# Chapter – VI

# 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 $\lambda_r^*$. 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 $\lambda_r^*$ 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.

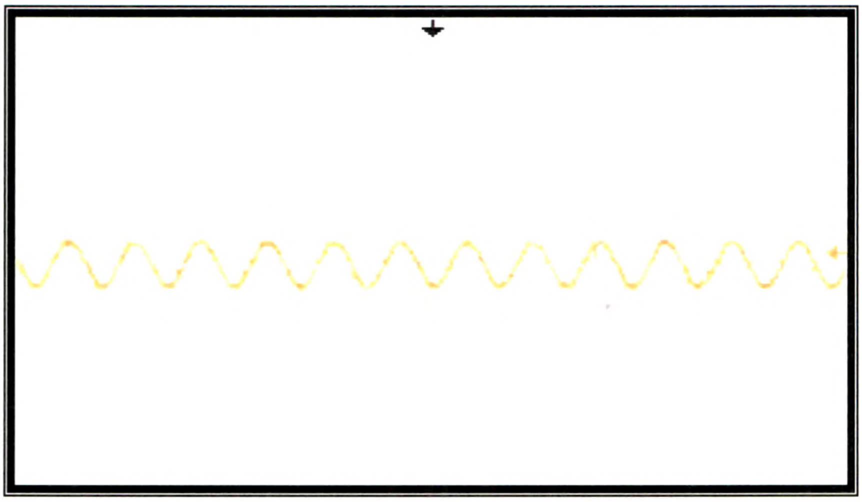

Figure 6.1 Three phase current when only one three phase set energized through inverter

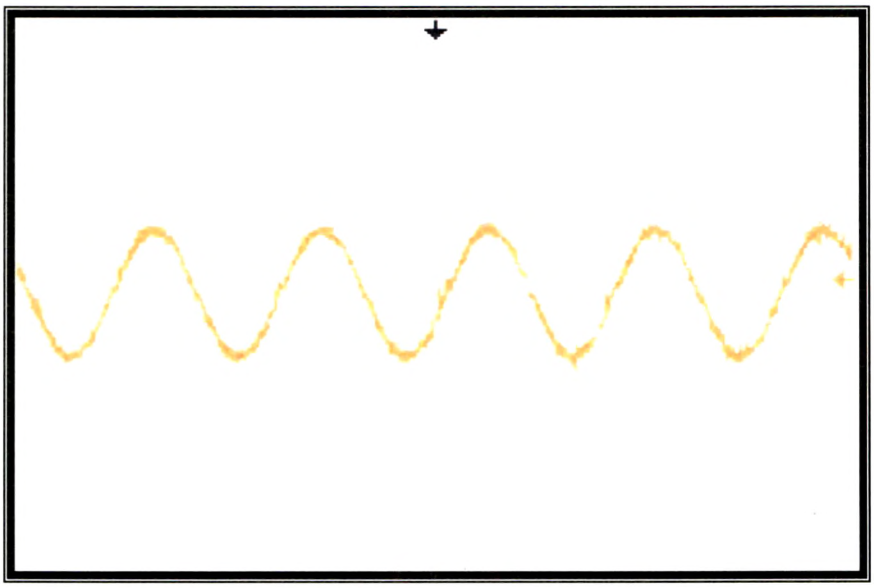

Figure 6.2 Six phase current when six phases energized through inverter

### 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)

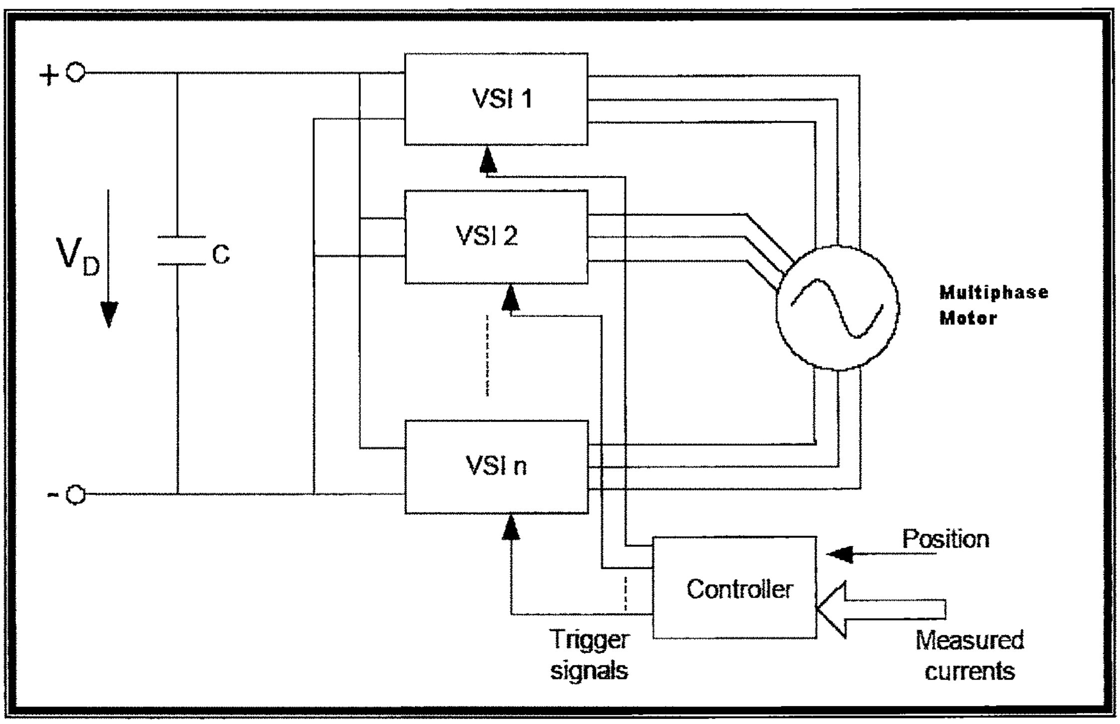


Figure 6.3 Multiphase Induction motor supplied from n number of inverters

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.

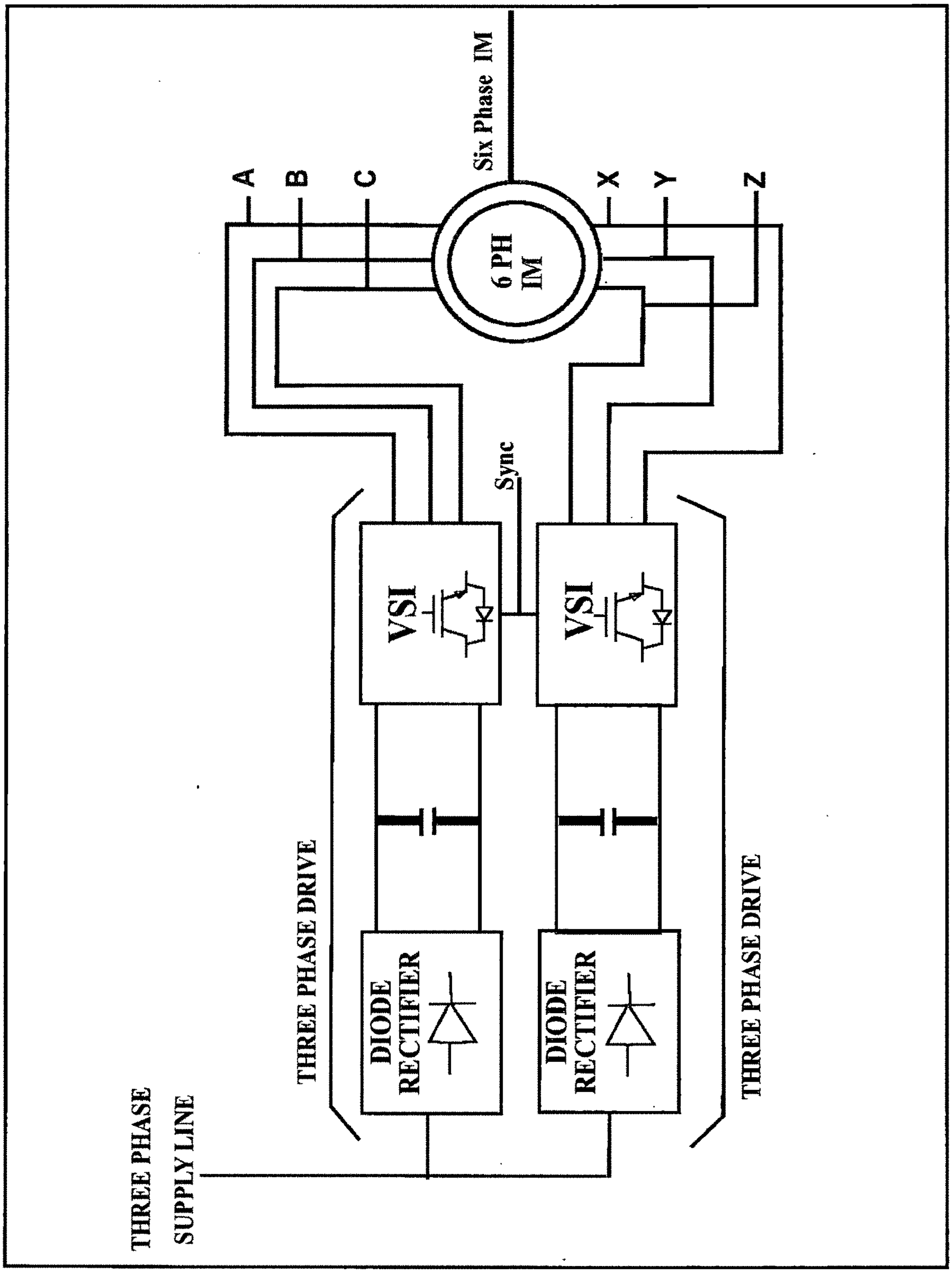


Figure 6.4 Block Diagram of six phase IM fed from two, three phase drives

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.

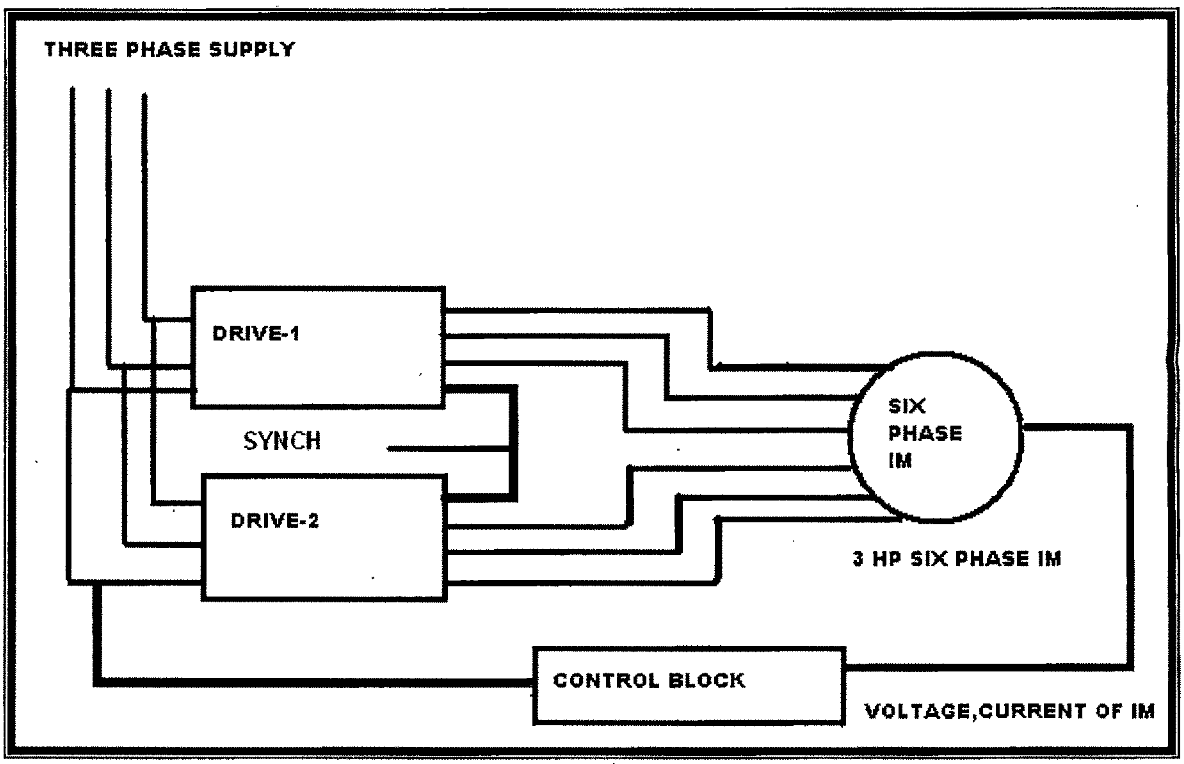


Figure 6.5 Multiphase Induction motor fed by two three phase drives with control block

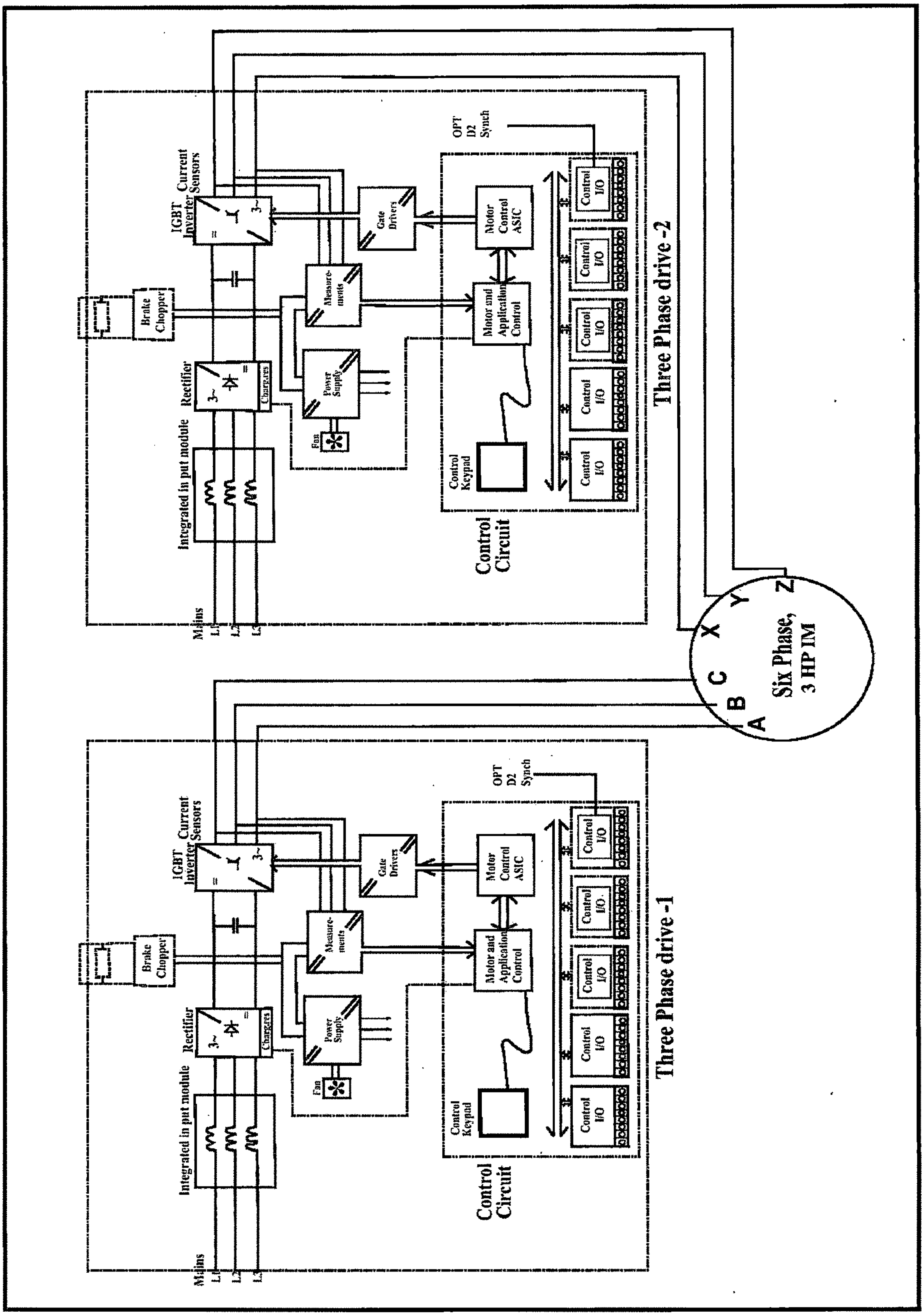


Figure 6.6 Internal circuit of two three phase Drives


**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

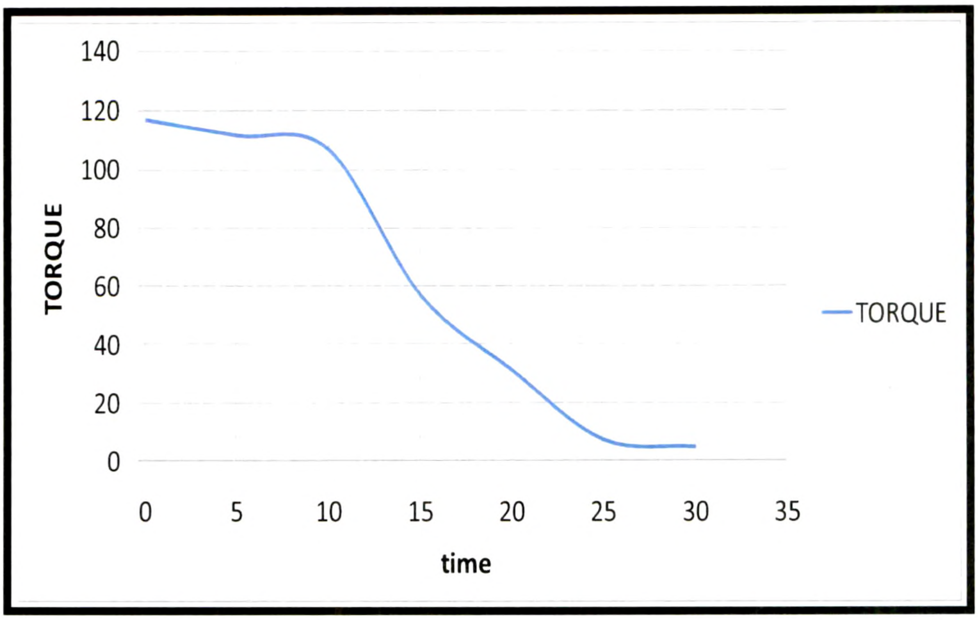


Figure 6.7 Torque of six phase IM for V/f control

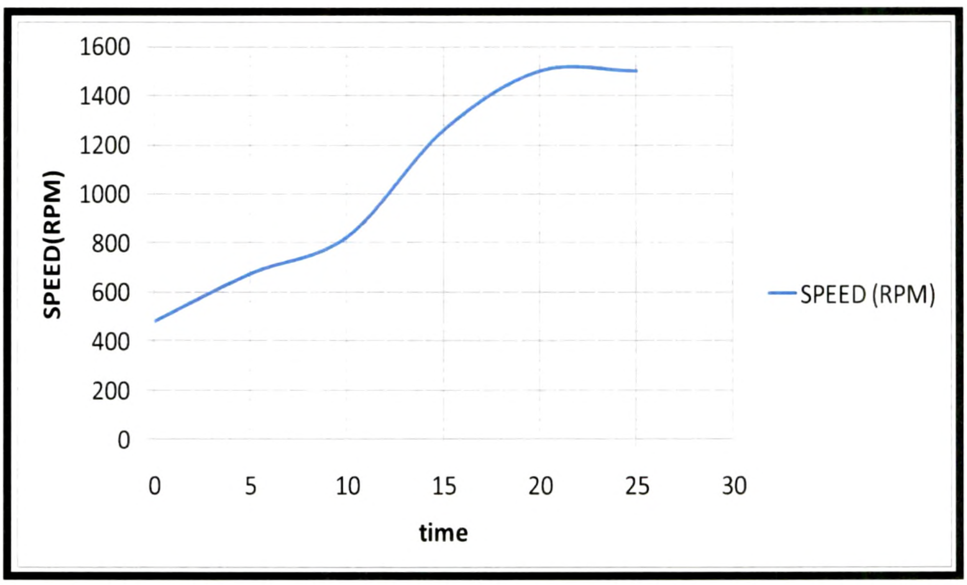


Figure 6.8 Speed of six phase IM for V/f control

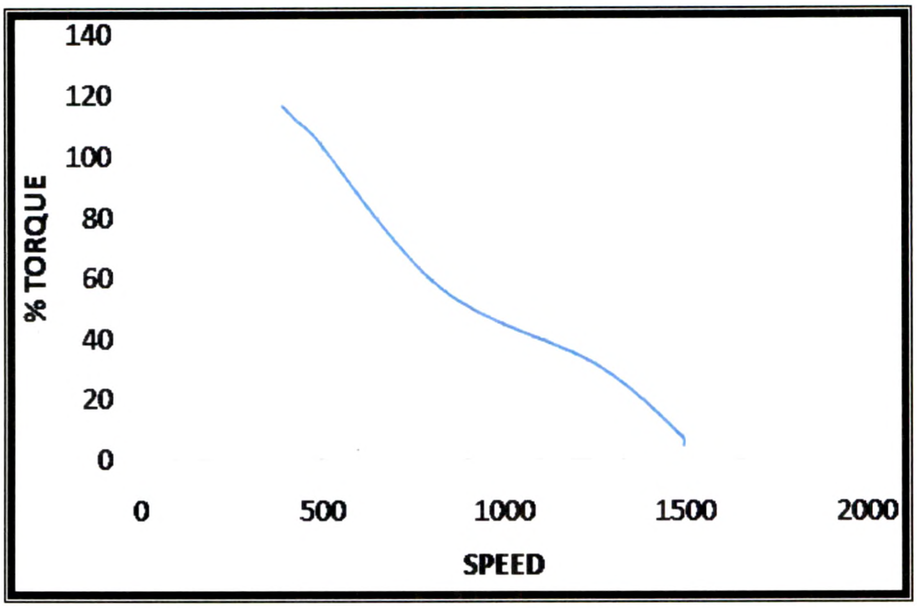


Figure 6.9 Speed Torque curve for V/f control

| 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

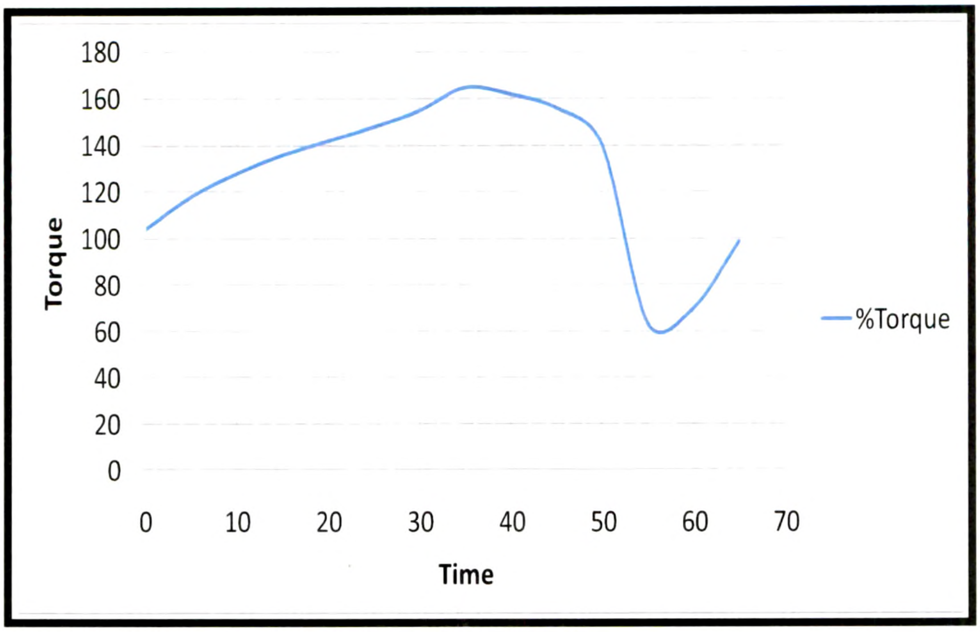


Figure 6.10Torque of Six phase IM for vector control

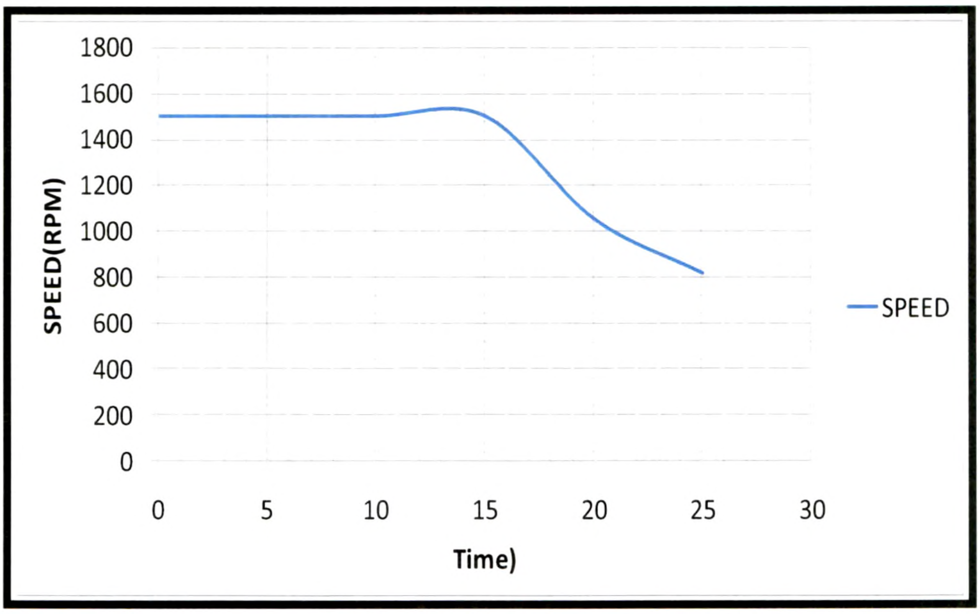


Figure 6.11 Speed of six phase IM for vector control

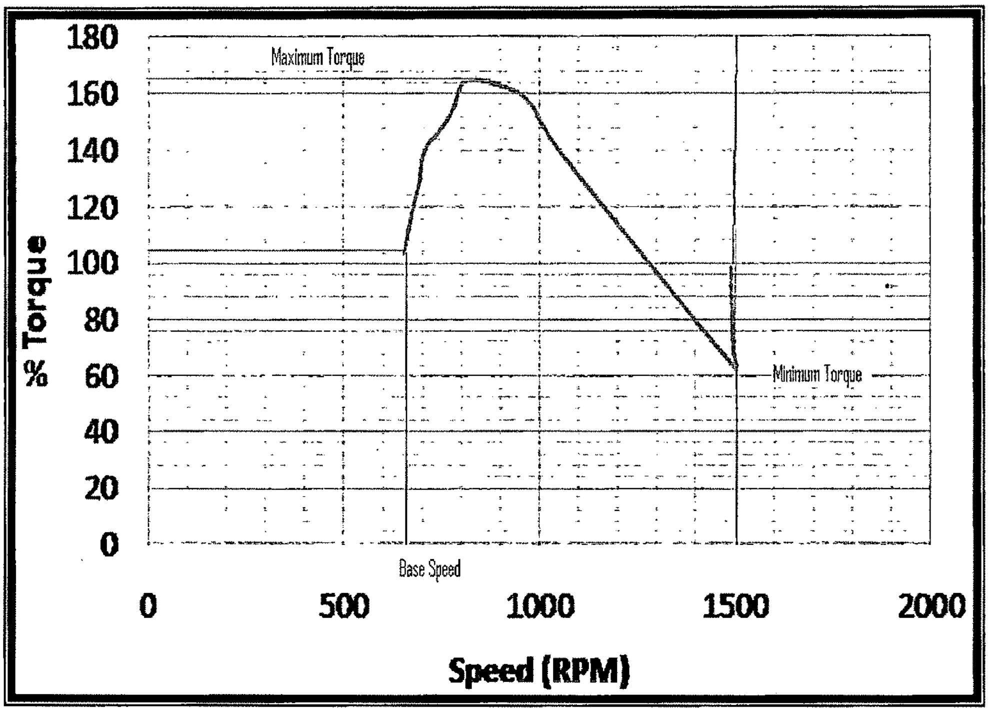


Figure 6.12 Speed-torque curve for vector control of six phase IM

## 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.