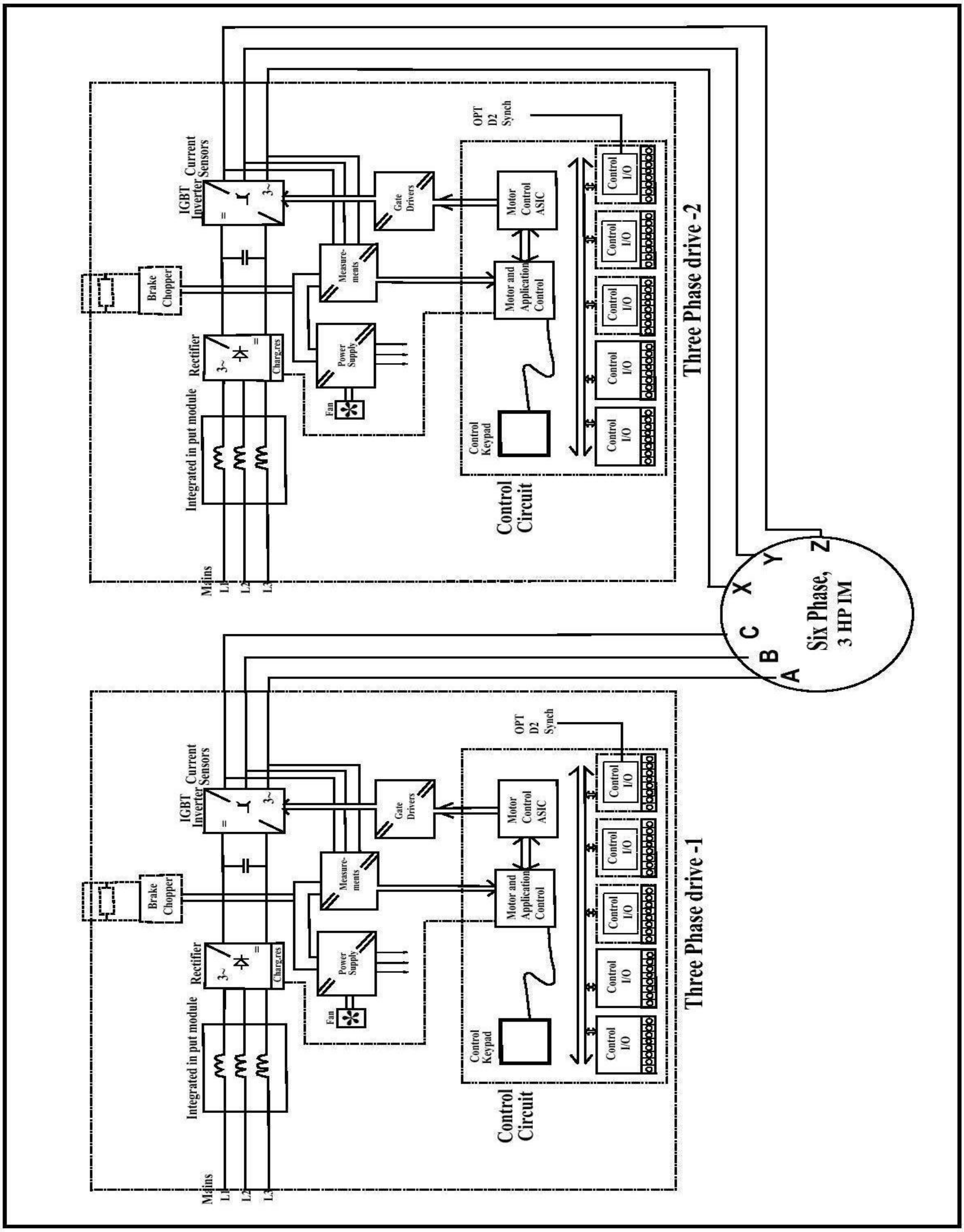
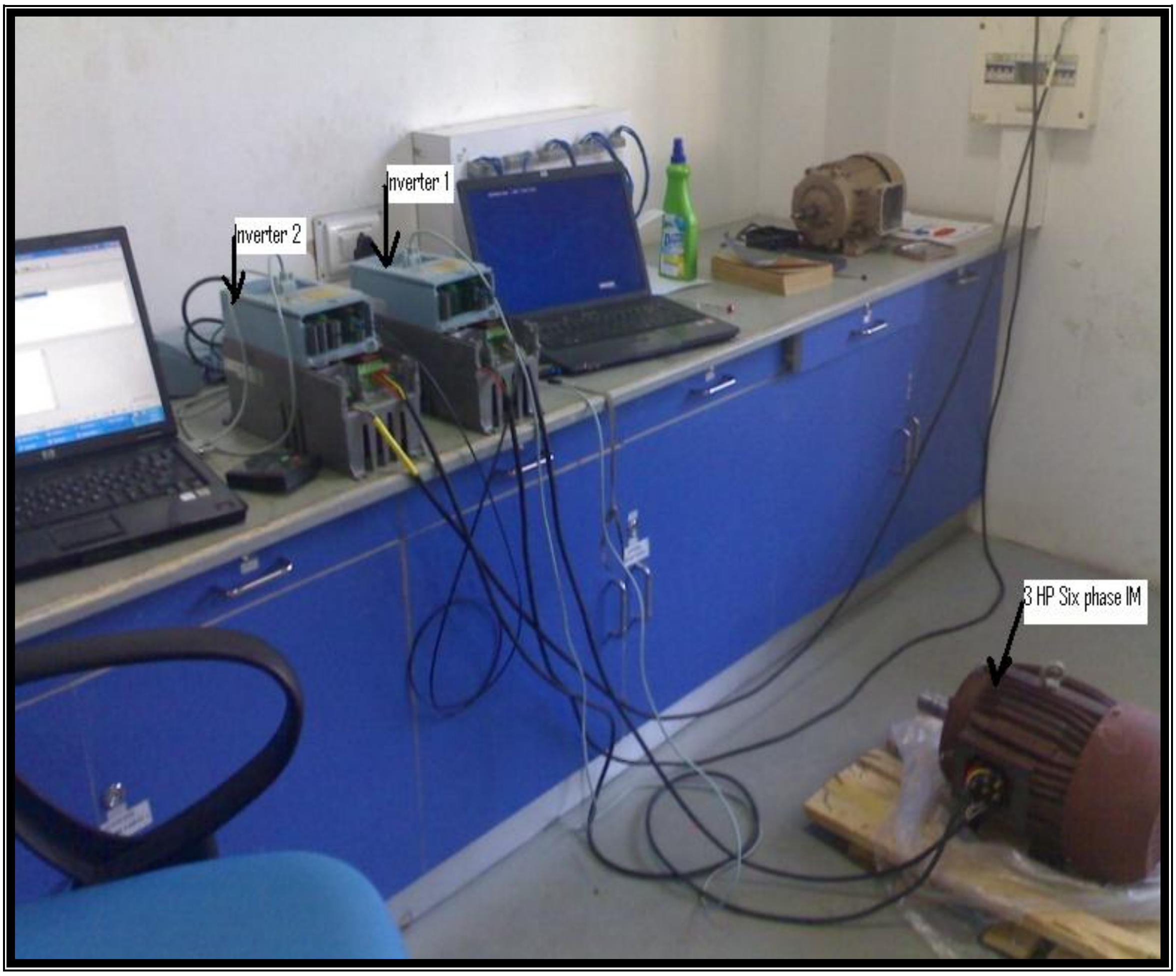


Figure 6.6 Internal circuit of two three phase Drives



Photograph 6.1. Actual experimental set up for speed control of prototype six phase induction motor when fed from two, NXP drives at Chennai based Industry.

Figure 6.6 shows the internal circuit of two, three phase drives consisting of L-C filter , choke, rectifier unit, inverter unit. The control circuit consists of control key pad, motor and application control, input/output cards as per application and requirement. The synch-OPT-D2 card is inserted in both the drives. "NXP00002V178.VCN" software is used for two similar rating NXP drives (Drive having rectifier, SVPWM Inverter with FPGA). All the motor parameters are fed into the software.

Also control algorithm is fed into the software.

The motor speed control is carried out in two modes:

1. Volts per hertz (v/f) , Scalar control (Frequency control Mode)
2. Sensor less vector control. (Speed control Mode)

The observations are as under:

Sl no	Follower's phase shift	Set frequency	Output voltage (Master)	Output voltage (Follower)	Drive current (Master)	Drive current (Follower)	Motor torque	Speed
	Deg	Hz	V	V	Amps	Amps	%	RPM
1	90	50	200	200	1.17	1.2	4.4	1500
2	75	50	200	203	1.4	5.4	7	1500
3	60	42	169	172	2.58	9	31	1260
4	45	27.5	113	114	3.26	8.44	56.8	825
5	30	22.5	94	95	4.14	8.8	81.4	675
6	15	28.5	80	78	8.7	5.1	85.8	855
7	0	16	70.6	69	9	5.5	106.8	480
8	-15	14.5	64.9	63	8.5	6.6	111.6	435
9	-30	13	59.3	57	8	7	117	390

Table 6.1 Observations for V/f (Scalar) control of Six phase IM

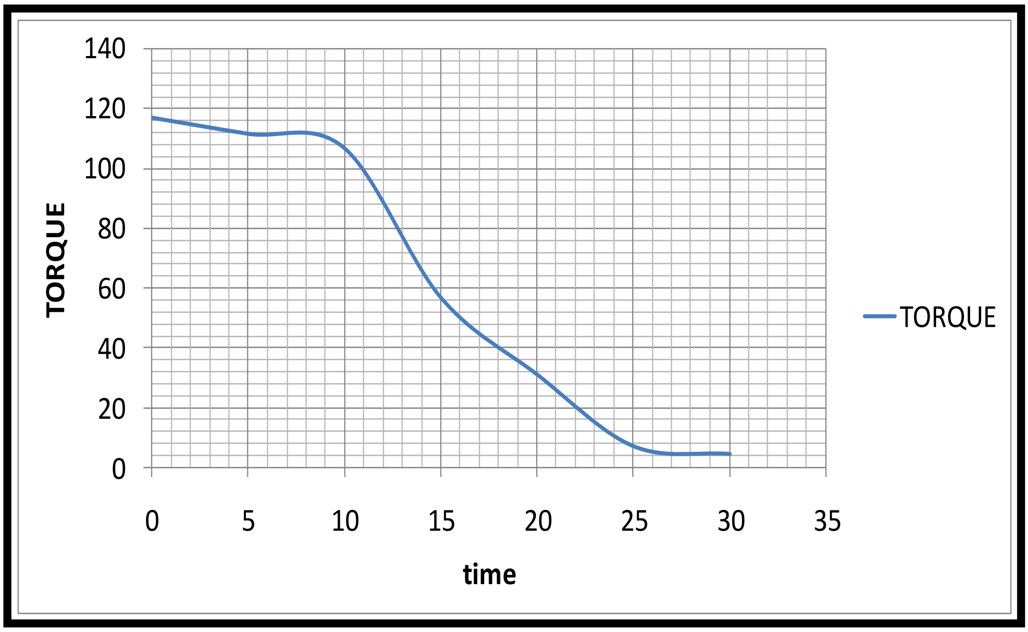


Figure 6.7 Torque of six phase IM for V/f control

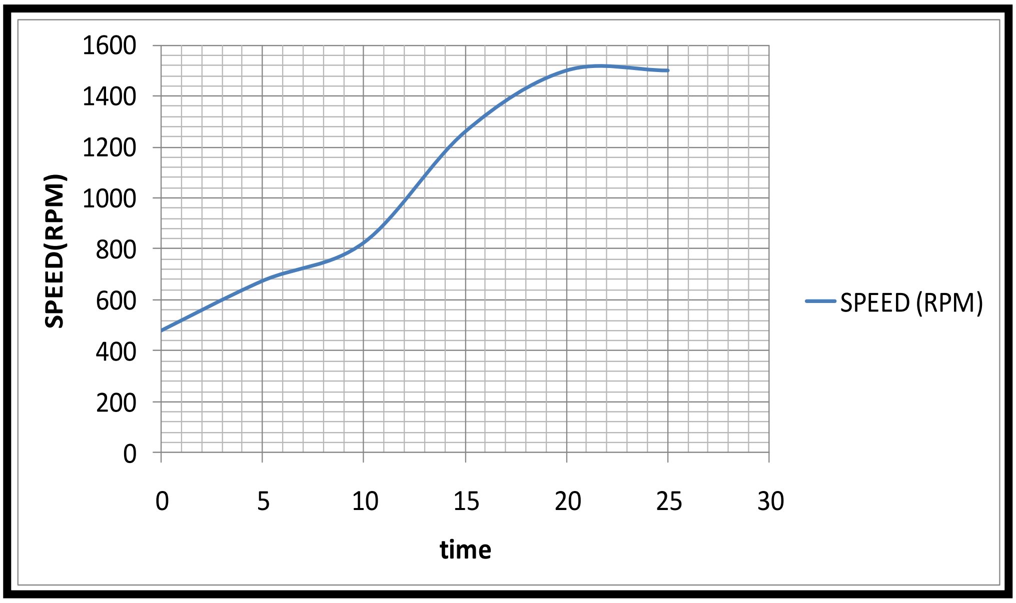


Figure 6.8 Speed of six phase IM for V/f control

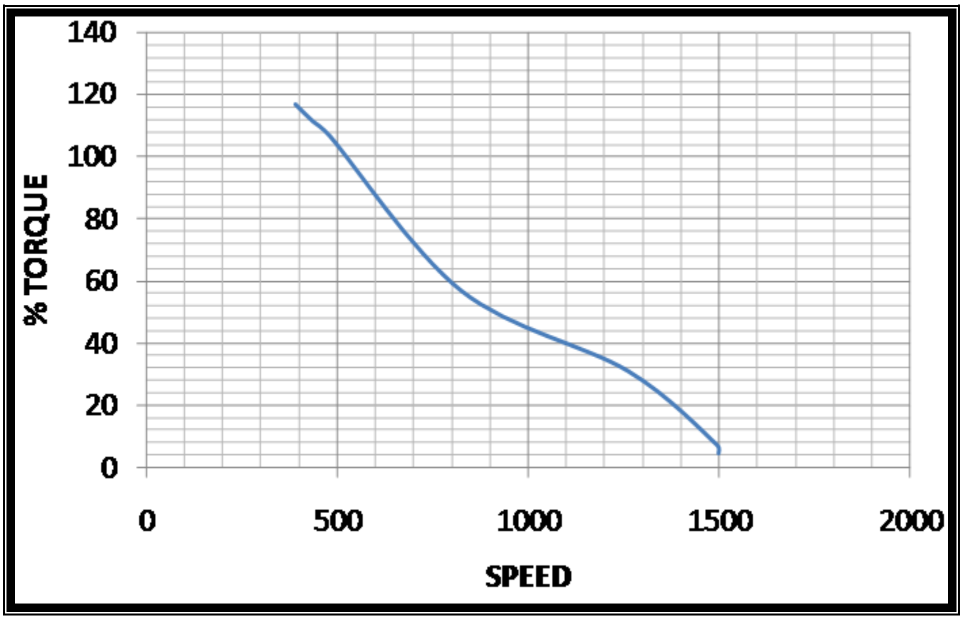


Figure 6.9 Speed Torque curve for V/f control

Sl no	Follower's phase shift	Set frequency	Output voltage (Master)	Output voltage (Follower)	Drive current (Master)	Drive current (Follower)	Motor torque	U1-U2	V1-V2	W1-W2	speed
	Deg	Hz	V	V	Amps	Amps	%	V	V	V	RPM
1	-30	27.1	112.1	113	5.19	9	165	125	125	125	813
2	75	35	156.6	156	4.2	8.5	140	144	144	144	1050
3	60	50	200	198	2.82	7.7	98.5	153	152	153	1496
4	45	50	200	198	2.73	2.88	63.1	133	134	134	1498
5	40	50	200	198.5	1.2	1.3	9.76	132	132	132	1500
6	0	50	200	174	2.73	9	69.6	30	30	30	1500
7	30	50	172.6	175	2.54	8.9	65.8	28	28	28	1500

Table 6.2 Observations for Vector control of Prototype Six phase IM

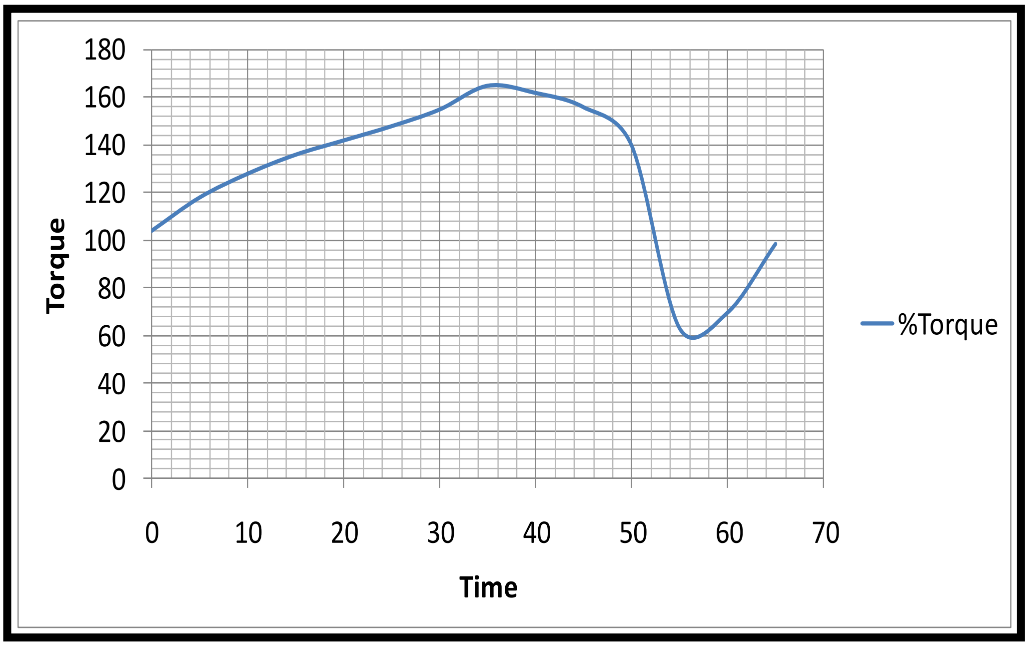


Figure 6.10Torque of Six phase IM for vector control

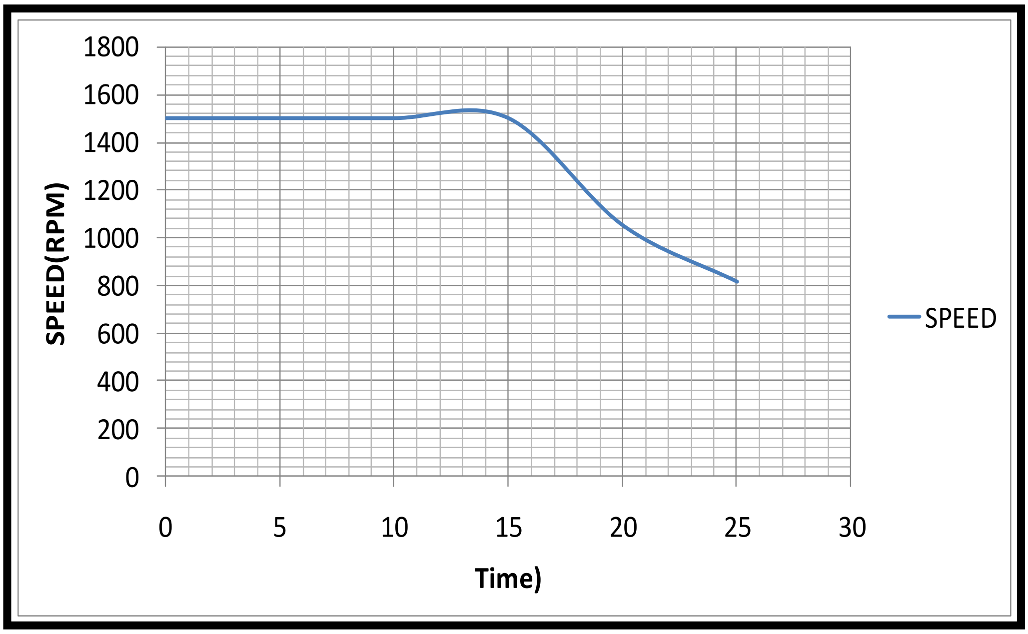


Figure 6.11 Speed of six phase IM for vector control

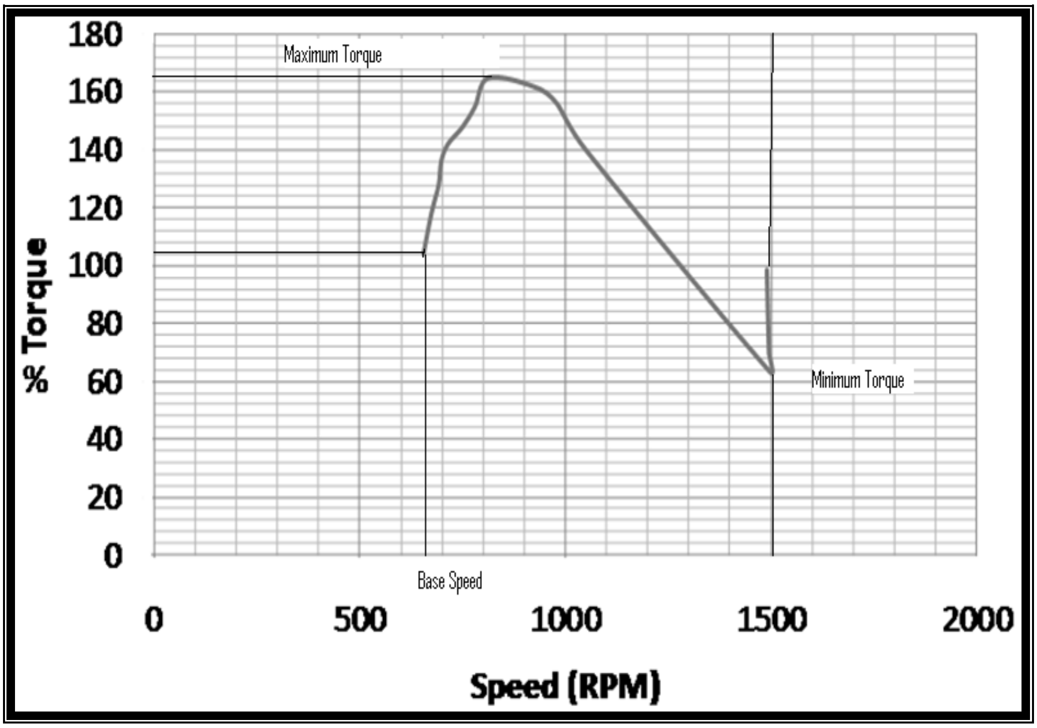


Figure 6.12 Speed-torque curve for vector control of six phase IM

6.3 DISCUSSION

By adjusting phase shift using Synch in two drives, the motor speed is controlled in two modes , viz. V/f (scalar control) and Vector control. In V/f control rotor position is not taken into account and V/f ratio is maintained constant. Here it is maintained at 4 approximately. In vector control the rotor position i.e. rotor speed with the rotor position (phase angle) is considered. The rotor speed is not measured directly with any speed sensor but the speed and rotor position is calculated from the readings of voltage and current as per the formulae fed into the control software.

Initially the motor is run at rated speed at 90 deg phase shift then V/f ratio is maintained constant at various frequencies. A set of readings is taken and observations noted as shown above. Finally at 30 deg lagging phase shift, the highest % torque is obtained the speed is reduced to 390 Rpm . The vector control mode is started at 30 deg lagging phase shift, with 813 Rpm where highest % torque is obtained. Then gradually the speed is increased upto rated speed.

The results obtained are compared with equivalent three phase Induction motor of same rating. It is found that six phase current is almost twice the three phase current. Also the torque is 1.6 times that of three phase motor as expected from the results obtained by simulation. (Figure 6.1 and 6.2)

The speed-Torque curve for Sensor-less vector control is superior to V/f i.e. scalar control. Smooth and fine control is obtained in sensor-less vector control as compared to scalar control. The speed-Torque curve in Vector control mode matches with standard speed-torque curve of induction motor. While scalar control mode speed-torque curve does not match because rotor position is not taken into consideration.(Figures 6.9 and 6.12)

The prototype six phase induction motor is controlled when fed from two, properly synchronized three phase inverters.

6.4 CONCLUSION

The innovative and remarkable achievements of this designed and developed six phase induction motor-prototype are:

1. There is no criterion of maintaining 30 degrees phase shift, i.e. arbitrary phase shift, obvious from observation. All control schemes developed till date were for 30 degree phase shift only. [20]-[46]
2. No third harmonic current injection or current sensor required for torque improvement: In this novel prototype six phase induction motor, the torque is found to be 1.6 times that of three phase induction motor torque. This is higher than 1.4 times as described in references [5],[1],[28]. This is achieved without third harmonic current injection for torque improvement and control with arbitrary phase displacement. (Table 6.2)

The other features of a developed prototype six-phase induction motor are summarized as:

1. Improved reliability, i.e. if one inverter fails, the motor continues to run (though at reduced rating) thus continuity of operation is maintained, this is because the two neutrals are kept open.

2. As losses are reduced, efficiency is improved as there are no circulating currents because of harmonic reduction due to 30 deg phase shift.
3. By using 30 degrees phase displacement, for the same air gap flux, the inverter dc bus voltage is reduced by approximately a half (Because of 30 degrees displacement, voltage relations are like star-delta).
4. Also control is economical as sensor less vector control is implemented.

   Motor design is incomplete unless its speed is controlled. Thus the novel six phase induction motor development proved to be successful.

CHAPTER 7

CONCLUSIONS AND FUTURE SCOPE

7.1 INTRODUCTION

This chapter concludes the work and comments on results. Summary of results obtained with discussion is presented. At the end future scope is discussed. There has been growing interest in multiphase induction motors as due to their features like reliability, high torque etc. which makes them suitable to be used in Aerospace, hybrid electric vehicles and electric ship propulsion.

7.2 REMARKABLE ACHIEVEMENTS

The innovative and remarkable achievements of this designed and developed six phase induction motor-prototype are summarized below:

3. There is no criterion of maintaining 30 degrees phase shift, i.e. arbitrary phase shift. All control schemes developed till date were for 30 degree phase shift only. [20]-[46]
4. No third harmonic current injection or current sensor required for torque improvement: In this novel prototype six phase induction motor, the torque is found to be 1.6 times that of three phase induction motor torque. This is higher than 1.4 times as described in references [5], [1], [28]. This is achieved without

third harmonic current injection for torque improvement and control with arbitrary phase displacement by small changes in design and dimensions of motor.

The other features of a developed prototype six-phase induction motor are summarized as:

5. Improved reliability, i.e. if one inverter fails, the motor continue to run (though at reduced rating) thus continuity of operation is maintained, this is because the two neutrals are kept open.
6. Harmonic reduction because all the harmonics of the order ($6n \pm 1$) where n = 1, 3, 5, 7------- get cancelled because of 30 degrees phase displacement. Reduced torque pulsations because of harmonic reduction.
7. As losses are reduced efficiency is improved as there are no circulating currents because of harmonic reduction.
8. By using 30 degrees phase displacement, for the same air gap flux, the inverter dc bus voltage is reduced by approximately a half (Because of 30 degrees displacement, voltage relations are like star-delta).
9. Also control is economical as sensor less vector control is implemented.

7.2.1 Limitations of the design and development:

1. For higher rating, the size of the motor and hence inverter size becomes very large, which may increase the overall cost.
2. Although sensor-less vector control is economical, the parameter variation problem particularly near zero speed imposes a challenge in the accuracy of speed estimation.(as seen from figure In Sensor less control there is no feedback so no error correction, Speed is estimated from the readings of output voltage and current.

7.3 FUTURE SCOPE:

1. The same motor can be controlled using direct torque control, DTC which may give better speed control.
2. Six phase motor can be designed with two stator windings with different number of poles so that two different speeds can be obtained as per number of poles.
3. Multi motor operation, i.e. two or more multiphase motors can be supplied from single six phase inverter to get more torque wherever required, e.g. Electric Ship Propulsion.
4. Same design can be extended in multiples of three, i.e. 9 phase, 12 phase, 15 phase motor as per the requirement of torque.

Papers Presented / Published / Accepted

1. "FOC Of Tandem Inverter Fed Induction Motor", ICTAETS2008, Saurashtra University, Rajkot,13-14 January-2008. Paper accepted and published in Conference proceedings.
2. "Control of Multiphase Induction Motors", IEEE National Conference, CITC, Changa, September 2008. Paper presented and published in Conference proceedings.
3. "Multi Motor Drive Control", Paper Selected At Nucone-2008, A National Conference At Nirma Institute Of Technology, Ahmedabad.
4. "Vector Control Of Multi motor Drives", World Academy of Science & Engineering Technology,(WASET) IEEE International Conference, France, 21st -23rd Nov.2008. Paper accepted for conference and then published in online Journal of WASET 2008.
5. "Multiphase Induction Motor, Modeling and Control", International Journal IJ-ETA-ETS, Amoghsiddhi Education Society. January-June 2009 Issue. ISSN: 0975 – 6736.
6. "Application of Multiphase Induction Motor in Ship Propulsion". Work Boat Ship Propulsion Seminar, Abu-Dabhi, UAE, 5th -7th October 2009. Paper was presented in seminar and

then same was published In “Sea trade-Journal”, November 2009.

7. “Comparison Of Three Phase Induction Motor With Six Phase Induction Motor Using Matlab Simulation”, International Journal Of Research in Electrical Engineering, ISSN: 0975 – 6736| Nov 09 To Oct 10 | Volume 1.
8. “Multiphase Induction motor drives” Paper accepted by SERBIAN Journal of Electrical Engineering, 2010 issue.
9. “Design of Multiphase Induction Motor for Ship Propulsion” IEEE Conference Electrical Ship Propulsion Technologies Symposium, (ESTS 2011) Alexandria, Virginia, USA, April 2011. Paper Put On IEEE-Explore.
10. “Design and Control of Multiphase Induction Motor” IEEE International Machines & Drives Conference, “IEMDC 2011” At Nigara Falls, Canada, May 2011. Paper is accepted for the conference and put on online-IEEE Conference papers.
11. “Design, Development and testing of six phase induction motor”, IJBER, ISSN: 0975-0479), International Journal of Business & Engineering Research-2012.
12. “Vector Control Of Tandem Inverter Fed Induction Motor”, National Conference At Patiala, Punjab, April 2007. Paper

accepted for conference and published in conference proceedings

13. “FOC of Tandem Inverter Fed Induction Motor”, Grid safe-April 2007, Institution Of Engineers, Nagpur. Paper accepted for conference and published in conference proceedings

14. “Tandem inverter fed field oriented controlled induction motor” , RACE International Conference at Bikaner, 24-25 march 2007. Paper presented and published in conference proceedings

15. “Vector Control of Induction Motor”, ELCON06- National Conference at National Engg College Kovilpatti, October 2006. Paper accepted and published in conference proceedings.

16. “Control of VSI Fed Induction Motor Drives”, ELCON05 National Conference at National Engg College Kovilpatti, October 2006. Paper accepted and published in conference proceedings.

17. “Sliding Mode Controller For Dc Servo Motor”, IPROMM2000 Priyadarshini College of Engineering, Nagpur 31st Dec 1999-1st Jan 2000. Paper presented and published in conference proceedings.

BIBLIOGRAPHY

1. Emil Levi, “Recent Developments in High Performance Variable-Speed Multiphase Induction Motor Drives” Sixth International Symposium Nikola Tesla, Belgrade, Serbia. 18th – 20th October, 2006.
2. Robert H. Nelson, Thomas A. Lipo, and Paul C. Krause, “Stability Analysis of a Symmetrical Induction Machine” IEEE Transactions on Power Apparatus and Systems, Vol. 88, No. 1, November 1969.
3. L. Romeral, “Motion Control for Electric Drives” XVI Journal of Conference in Electronics Engineering, JCEE-2002, Terrasa, Spain, pp 26-30. November 2002.
4. Samir Hamdani, Omar Touhami, Rachid Ibtiouen, “ A Generalized Two Axes Model of a squirrel-Cage Induction Motor for rotor Fault Diagnosis” Serbian Journal Of Electrical Engineering Vol. 5, No. 1, 155-170. May 2008.
5. K. Gopalkumar, Mahopatra, “A novel scheme for six phase induction motor with open end windings.” 28th Annual Conference of IEEE Industrial Electronics Society, Spain. 5th - 8th November, 2002.
6. Krishna K. Mahopatra, R. S. Kanchan, M. R. Baiju, P. N. Tekwani, K. Gopakumar “Independent Field oriented control

of two split phase induction motors from a single six phase inverter”, IEEE Transaction on Industrial Electronics, Vol. 52, No. 5, October 2005.

7. Hamid Toliyat, Emil Levi, “A novel concept of a multiphase, multi-motor vector controlled drive system supplied from a single voltage source inverter” IEEE Transactions on Power Electronics, Vol. 19, No. 2, pp. 320-335. March 2004.
8. V. Oleschuk, G. Griva, F. Profumo, A. Tenconi, “Combined Synchronised PWM for Symmetrical split-Phase Drives with low Switching Frequency” Power Electronics Specialists Conference (Rhodes, Greece) (pp.1522-1527) ISBN: 9781424416684. January, 2008.
9. G. R. Arab Markadeh, J. Soltani, N. R. Abjadi, M. Hajian, “Sensor less Control of a Six-Phase Induction Motors Drive Using FOC in Stator Flux Reference Frame” World Academy of Science, Engineering and Technology (WASET), Issue 58, pp 890 – 896. October, 2009.
10. Dejan D. Reljic, Darko B. Ostojic, Veran V. Vasic, “Simple Speed Sensorless Control of Induction Motor Drive”, Sixth International Symposium Nikola Tesla, Belgrade, Serbia, 18th – 20th, October, 2006.

11. Martin Jones, Slobodan N. Vukosavic, Emil Leviand Atif Iqbal, “A Six-Phase Series-Connected Two-Motor Drive With Decoupled Dynamic Control” IEEE Transactions On Industry Applications, Vol. 41, No. 4, July / August 2005.

12. E. Levi, M. Jones, S. N. Vukosavic, H. A. Toliyat, ”A Five-Phase Two-Machine Vector Controlled Induction Motor Drive Supplied from a Single Inverter” European Power Electronics & Drives Journal, Vol. 14. No. 3. August, 2004.

13. Shyh-Shing Perng Yen-Shin Lai, Chang-Huan Liu, “Sensorless Vector Controller for Induction Motor Drives with Parameter Identification” Proceedings of the 24th Annual conference of the IEEE Industrial Electronics Society IECON '98, Aachen, Germany. pp. 1008 – 1013. August 31 – September 4, 1998.

14. Kazutoshi Kaneyuki And Dr. Masato Koyama, “Motor-Drive Control Technology for Electric Vehicles” Mitsubishi Electric Advance -Technical report, March, 1997.

15. Thomas A. Lipo, And Paul C. Krause, “Stability Analysis of a Rectifier-Inverter Induction Motor Drive” IEEE Transactions on Power Apparatus And Systems, Vol. 88, No. 1, January, 1969.

16. Jui-Jung Liu, I-Chung Kung, And Hui-Cheng Chao, “Speed Estimation of Induction Motor Using a Non-linear Identification Technique” Proceedings of the National Science Council, Republic of China, Part A: Physical Science and Engineering : Vol. 25 No.2 PP. 107-114, January 2001.
17. Alfredo, Thomas A. Lipo and Donald W. Novotny, “A New Induction Motor V/f Control Method Capable of High-Performance Regulation at Low Speeds” IEEE Transactions on Industry Applications, Vol. 34, No. 4, July / August 1998.
18. Maria Imecs, Andrzej M. Trzynadlowski, Ioan I. Incze, and Csaba Szabo, “Vector Control Schemes for Tandem-Converter Fed Induction Motor Drives” IEEE Transactions On Power Electronics, Vol. 20, No. 2, March 2005.
19. Janne Salomaki and Jorma Luom, ”Vector Control of an Induction Motor Fed by PWM Inverter with Output LC Filter” European Power Electronics and Drives Association Journal, Vol. 16 No. 1, pp. 37-43 2006.
20. G. K. Singh, “Multiphase Induction Machine drive research”, Elsevier Journal, Electric Power System Research, Vol. 61, pp. 139-147, 2002.

21. A. K. Chattopadhyay, “Advances in vector control of ac motor drives - A review” Sadhana, Vol. 22, Part 6, pp. 797-820, December 1997.

22. J. Prieto, F. Barrero, S. Toral, M. R. Arahal and M. J. Duran, “ FPGA Implementation of a Multiphase Space Vector Modulation for Asymmetrical Dual Three-phase AC Machines. International Conference on renewable Energies and Power Quality (ICRPQ’09), Valencia, Spain, 15th- 17th April 2009.

23. Pillay P, Odendal E. J., Harley R. G., “Torque and speed harmonic analysis of a PWM CSI-fed induction motor drive” The Transactions Of The South African Institute Of Electrical Engineers, December 1984.

24. Anibal T. De Almeida and Fernando Ferreira, “Efficiency Testing of Electric Induction Motors” Conference on Electrical Engineering**,** Coimbra**,** 26-28 November 2007.

25. Ibrahim K. Al Abbas, “Reduced Order Models of a Current Source Inverter Induction Motor Drive”, American Journal of Engineering and Applied Scinces – Vol. 2 No. 1, pp 39 - 43, 2009.

26. S. Ghatak Choudhuri, Bhim Singh, “DSP Based Implementation of Digital Speed Controller for Vector

Controlled Induction Motor Drive" Journal of Institution of Engineers (India), March 2005.

27. Teodor Pana, "Sensorless vector-controlled induction motor drive system with rotor resistance estimation using parallel processing with floating point dsp" Workshop on Electrical Machines' Parameters Technical University of Cluj-Napoca, Romania, 26th May 2001.
28. Bojoi I. R.; Tenconi A. ; Griva G. ; Profumo F., "Vector Control of Dual-Three Phase Induction Motor Drives Using Two Current Sensors", IEEE Industry Application Society Conference (Hong Kong (China)) pp.1805-1812 ISBN:0780392094, 2nd -6th October, 2005.
29. R. Gregor, F. Barrero, S. Toral and M. J. Durán, "Realization of an Asynchronous Six-Phase Induction Motor Drive Test-Rig" International conference on renewable energies and Power Quality. ICREPQ'08. Santander, Spain, 12, 13 and 14 March, 2008.
30. Wang Xiangheng & WU Xin Zhen, "Research on dual-stator winding multi-phase high-speed induction generator with rectifier load" Science in China Series E: Technological Sciences, Vol.51, Issue-6, 2008.

31. S. Ekram, Dr. B. Sarkar, “Effects of Harmonics on PWM Inverter fed Induction Machines” Institution of Engineers Journal, Vol 85, June 2004.

32. Epaminondas D. Mitronikas and Athanasios N. Safacas, “An improved Sensorless Vector Control Method for an Induction motor drive”, IEEE Transactions on Industrial Electronics, Vol. 52, No. 6, December 2005.

33. Huang Jin, Kang Min, Yang Jia-qiang, “Analysis of a new 5-phase bearingless induction motor”, Huang et al. / J Zhejiang University of Science A, Vol. 8, No. 8, pp 1311-1319, China. 2007.

34. A. M. Rusakov, Yu. A. Safronenkov, I. A. Zherdev, and A. N. Solomin, “Prospects of Application of Induction Machines with Excitation Winding”, ISSN 1068-3712, Russian Electrical Engineering, 2008, Vol. 79, No. 4, pp. 201–206. © Allerton Press, Inc., 2008.

35. I. P. Kopylov, “Generalized Electric Machine and Generalized Electro–Mechanical Converter”, ISSN 1068-3712, Russian Electrical Engineering, 2008, Vol. 79, No. 2, pp. 99–103. © Allerton Press, Inc., 2008.

36. V. A. Mishchenko, ZAO Optimum Elektron, “Vector Theory of an Induction Motor” ISSN 1068-3712, Russian Electrical

Engineering, 2007, Vol. 78, No. 6, pp. 280–286. © Allerton Press, Inc., 2007.

37. Michael Filippich, “Digital Control of a Three Phase Induction Motor” School of Information Technology and Electrical Engineering - Innovation Project - Electronics, University of Queensland, Australia, October 2002.

38. Michael van der Giet and Kay Hameyer, Stephan Risse, “Induction motor with pole-changing winding for variable supply frequency” 6th International Machines and Drives Conference, IEMDC-2007, Antalya, Turkey, 3 – 5 May, 2007.

39. Victor M. Moreno, Alberto Pigazo, “Future trends in Electric Propulsion Systems For Commercial Vessels”, Journal of Maritime Research, Santander, Spain, Vol IV, No. 2. pp 87 – 100, August, 2007.

40. G. Esmaily, A. Khodabakhshian, K. Jamshidi, “Vector Control Of Induction Motors Using Upwm Voltage Source Inverter” AUPEC-1999, Australian Universities Power Engineering Conferences, Northen Territory University, Darwin, September, 26 – 29, 1999.

41. Renato O. C. Lyra, Thomas A. Lipo, “Torque Density Improvement in a Six-Phase Induction Motor With Third

Harmonic Current Injection” IEEE Transactions on Industry Applications, Vol. 38, no. 5, pp. 1351-1360, September – October, 2002.

42. G. K. Singh, S. K. Lim, “A Simple Indirect Field-oriented Control Scheme for Multiphase Induction Machine”, IEEE Transactions on Industrial Electronics, Vol. 52, No. 4, August 2005.
43. Maria Imecs, Csaba Szabo, Janos Job Incze, “Vector Control of the Cage Induction motor with dual Field Orientation”, 9th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics” Budapest, Hungary, November 6 - 8, 2008.
44. K. Gopakumar, V. T. Rangnathan, S. R. Bhatt, “Vector Control of Induction Motor With Split Phase Stator Windings”, European Power Electronics (EPE) Journal , Vol. 7, no. 1 - 2, pp. 62 - 67, August 1997.
45. K. L. Shi, T. F. Chan, Y. K. Wong, S. L. Ho, “Modelling And Simulation Of The Three Phase Induction Motor Using Simulink”, International Journal of Electrical Engineering Education, Vol. 36, pp 163 - 172. Manchester, 1999.
46. Martin Jones, Slobodan N. Vukosavic, Emil Levi, Atif Iqbal, “A Six Phase Series Connected two Motor Drive with

decoupled Dynamic Control", IEEE Transactions on Industry Applications, Vol. 41, No. 4, July / August 2005.

47. Mario J. Duran, F. Barrero, S. Toral, "Multiphase Space Vector Pulse Width Modulation: Applications and Strategies" International Conference On Renewable Energies And Power Quality (ICREPQ'07)", Sevilla (Sr. No. 341), 28,29 and 30 Mach 2007.

48. Zeraouila, M. Benbouzid, H. Diallo, "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study" Vehicle Power and Propulsion, 2005 IEEE Conference, pp. 280-287, 7th -9th September 2005.

49. Zhang Jian, Wen Xuhui ,Hua Yang, "A novel speed-sensor less vector control technique of Induction motor for electrical vehicle propulsion", IEEE Vehicle Power and Propulsion Conference (VPPC), Harbin, China 3-5, September, 2008

50. Shady M. Gadoue Ayman S. Abdel-Khalik, "Speed Estimation performance for Multiphase Induction Machines under Fault Conditions", Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10), Cairo University, Egypt, Paper ID 218, pp. 515-520, 19-21, December, 2010

51. David G. Dorrell, Chee Yeow Leong, and Richard A. McMahon, “Analysis and Performance Assessment of Six-Pulse Inverter-Fed Three-Phase and Six-Phase Induction Machines” IEEE Transactions On Industry Applications, Vol. 42, No. 6, November/December 2006
52. Steve Williamson, Sandy Amith, “Pulsating Torque and Losses in Multiphase Induction Machines”, IEEE Transactions on Industry Applications, Vol. 39, No. 4, July/August 2003.
53. Juri Jatskevich, Mirko Maksimcev, “Modeling Multiphase Induction motors for Electric Ship Propulsion Systems”, WSEAS/IASME International Conference on Electro science and Technology for Naval Engineering and All-Electric Ship, Miami, Florida, USA, pp. 10-16, 17-19 November 2005
54. Epaminondas D. Mitronikas, Athanasios N. Sefacas, “An Improved Vector Control Method for an Induction Motor Drive”, IEEE Transactions on Industrial Electronics, Vol-52, No.6, December 2005.
55. Modern Power Electronics and AC Drives by Bimal K. Bose, Prentice Hall, USA. ISBN 0-13-016743-6, Printed in 2002.

56. Electric Motor drives- Modeling, Analysis and control By R. Krishnan, Prentice Hall of India Private Limited, New Delhi, India, ISBN-81-203-2168-5, Printed in 2002.

57. DSP based Electromechanical motion control by Hamid A. Toliyat and Steven G. Campbell, (Chemical Rubber Company) CRC Press, Taylor and Francis Group. ISBN:9780849319181, Printed in 2003.

58. A course in Electrical Machine Design- A. K. Sawhney, Dhanpat Rai & Co.(P) Ltd. New Delhi, 5th Edition - Reprint 2005.

59. Fundamentals of Electrical Drives by G.K.Dubey, Narosa Publishing House, New Delhi, Second Edition 2001, Reprint 2002.

60. Chien-Feng Hu and Chang-Huan Liu, "Controller design and FPGA implementation of a speed-sensorless vector-controlled induction motor drive based on stability consideration" Journal of the Chinese Institute of Engineers, Vol. 29, No. 5, pp. 813-825 ,2006.

APPENDIX-I

Output Equation of AC motor

Let Q = KVA rating of motor

E_{ph} = Output voltage per phase

I_{ph} = Current per phase

f = Supply Frequency

Φ = Flux per pole in Weber

T_{ph} = Turns per phase

K_w = Winding factor

p = No. of poles

n_s = Synchronous speed

D = Stator Diameter

L = Core length

B_{av} = Specific Magnetic loading

ac = Specific Electric loading

I_s = Current in each conductor

Z = Total armature conductors

Z_{ss} = Armature conductors per slot

m = No. of phases

C_0 = Output Coefficient

Consider an m phase motor having one circuit per phase.KVA rating of motor

Q = number of phases × output voltage per phase × current per phase × 10^{-3}

$Q = m.E_{ph}I_{ph}.10^{-3}$ [1.1]

Terminal voltage of each phase may be taken equal to the induced emf per phase,

We have, Induced emf per phase [58]

$E_{ph} = 4.44\ f\ \Phi\ T_{ph}\ K_w$ [1.2]

$\therefore$ **Q = m** $\times 4.44\ f\ \Phi\ T_{ph}\ K_w\ I_{ph} \times 10^{-3}$ [1.3]

But $f = pn_s / 2$ [1.4]

Therefore we can write,

$Q = \mathbf{m} \times 4.44\ (pn_s / 2)\ \Phi\ T_{ph}\ K_w\ I_{ph} \times 10^{-3}$ [1.5]

$Q = 1.11\ K_w\ (p\Phi)\ (2m\ I_{ph}\ T_{ph})\ n_s \times 10^{-3}$ [1.6]

Now current in each conductor

$I_s = I_{ph}$ (As there is only one circuit per phase).

Total number of armature conductors

Z = number of phases × (2 × turns per phase) = $2m\ T_{ph}$

$\therefore$ **Total electric loading** $I_s Z = 2m\ I_{ph}\ T_{ph}$

Hence, $Q = 1.11\ K_w\ (p\Phi)\ (I_s Z)\ n_s \times 10^{-3}$ [1.7]

$= 1.11\ K_w$ (total magnetic loading) (total electric loading) (synchronous speed $\times 10^{-3}$)

But $p\Phi = \boldsymbol{\pi}\ DL\ \mathbf{B_{av}}$ **and** $I_s Z = \boldsymbol{\pi}\ D\ \mathbf{ac}$

Substituting these values in equation [1.7],

$$\mathbf{Q = 1.11}\ K_w\ (\boldsymbol{\pi}\ DL\ \mathbf{B_{av}})\ (\boldsymbol{\pi}\ D\ \mathbf{ac})\ n_s \times 10^{-3}$$

$$\mathbf{Q = (1.11\pi^2\ B_{av}\ ac\ K_w} \times 10^{-3})\ D^2\ L\ n_s$$

$$= (11\ \mathbf{B_{av}\ ac\ K_w} \times 10^{-3})\ D^2\ L\ n_s \qquad [1.8]$$

$$Q = C_0\ D^2\ L\ n_s \qquad [1.9]$$

$$C_0 = 11\ \mathbf{B_{av}\ ac\ K_w} \times 10^{-3} \qquad [1.10]$$

Equation [1.10] is known as the output equation of an a.c. machine. Quantity C_0 is called the output coefficient.

Motor Specifications at "Jyoti Switchgear Ltd".

KW= 2.2 POLE= 4.0 VOLT= 320.0 FRAME= CTF-112 FRAME NO.= 112.0

DATE OF RUN: 08/01/2009 TIME OF RUN: 13:47:35.33

INPUT DATA PROJECT NEW ROTOR TYPE = SINGLE CAGE

STATOR DATA		ROTOR DATA	
O.D.=	165.000	O.D.=	105.000
I.D.=	105.000	I.D.=	33.500
STACKLENGTH=	110.000	STACKLENGTH=	110.000
STACKING FACTOR=	.950	STACKING FACTOR=	.950
NO. OF DUCTS=	.000	NO. OF DUCTS=	.000
WIDTH OF DUCT=	12.700	WIDTH OF DUCT=	12.700
NO. OF SLOTS=	36.000	NO. OF SLOTS=	33.000
SLOT DIMENSIONS		SLOT DIMENSIONS	
SLOT OPENING=	2.500	SLOT OPENING=	.800
WIDTH AT TOP=	7.000	WIDTH AT TOP=	5.300
WIDTH AT BOTTOM=	4.600	WIDTH AT BOTTOM=	1.900
LIP HEIGHT=	.500	LIP HEIGHT=	.750
WEDGE HEIGHT=	.500	NECK HEIGHT=	.750
HEIGHT ABOVE WEDGE=	13.800	HEIGHT BELOW NECK=	16.200
CONDUCTOR PER SLOT=	96.000	BAR LENGTH=	140.000
CONDUCTOR SIZE= 1/ .60 0/ .00 0/ .00			
CONDUCTOR AREA=	.283	AREA OF BAR	60.608
ENAMEL AREA=	.454	AREA OF RING	150.000
COIL PITCH=	9.000	WIDTH OF S.C.RING=	15.000
NO. OF PARALLEL PATH=	3.000	DEPTH OF S.C.RING=	10.000
STATOR CONNECTION=	STAR	ROTOR SKEW =	1.000
AIR GAP=	.300	DENSITY OF IRON=	7.650
RHO OF COPPER(75C)=	.022	DENSITY OF COPPER=	8.900
RHO OF BAR=	.044	DENSITY OF BAR=	8.900
RHO FOR RING=	.044	DENSITY OF RING=	8.900
CLASS OF INSULATION=	B	IRON LOSS PER KG=	5.300
SUPPLY FREQUENCY(Hz)=	50.000	STAMPING GRADE=	500C

PERFORMANCE ANALYSIS AT 100% VOLTAGE

WINDING FACTOR=	.960	SLOT FILL FACTOR(%)=	53.330
CK1=	1.271	OVERHANG PROJECTION=	28.051
CK2=	1.035	MEAN LENGTH OF CONDUCTOR=	258.343
CK3=	1.000	ST. RESISTANCE AT 75 C=	2.351
EFFECTIVE CARTER FACTOR=	1.316	ST. RESIST AT 30 C=	2.010

MAGNETIC CIRCUIT CALCULATION

FLUX PER POLE IN WEBERS= .0045 ALPHA= 1.469

STATOR TOOTH	WIDTH	AVERAGE DENSITY	MAXIMUM DENSITY	ROTOR TOOTH	WIDTH	AVERAGE DENSITY	MAXIMUM DENSITY
BTS1=	4.738	1.013	1.488	BTR1=	4.410	1.139	1.674
BTS2=	4.742	1.012	1.487	BTR2=	4.568	1.100	1.616
BTS3=	4.746	1.011	1.485	BTR3=	4.726	1.063	1.562

STATOR CORE HEIGHT =		15.200	ROTOR CORE HEIGHT =	18.050
STATOR CORE DENSITY=		1.421	ROTOR CORE DENSITY=	1.104
AIR GAP DENSITY=	.497	.731		
STATOR TOOTH AT=		12.496	ROTOR TOOTH AT=	38.815
STATOR CORE AT=		11.651	ROTOR CORE AT=	1.966
AIR GAP AT		229.560	TOTAL AT=	294.488
SATURATION FACTOR=		1.283		

LEAKAGE REACTANCE

XSL1=	.555	PS11=	.000
XZZ1=	.565	XZZ2=	.953
XHANG=	.935	XER=	.135
XM=	68.894	XSKL=	.672
KP=	.960	MAG. CURRENT=	2.367
R2=	1.437	XSL2=	.949
X1=	2.728	X2=	2.036
CORR FACTOR FOR RESIST(KR)=	1.139	LOCKED ROTOR RESISTANCE=	1.574
CORR.FACTOR FOR REACT(KI)=	.960	LOCKED ROTOR REACTANCE=	4.592

IRON LOSSES

IRON LOSS IN TEETH=	.063	IRON LOSS IN CORE=	.047
TOTAL IRON LOSS=	.109		

NO LOAD-LOCKED ROTOR-PULL OUT PERFORMANCE

	NO LOAD	LOCKED ROTOR	PULL-OUT
SLIP(%)	.050	100.000	27.049
STATOR CURRENT	2.584	30.460	20.714
ROTOR CURRENT	.062	29.543	19.947
INPUT POWER	.190	10.828	9.571
POWER FACTOR	.133	.641	.834
TORQUE RATIO	-.001	187.323	289.273
CURRENT RATIO	.465	5.488	3.732

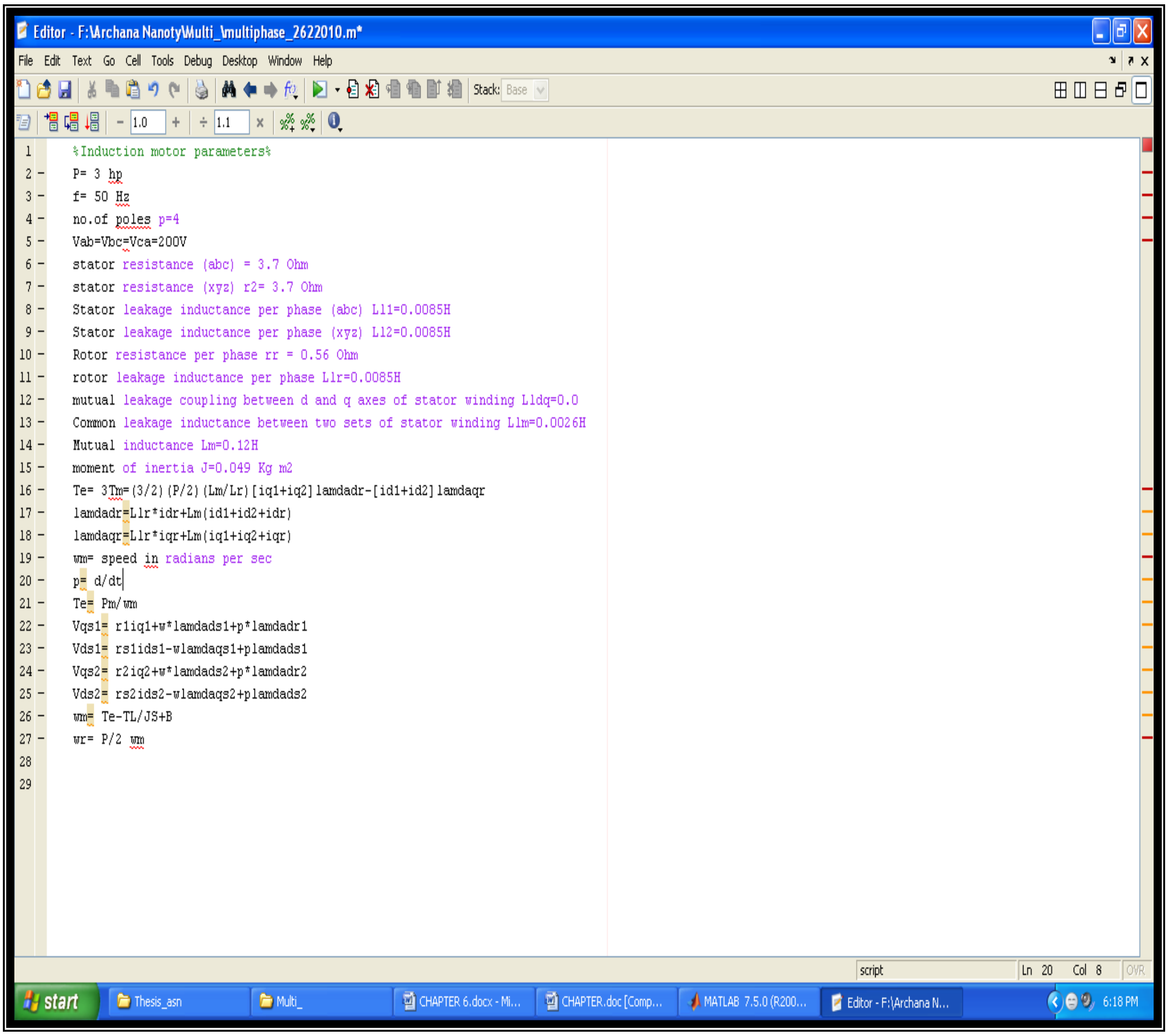
LOAD PERFORMANCE

% LOAD	125(%)	100(%)	75(%)	50(%)	25(%)
OUTPUT-KW=	2.747	2.200	1.650	1.100	.550
SLIP=	5.378	4.060	2.903	1.867	.923
STATOR CURRENT=	6.827	5.551	4.443	3.529	2.873
ROTOR CURRENT=	6.050	4.679	3.414	2.235	1.122
STATOR COPPER LOSS=	.329	.217	.139	.088	.058
ROTOR COPPER LOSS=	.158	.094	.050	.022	.005
STRAY LOAD LOSS=	.017	.013	.010	.007	.004
FRICTION-WINDAGE LOSS=	.030	.030	.031	.032	.032
IRON LOSS=	.109	.109	.109	.109	.109
TOTAL LOSSES=	.642	.465	.340	.257	.209
EFFICIENCY-%=	81.051	82.559	82.914	81.040	72.443
POWER FACTOR=	.896	.866	.808	.694	.477
CURRENT DENSITY=	8.044	6.540	5.235	4.158	3.385
AMP-CON PER CM=	238.404	193.850	155.174	123.247	100.336
QUE-ALPHA=	1917.607	1267.833	812.398	512.490	339.661

ROTOR BAR CURRENT DENSITY 2.587 ROTOR RING DENSITY= 2.745

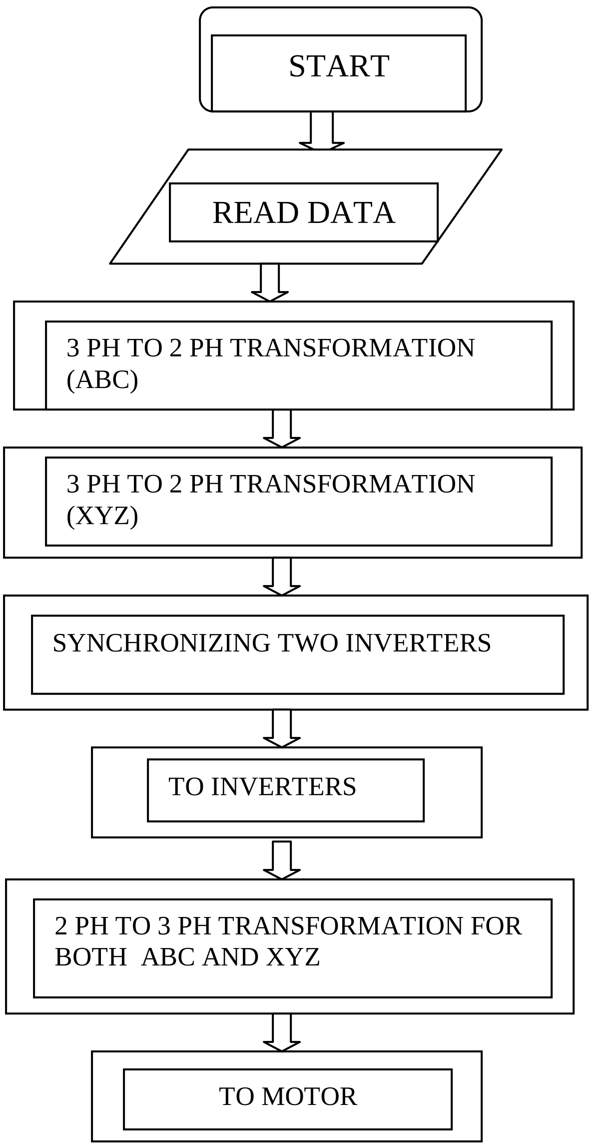
APPENDIX- II

I] Matlab – software program in m-file for six phase Proto type Induction motor parameter:-

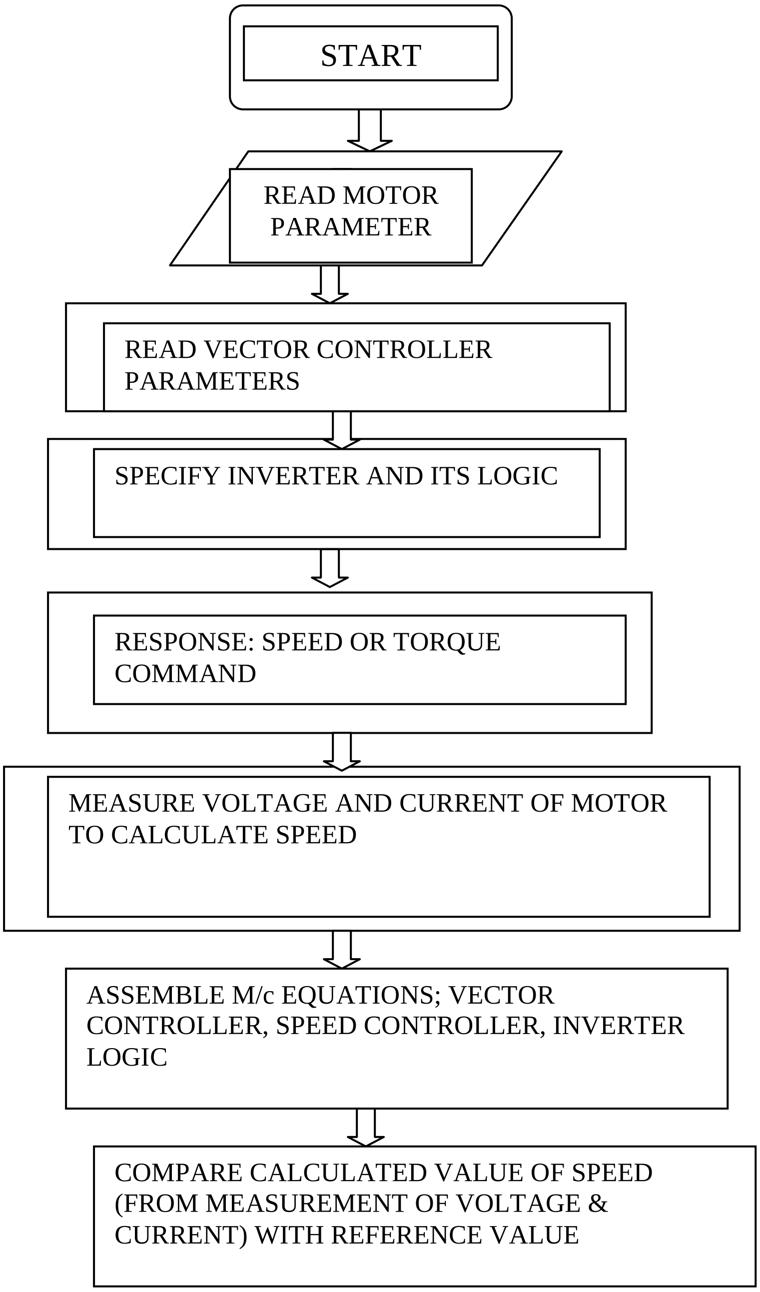


```
%Induction motor parameters%
P= 3 hp
f= 50 Hz
no.of poles p=4
Vab=Vbc=Vca=200V
stator resistance (abc) = 3.7 Ohm
stator resistance (xyz) r2= 3.7 Ohm
Stator leakage inductance per phase (abc) Ll1=0.0085H
Stator leakage inductance per phase (xyz) Ll2=0.0085H
Rotor resistance per phase rr = 0.56 Ohm
rotor leakage inductance per phase Llr=0.0085H
mutual leakage coupling between d and q axes of stator winding Lldq=0.0
Common leakage inductance between two sets of stator winding Llm=0.0026H
Mutual inductance Lm=0.12H
moment of inertia J=0.049 Kg m2
Te= 3Tm=(3/2)(P/2)(Lm/Lr)[iq1+iq2]lamdadr-[id1+id2]lamdaqr
lamdadr=Llr*idr+Lm(id1+id2+idr)
lamdaqr=Llr*iqr+Lm(iq1+iq2+iqr)
wm= speed in radians per sec
p= d/dt
Te= Pm/wm
Vqs1= r1iq1+w*lamdads1+p*lamdadr1
Vds1= rs1ids1-wlamdaqs1+plamdads1
Vqs2= r2iq2+w*lamdads2+p*lamdadr2
Vds2= rs2ids2-wlamdaqs2+plamdads2
wm= Te-TL/JS+B
wr= P/2 wm
```

II] FLOW CHART FOR THREE PHASE TO TWO PHASE TRANSFORMATION

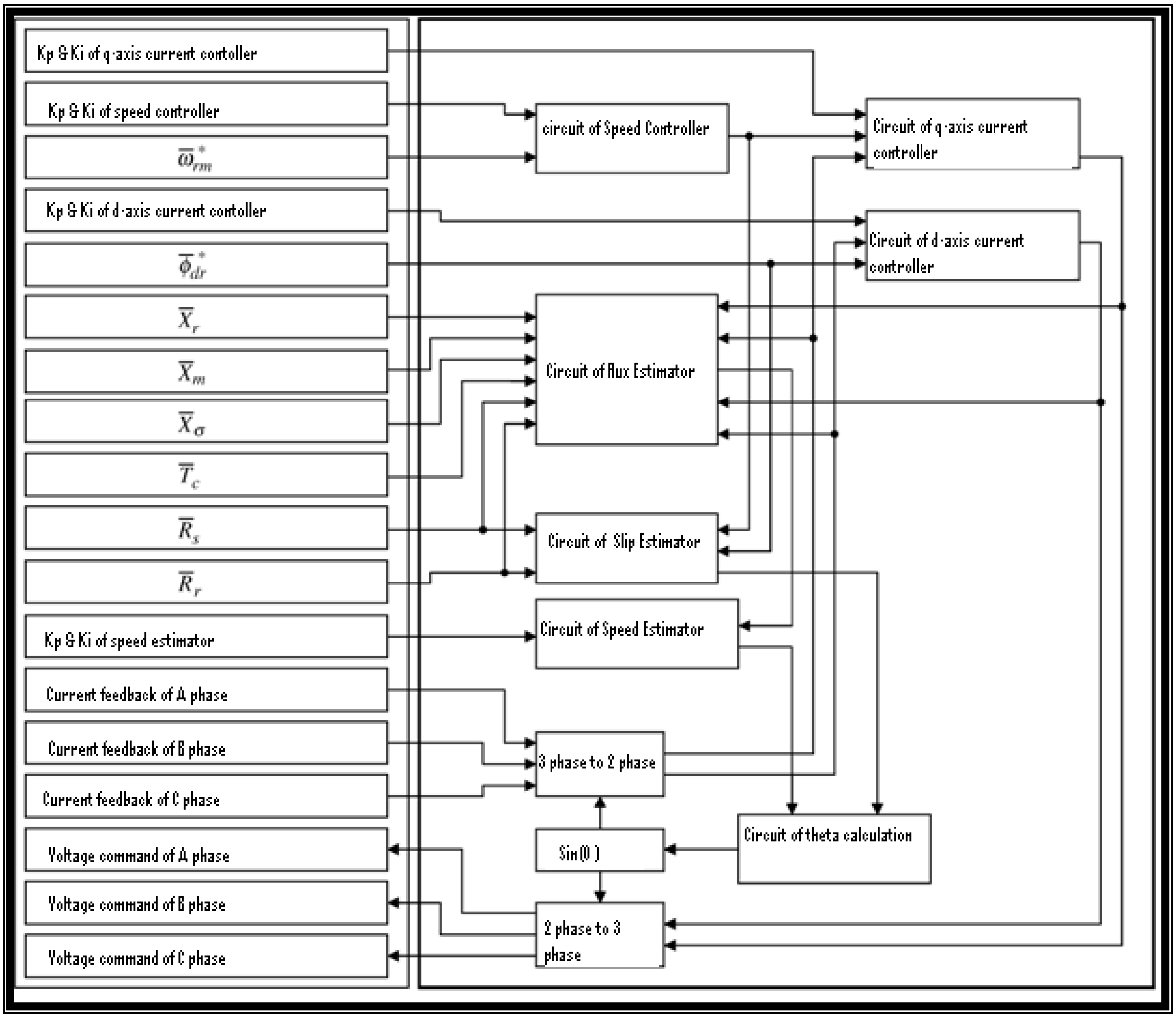


III] FLOW CHART FOR VECTOR CONTROL



IV] FPGA Implementation

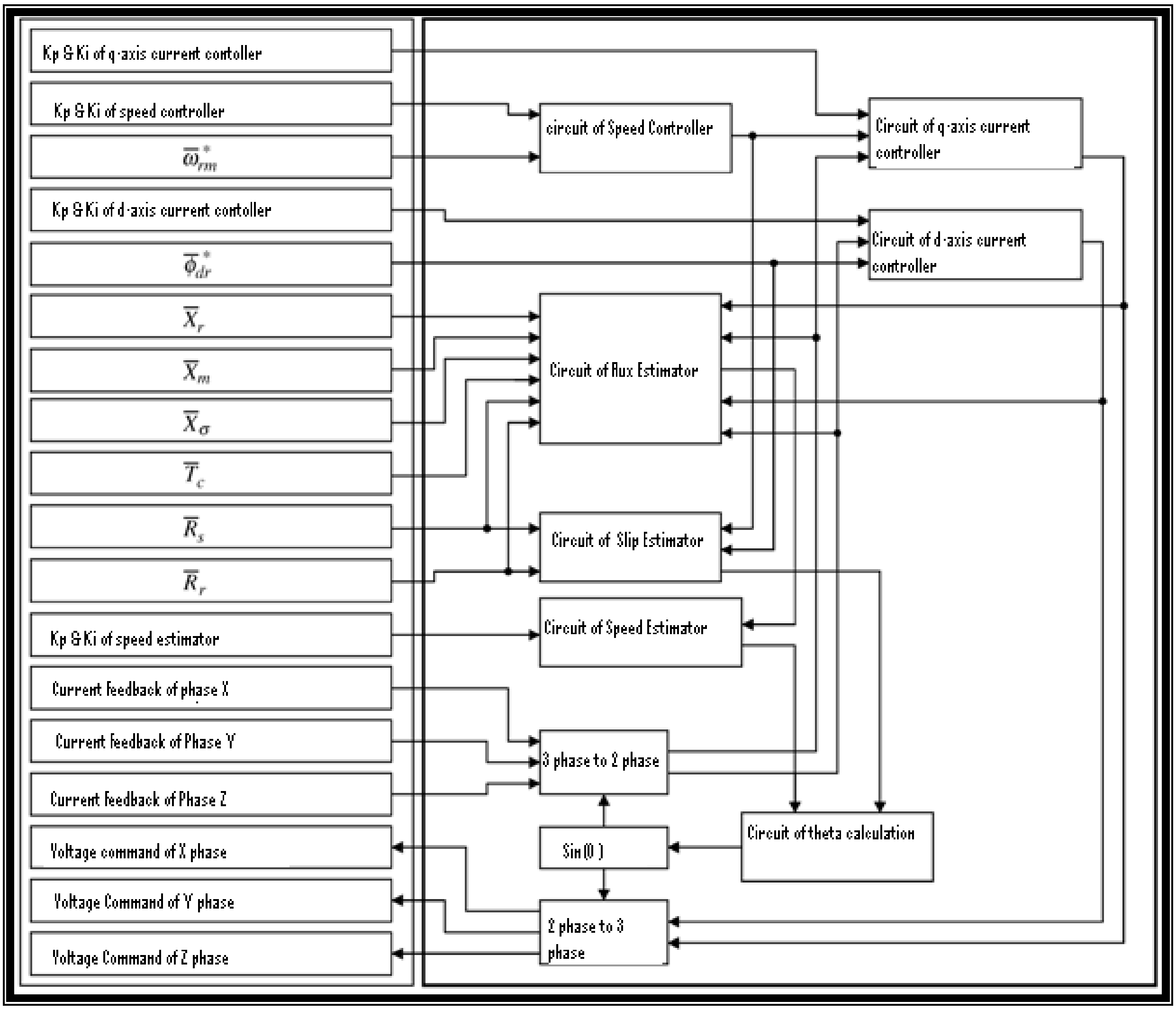
A:-FPGA implementation of Sensor-less vector control Algorithm (For three phase set ABC)



Interface between FPGA and Microprocessor

FPGA Implementation

B:-FPGA implementation of Sensor-less vector control Algorithm (For three phase set XYZ)



Interface between FPGA and Microprocessor

FPGA Implementation

APPENDIX-III

Technical Data for VACON Drive:

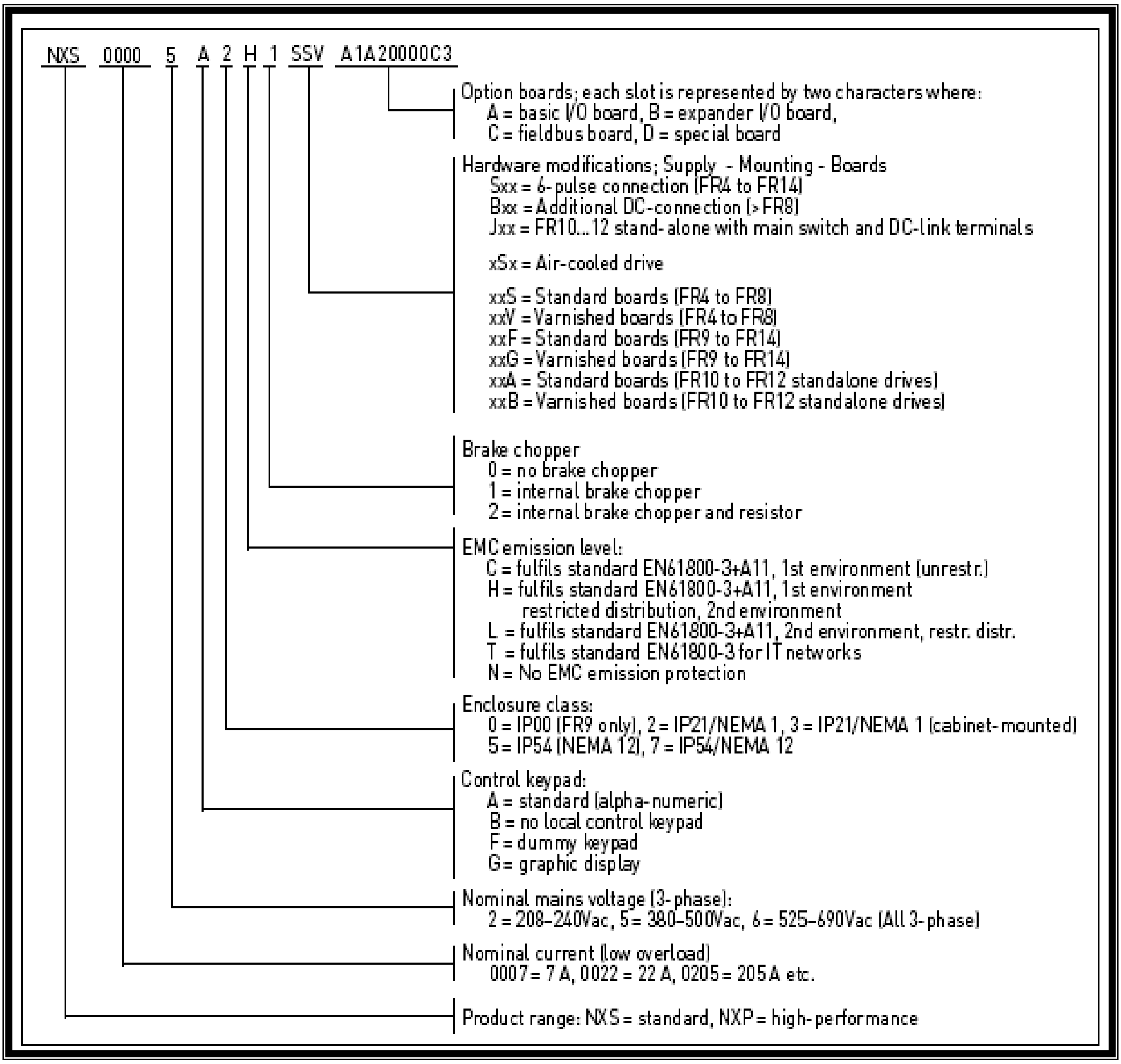


Figure III A. VACON NXP drive Type destination code

Mains connection	Input voltage U_{in}	208...240V; 380...500V; 525...690V; −15%...+10%
	Input frequency	45...66 Hz
	Connection to mains	Once per minute or less
	Starting delay	2 s (FR4 to FR8); 5 s (FR9)
Motor connection	Output voltage	0— U_{in}
	Continuous output current	I_H: Ambient temperature max. +50°C, overload 1.5 x I_H (1 min./10 min.) I_L: Ambient temperature max. +40°C, overload 1.1 x I_L (1 min./10 min.)
	Starting current	I_S for 2 s every 20 s
	Output frequency	0...320 Hz (standard); 7200 Hz (special software)
	Frequency resolution	0.01 Hz (NXS); Application dependent (NXP)
Control characteristics	Control method	Frequency control U/f Open Loop Sensorless Vector Control Closed Loop Vector Control (NXP only)
	Switching frequency (see parameter 2.6.9)	NX_2/NX_5: Up to NX_0061: 1...16 kHz; Default: 10 kHz NX_2: NX_0075 and greater: 1...10 kHz; Def: 3.6 kHz NX_5: NX_0072 and greater: 1...6 kHz; Def: 3.6 kHz NX_6: 1...6 kHz; Default: 1.5 kHz
	<u>Frequency reference</u> Analogue input Panel reference	 Resolution 0.1% (10-bit), accuracy ±1% Resolution 0.01 Hz
	Field weakening point	8...320 Hz
	Acceleration time	0.1...3000 sec
	Deceleration time	0.1...3000 sec
	Braking torque	DC brake: 30% * T_N (without brake option)
Ambient conditions	Ambient operating temperature	–10°C (no frost)...+50°C: I_H –10°C (no frost)...+40°C: I_L –10°C (no frost)...+35°C: for IP54/Nema12 NX 520 5 and 416 6
	Storage temperature	–40°C...+70°C
	Relative humidity	0 to 95% RH, non-condensing, non-corrosive, no dripping water
	Air quality: - chemical vapours - mechanical particles	 IEC 721-3-3, unit in operation, class 3C2 IEC 721-3-3, unit in operation, class 3S2
	Altitude	100% load capacity (no derating) up to 1,000 m 1-% derating for each 100m above 1000. Max. altitudes: NX_2: 3000m; NX_5: 3000m/2000m (corner-grounded network); NX_6: 2000m
	Vibration EN50178/EN60068-2-6	5...150 Hz Displacement amplitude 1 mm (peak) at 5...15.8 Hz (FR4...9) Max acceleration amplitude 1 G at 15.8...150 Hz (FR4...FR9) Displacement amplitude 0.25 mm (peak) at 5-31 Hz (FR10...12) Max acceleration amplitude 0.25 G at 31...150 Hz (FR10...12)
	Shock EN50178, EN60068-2-27	UPS Drop Test (for applicable UPS weights) Storage and shipping: max 15 G, 11 ms (in package)
	Enclosure class	IP21/NEMA1 standard in entire kW/HP range IP54/NEMA12 option in entire kW/HP range Note! Keypad required for IP54/NEMA12

EMC (at default settings)	Immunity	Fulfils EN61800-3, first and second environment
	Emissions	Depend on EMC level. See chapters 2 and 3.
Safety		EN 50178 (1997), EN 60204-1 (1996), EN 60950 (2000, 3rd edition) (as relevant), CE, UL, CUL, FI, GOST R; (see unit nameplate for more detailed approvals)
Control connections (apply to boards OPT-A1, OPT-A2 and OPT-A3)	Analogue input voltage	0…+10V, R_i = 200kΩ, (–10V…+10V joystick control) Resolution 0.1%, accuracy ±1%
	Analogue input current	0(4)…20 mA, R_i = 250Ω differential
	Digital inputs (6)	Positive or negative logic; 18…30VDC
	Auxiliary voltage	+24V, ±10%, max volt. ripple < 100mVrms; max. 250mA Dimensioning: max. 1000mA/control box
	Output reference voltage	+10V, +3%, max. load 10mA
	Analogue output	0(4)…20mA; R_L max. 500Ω; Resolution 10 bit; Accuracy ±2%
	Digital outputs	Open collector output, 50mA/48V
	Relay outputs	2 programmable change-over relay outputs Switching capacity: 24VDC/8A, 250VAC/8A, 125VDC/0.4A Min.switching load: 5V/10mA
Protections	Overvoltage trip limit Undervoltage trip limit	NX_2: 437VDC; NX_5: 911VDC; NX_6: 1200VDC NX_2: 183VDC; NX_5: 333VDC; NX_6: 460 VDC
	Earth fault protection	In case of earth fault in motor or motor cable, only the frequency converter is protected
	Mains supervision	Trips if any of the input phases is missing
	Motor phase supervision	Trips if any of the output phases is missing
	Overcurrent protection	Yes
	Unit overtemperature protection	Yes
	Motor overload protection	Yes
	Motor stall protection	Yes
	Motor underload protection	Yes
	Short-circuit protection of +24V and +10V reference voltages	Yes

Figure III B. Technical Data

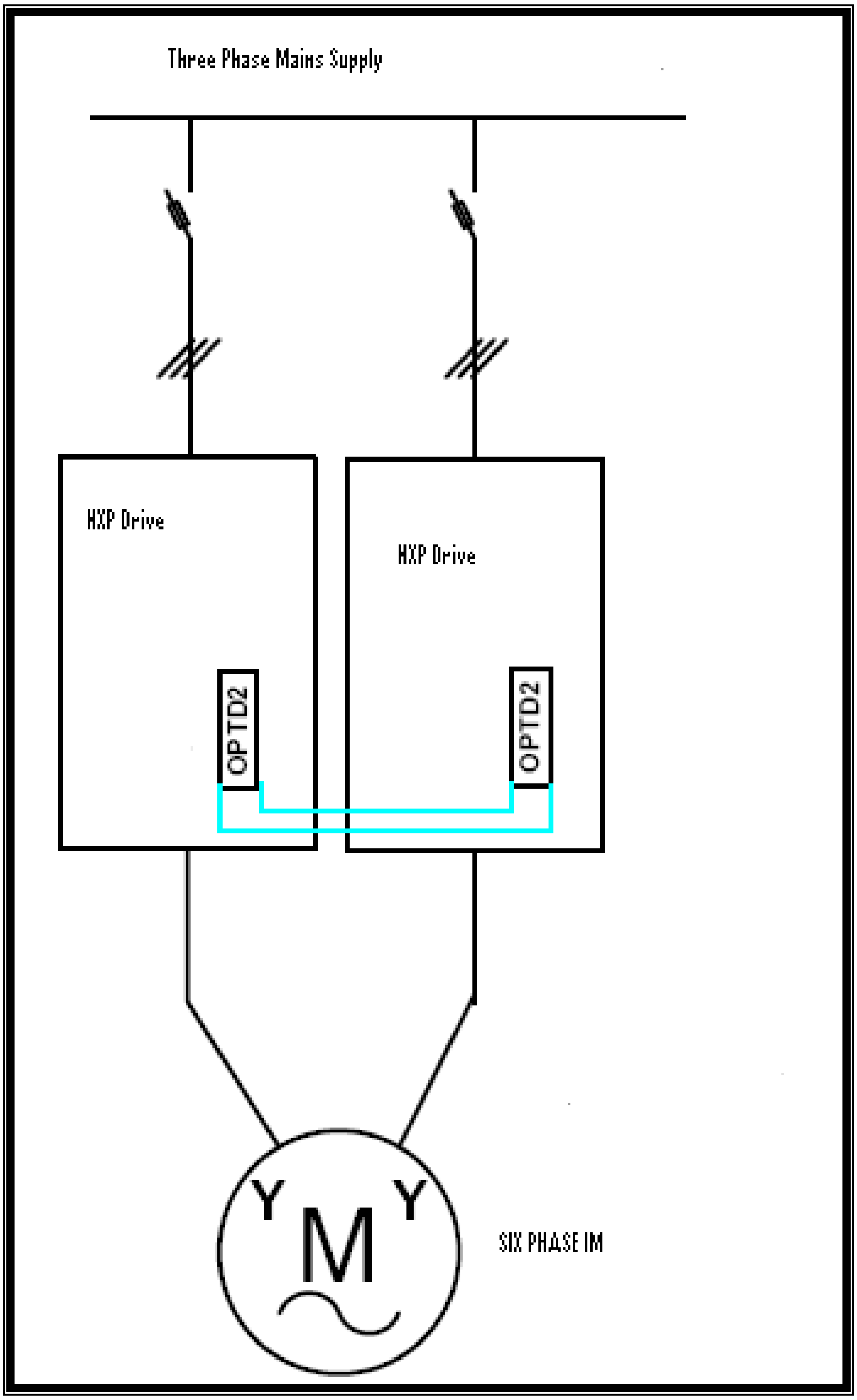
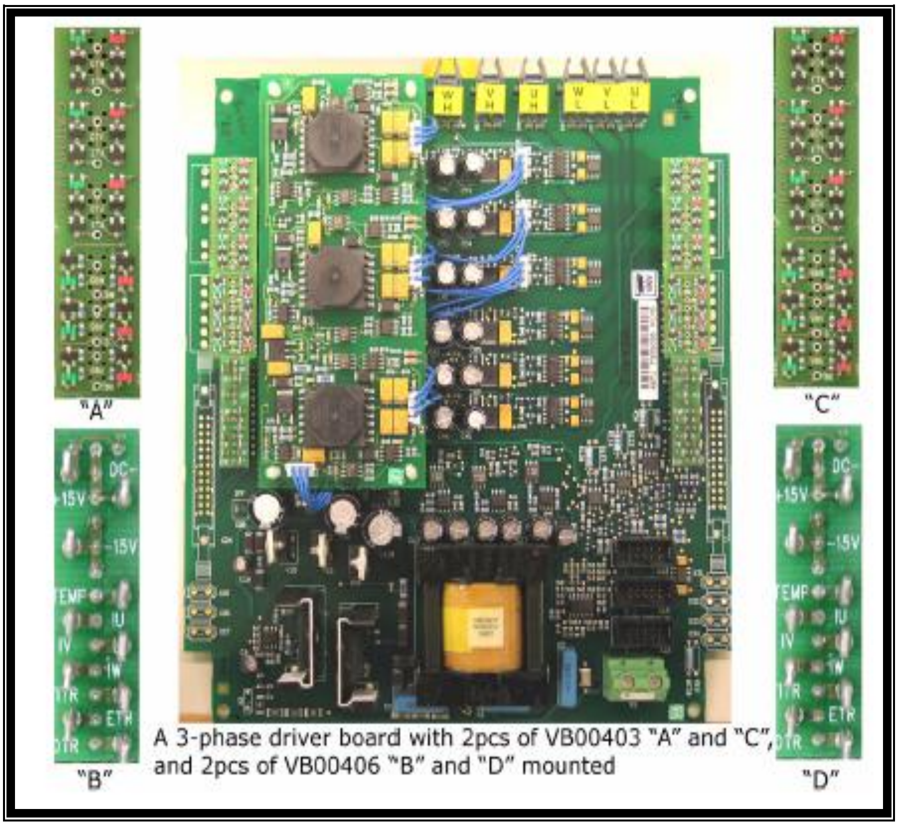


Fig.III C Multiphase IM fed from Vacon drives



Photograph of Driver Board

A:- I/O Board (Input / Output Board)

B :- Expander I/O Board

C :- Field Bus Board

E :- Special Board

M File Codings To Generate SVPWM

```
function [gp]=svpwm(t)
st=t*314;
teta=mod(st,2*pi);
s=1+fix(teta/(pi/3+1*10^-30));
v_ref=100;
vdc=200;
tz=0.000333;
fu=sqrt(3)*tz*v_ref/vdc;
t1 = fu*(sin(s*pi/3)*cos(teta)-cos(s*pi/3)*sin(teta));
t2 = fu*(cos((s-1)*(pi/3))*sin(teta)-sin((s-1)*(pi/3))*cos(teta));
t0=tz-(t1+t2);
if s==1
ta=(t1+t2+t0/2);
tb=(t0/2);
tc=(t0/2+t1);
elseif s==2
ta=(t1+t2+t0/2);
tb=(t0/2+t2);
tc=(t0/2);
elseif s==3
ta=(t0/2+t1);
tb=(t1+t2+t0/2);
tc=(t0/2);
elseif s==4
ta=(t0/2);
tb=(t1+t2+t0/2);
tc=(t0/2+t2);
elseif s==5
ta=(t0/2);
tb=(t0/2+t1);
tc=(t1+t2+t0/2);
else
ta=(t0/2+t2);
tb=(t0/2);
tc=(t1+t2+t0/2);
end
d=rem(t,tz);
sum1=ta-d;
sum2=tb-d;
sum3=tc-d;
ta1=ta(1);
tb1=tb(1);
tc1=tc(1);
time=t;
sw1=sum1(1);
sw2=sum2(1);
sw3=sum3(1);
h=d(1);
```

```
if sw1>0
va=200;
else
va=-200;
end
if sw2>0
vb=200;
else
vb=-200;
end
if sw3>0
vc=200;
else
vc=-200;
end
s11h=va(1);
s22h=vb(1);
s33h=vc(1);
vab=s11h-s22h;
vbc=s22h-s33h;
vca=s33h-s11h;
vabb=vab(1);
vbcc=vbc(1);
vcaa=vca(1);
loc2=(vabb<0);
g2=loc2;
loc4=(vbcc<0);
g4=loc4;
loc6=(vcaa<0);
g6=loc6;
g22=g2(1)*1;
g44=g4(1)*1;
g66=g6(1)*1;
loc1=(vabb>0);
g1=loc1;
loc3=(vbcc>0);
g3=loc3;
loc5=(vcaa>0);
g5=loc5;
g11=g1(1)*1;
g33=g3(1)*1;
g55=g5(1)*1;
gp=[g11,g22,g33,g44,g55,g66];
```

Universal Bridge
No of bridge arms:3
Snubber resistance(RS)= 1e5
Snubber capacitance(CS)= inf
Ron=1e-3
Power electronic device: MOSFET/DIODE

APPENDIX-IV

VACON Software details (Vacon NC1131-3)

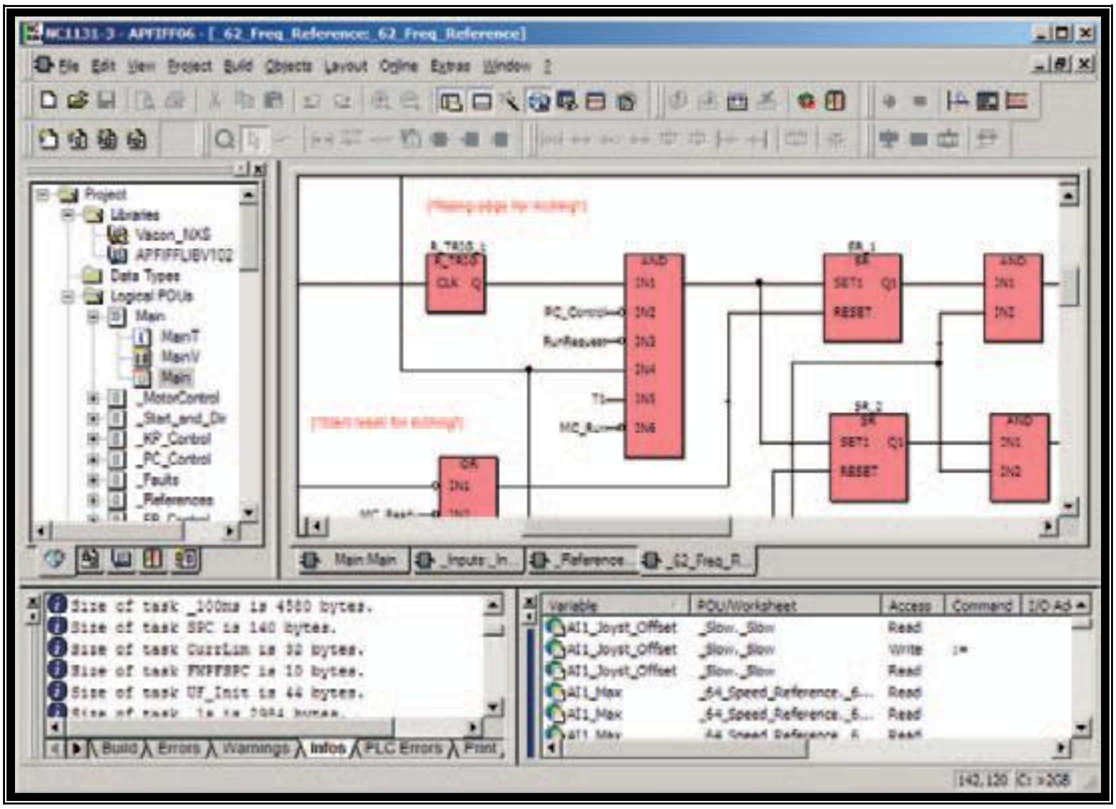
The Vacon NC1131-3 is a graphical programming tool for creating professional and efficient NX applications. It complies with the IEC 61131-3 PLC programming standard. All methods defined in the standard can be used:

- functional block diagrams
- structured text
- ladder diagrams
- instruction list and
- State diagrams.

These can be used separately or in combination.

One application can contain about 2000 blocks, depending on their size and complexity. When new applications are created, typically one of the existing applications is used as a template to minimize the effort, as the existing applications contain the majority of the functionality required.

The Vacon NC1131-3 Application Programming Suite supports many programming languages which are based on the IEC61131-3 standard. An entire application can be done in a few easy steps by using a specific tool for each programming phase. The Application Programming Suite offers a graphical programming environment for the functional design of an application.



Photograph of VACON- NC1131-3 software Screen for Block Diagram

Photograph of VACON- NC1131-3 software Screen for Parameter Setting

APPENDIX-V

Certificates from Industries

IAS-ANZ
ICS
www.jas-anz.com.au/register
ISO 9001 : 2000
Reg. No. : RQ91/5487

THE JYOTI GROUP

JSL INDUSTRIES LTD.

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Website: www.jyoti.com

8th December, 2009

TO WHOMSOEVER IT MAY CONCERN

This is to certify that Prof. Archana Nanoti, Asst.Prof. Electrical Engineering, Parul Institute of Engineering and Technology, Limda (Gujarat), has successfully completed Design of 6 Phase Induction Motor, as a part of her Ph.D. Project (Registered at MS University, Baroda), and developed a working pro-type at our Industry from December 2008 to September 2009. The pro-type is successfully Tested for its Routine Tests.

For JSL Industries Ltd.

Dr.K.K.Thakkar
Director

VACON
DRIVEN BY DRIVES

"TO WHOMSOEVER IT MAY CONCERN"

This is to certify that Prof. **Archana Nanoty**, Asst.Prof. Electrical, Parul Institute of Engineering & Technology has carried out V/f control and Sensor less vector control of six phase Induction motor (Designed by her at JSL, Mogar). And she has successfully completed the controlling of six phase Induction motor at VACON Drives & Controls Pvt Ltd, Chennai.

She worked here from 15th Dec 2009 to 20th Dec2009.
And 19th February to 25th February 2010.

Shailendra Salvi
Shailendra Salvi
Managing Director

Date: 26th Feb'2010
Place: Chennai

Vacon Drives & Controls Pvt Ltd
352, Kapaleeshwar Nagar • East Coast Road, Neelangarai • Chennai- 600041, India
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