Performance Improvement of Sensorless Vector Control of Induction Motor Drive by Improving Estimation of Rotor Resistance

Major Project Report

Submitted in partial fulfillment of the requirements for
Semester-IV of

MASTER OF TECHNOLOGY
IN
ELECTRICAL ENGINEERING
(Power Electronics, Machines & Drives)

By

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(13MEEP19)

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INSTITUTE OF TECHNOLOGY
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Certificate

This is to certify that the Major Project Report (Part-II) entitled **"Performance Improvement of Sensorless Vector Control of Induction Motor Drive by Improving Estimation of Rotor Resistance"** submitted by **Mr. Kunal vashi (Roll No: 13MEEP19)** towards the partial fulfillment of the requirements for Semester-IV of Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines & Drives of Nirma University is the record of work carried out by him under our supervision and guidance.The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.
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Abstract

The induction motor is more popular for its superior performance compared to its counterparts and it is widely used in industry. The popularity of squirrel cage induction motor is attributed to its ruggedness and simplicity of construction. Induction motor finds application in number of domestic as well as industrial application.But superior control of induction motor There are two control methods like scalar control and vector control.The scalar (V/f) control method is simple and cost effective. The dynamic response of scalar control of induction motor drive is average. Vector control method of induction motor drive gives fast dynamic response .The vector control of induction motor is used instead of scalar control aims at decoupling the torque and flux producing components of stator current under all operating speed and load conditions. The main problem with Sensorless vector control induction motor drive is estimation of induction motor parameters. It is very essential to estimate the rotor resistance accurately to improve the performance of induction motor drive. This project is focused on to come with the accurate and reliable technique to estimate rotor resistance accurately

List of Figures

Contents

Chapter 1

Introduction

1.1 Controling of Induction Motor

Electrical motors provide the driving large power for a large and still increasing part of our modern industry. There are various types of electrical motors available differ in their size, operating principle, applications.But they are broadly classified in two categories: AC motors and DC motors. An electric motor designed to operate with alternating current are called Ac motors.AC motors are broadly classified in two categories: Induction motors and Synchronous motors. But Induction motor is simple, rugged and usually is cheap to produce, due to these features of induction motors are more popular in the industry. They dominate in applications at power levels vary from fractional HP to hundreds of HP.Induction motors are further classified as squirrel-cage induction motor and wound-rotor induction motor. But squirrel cage induction motor is more popular in the industry due to its simple construction, ruggedness. But control of induction motors are must be needed in order to achieve superior performance.

1 There are two fundamental directions for the induction motor control:
  - Analog: direct measurement of the machine parameters (mainly the rotor speed), which are compared to the reference signals through closed control loops;
  - Digital: estimation of the machine parameters in the sensorless control schemes(without measuring the rotor speed).

2 Classification of controlling methods of induction motor based on control signal:

- Scalar control: This provides good steady state performance. This manifests itself in the deviation of the air gap flux linkages from their set values. This variation occurs in both phase and magnitude. This techniques are

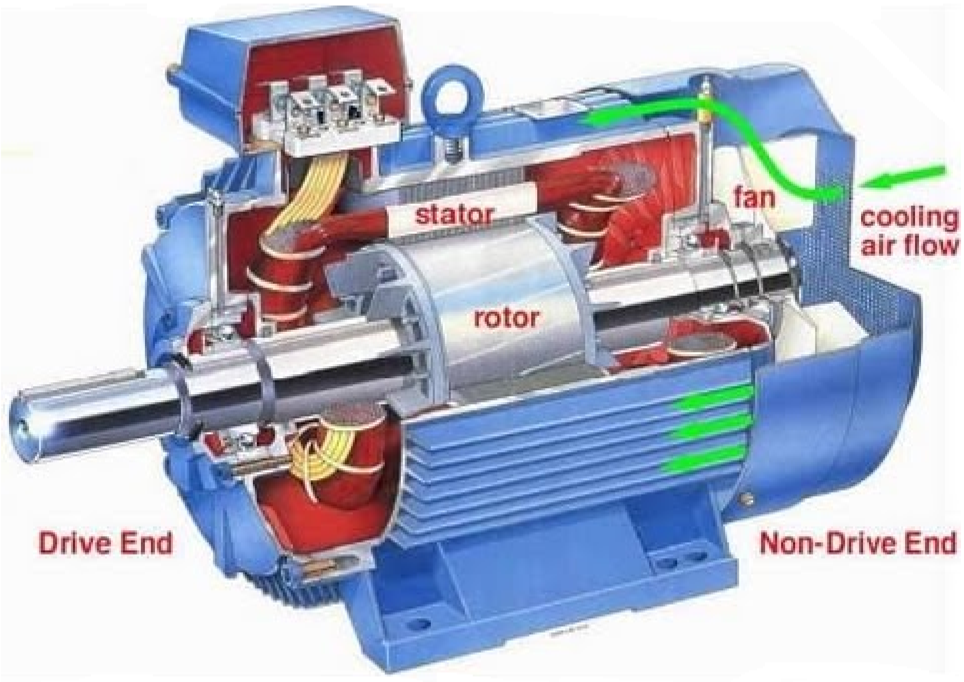


Figure 1.1: Induction Motor

mainly implemented through direct measurement of the machine parameters ;

a. Voltage/frequency (or v/f) control;

b. Stator voltage control and slip frequency control.

- Vector control:This method offers more precise control of ac motors as compared to scalar control.They are used in the high performance drives where Variations in the air gap flux linkages intolerable. This techniques are realised in both analog (direct measurements) and digital version (estimation techniques)

  a. Field Oriented Control: This includes two methods indirect method and direct method.

  b. Direct torque and stator flux vector control

1.2 What is Electric-Motor Drives?

Systems employed for motion control are called drives and may employ any of prime movers such as, diesel or petrol engines, gas or electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are called Electrical-motor drives. Figure 1.2 shows complete block diagram of electric-motor drive system.In a response to input command,electric drives effectively control the speed and the position of the mechanical load.The controller generates appropriate control signals to Power-processing unit consisting of power semiconductor devices,by comparing the input command for speed and/or position with actual values measured through Sensors The power processing unit gets its power from the utility source with 1- or 3- sinusoidal voltages of a fixed frequency and constant amplitude. The power processing unit converts these fixed-form input voltages into an output of appropriate form, i.e in frequency, amplitude and the number of phase which is suited for operating the motor. The input command comes from the computer, which generates a command to control the mechanical load.

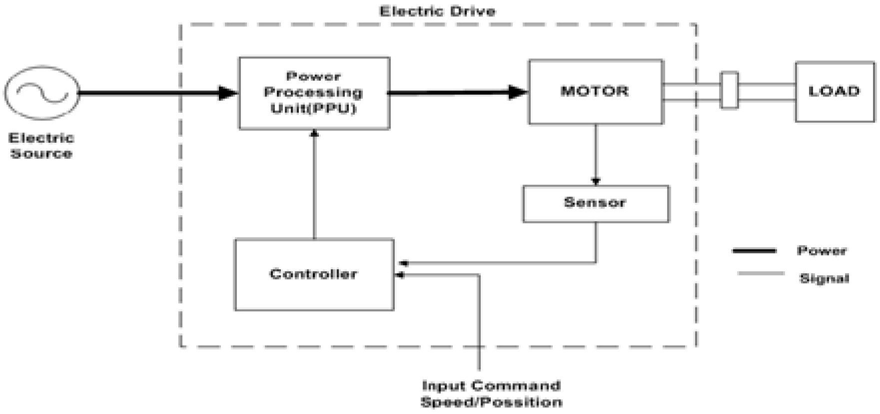


Figure 1.2: Block diagram of Electric drive system

1.3 Literature Survey

The Self-commissioning is one of the unique of feature of modern inverter-fed induction motor drives. The method is tested on the three frequency domain tests, performed at standstill, avoiding then the locked rotor test and no-load test [1]. Application of genetic algorithm, which incorporates a novel adaptive scheme, for the identification of Induction motor parameters is presented [2]. A new method of auto-tuning for vector controlled induction motor drives is presented in this paper. In auto-tuning method, algorithm is based on the rotor flux behavior of the induction motor for a stepwise torque current command [3].A novel approach for rotor resistance adaption scheme using neural learning algorithm for fuzzy logic based sensorless vector control of induction motor [4].The online rotor resistance estimation method using the transient state under the speed sensorless control of vector control is presented in this paper. Rotor resistance in the transient state without signal injection to the stator current is proposed with the help of least mean square algorithm and the adaptive algorithm [5].The basic idea about the induction motor modeling and sensorless vector control of induction motor is given in book [6][7].The another method for parameter identification of induction motor is offline identification of induction motor parameters. First DC or single phase AC is used as excitation signal, then voltage of DC bus and current of stator is measured.Then using T-form equivalent circuit parameters are estimated[8].The single phase test is used for finding equivalent circuit parameters of induction motors. In this paper, single phase test is performed using inverter. The test is performed for various frequencies. During this voltage, current and power factor is measured [9].The no load test, locked rotor test and DC test is modified under sensorless vector control of induction motor. In this no external hardware is requires. The inverter drive automatically performs DC test, no load test and locked rotor test for the driven induction motor [10].

Chapter 2

Vector control and sensorless vector control

2.1 What is Vector Control?

- Vector control, also called field-oriented control (FOC), is a variable-frequency drive (VFD) control method where the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector.One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates from the flux and torque references given by the drive's speed control the corresponding current component references. Typically proportional-integral (PI) controllers are used to keep the measured current components at their reference values. The pulse-width modulation of the variable-frequency drive defines the transistors witching according to the stator voltage references that are the output of the PI current controllers.

- FOC is used to control the AC synchronous and induction motors. It was originally developed for high-performance motor applications that are required to operate smoothly over the full speed range, generate full torque at zero speed, and have high dynamic performance including fast acceleration and deceleration. However, it is becoming increasingly attractive for lower performance applications as well due to FOC's motor size, cost and power consumption reduction superiority. It is expected that with increasing computational power of the microprocessors it will eventually nearly universally displace single-variable scalar volts-per-Hertz (V/f) control.

2.2 D.C Drive Analogy:

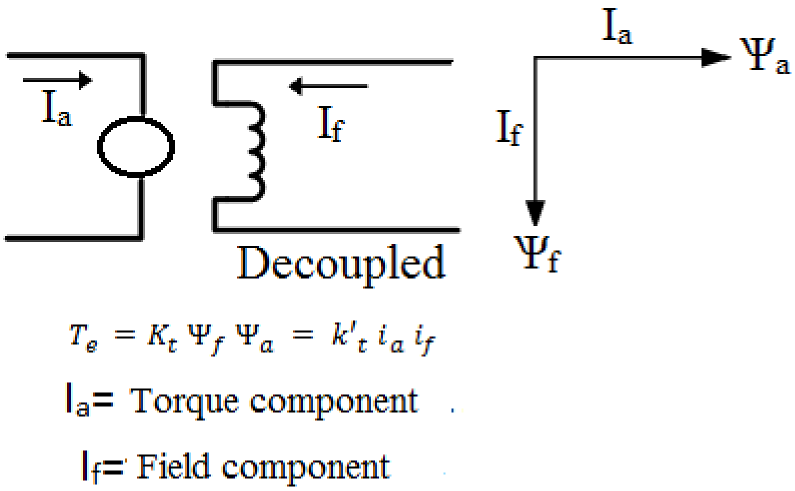


Figure 2.1: seperately Excited D.C. Motor

A vector controlled induction motor drive operates like a separately excited D.C motor drive,as shown in figure2.1.In a D.C machine,neglecting the armature reaction effect and field saturation , the devloped torque is given by:

$$T_e^{'} = K_t * I_a * I_f \tag{2.1}$$

where Ia= armature current If= field current The construction of D.C machine is such that the field flux produced by the current If is perpendicular to the armature flux,which is produced by the armature current Ia . Because the vectors are orthogonal, they are decoupled,i.e.The field current only controls the field flux and the armature current only controls the armature flux. D.C. Motor-like performance can be achived with an induction motor if the motor control is considered in the synchronously rotating reference frame (de-qe) where the sinusoidal variables appear as dc quantities in steady state.
I_{ds}(induction motor) = I_f (dc motor)
I_{qs}(induction motor) = I_a (dc motor)
Thus the torque is given by:

$$T_e = K_t * \Psi_r * i_{qs} = K_t * i_{ds} * i_{qs} \tag{2.2}$$

Where Ψ_r is a peak value of sinusoidal space vector.

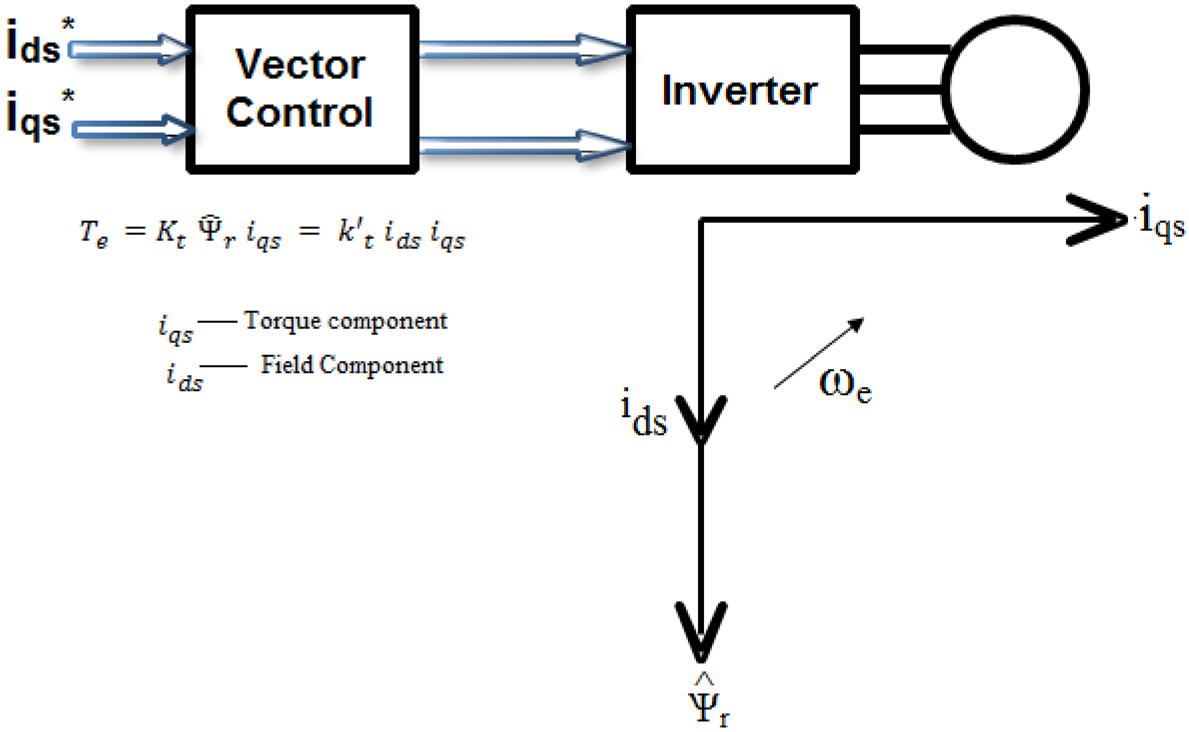


Figure 2.2: Indution motor with vector control

2.3 Equivalent Circuit:

The complex d_e-q_e equivalent circuit of an induction motor is shown in the below figure2.3 (neglecting rotor leakage inductance).Since the rotor leakage inductance has been neglected, the rotor flux $\Psi_m = \Psi_r$ the air gap flux.The stator current vector I_s is the sum of the i_{ds} and i_{qs} vectors.Thus, the stator current magnitude related to i_{ds} and i_q.

2.4 Phasor Diagrams for Induction Motor

The steady state phasor (or vector) diagrams for an induction motor in the de-qe(synchronously rotating) reference frame are shown below: The rotor flux vector $\Psi_r(= \Psi_m$) is aligned with the de axis and the air gap voltage is aligned with the q_e axis. The terminal voltage V_s slightly leads the air gap voltage because of the voltage drop across the stator impedance. iqs contributes real power across the air gap but i_{ds} only contributes reactive power across the air gap.The first figure shows an increase in the torque

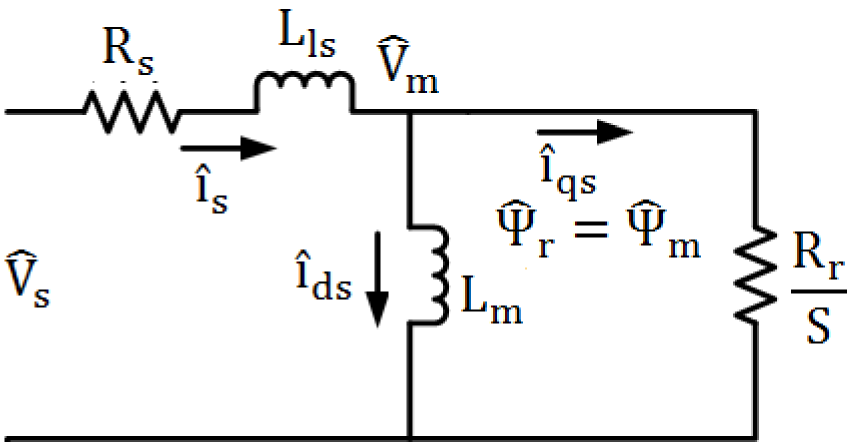


Figure 2.3: Equivalent Circuit: complex(qds) equivalent circuit in steady state(rotor leakage inductance neglected)

component of current i_{qs} and the second figure shows an increase in the flux component of current, i_{ds}. Because of the orthogonal orientation of these components, the torque and flux can be controlled independently. However, it is necessary to maintain these vector orientations under all operating conditions.

2.5 Principles of Vector Control

- The basic conceptual implementation of vector control is illustrated in the below block diagram
- The motor phase currents, ia, ib and ic are converted to idss and iqss in the stationary reference frame. These are then converted to the synchronously rotating reference frame d-q currents, ids and iqs
- In the controller two inverse transforms are performed:

  1 From the synchronous d-q to the stationary d-q reference frame

  2 From d*-q*to a*, b*, c*

- Direct field oriented current control: here the rotation angle of the iqse vector with respect to the stator flux qrs is being directly determined (e.g. by measuring air gap flux)

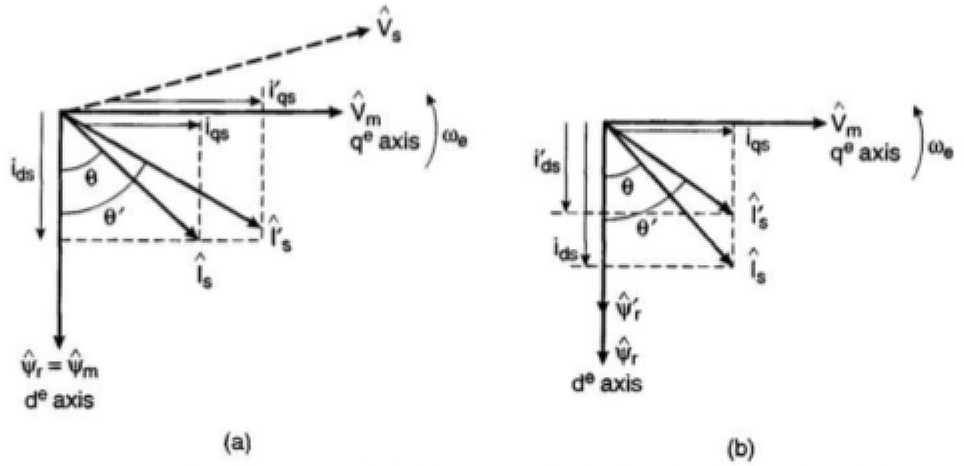


Figure 2.4: steady state phasor(a)increase of torque component of current (b) increase of fluxcomponent of current

- Indirect field oriented current control: here the rotor angle is being measured indirectly, such as by measuring slip speed

2.6 Sesnsorless vector control of induction motor drive

- Sensorless Vector control of an induction motor drive essentially means vector control without any speed sensor.
- Where efficiency, low cost, and control of the induction motor drive is a concern, the sensorless Field Oriented Control (FOC), also known as vector control, provides the best solution
- It makes use the dynamic equations of the IM to estimate the rotor speed component for control purposes. Estimation is carried out using the terminal voltages and currents which are readily available using sensors.
- Sensor less vector control induction motor drive essentially means vector control without any speed sensor.
- An incremental shaft mounted speed encoder, usually an optical type is required for closed loop speed or position control in both vector control and scalar controlled drives. A speed signal is also required in indirect

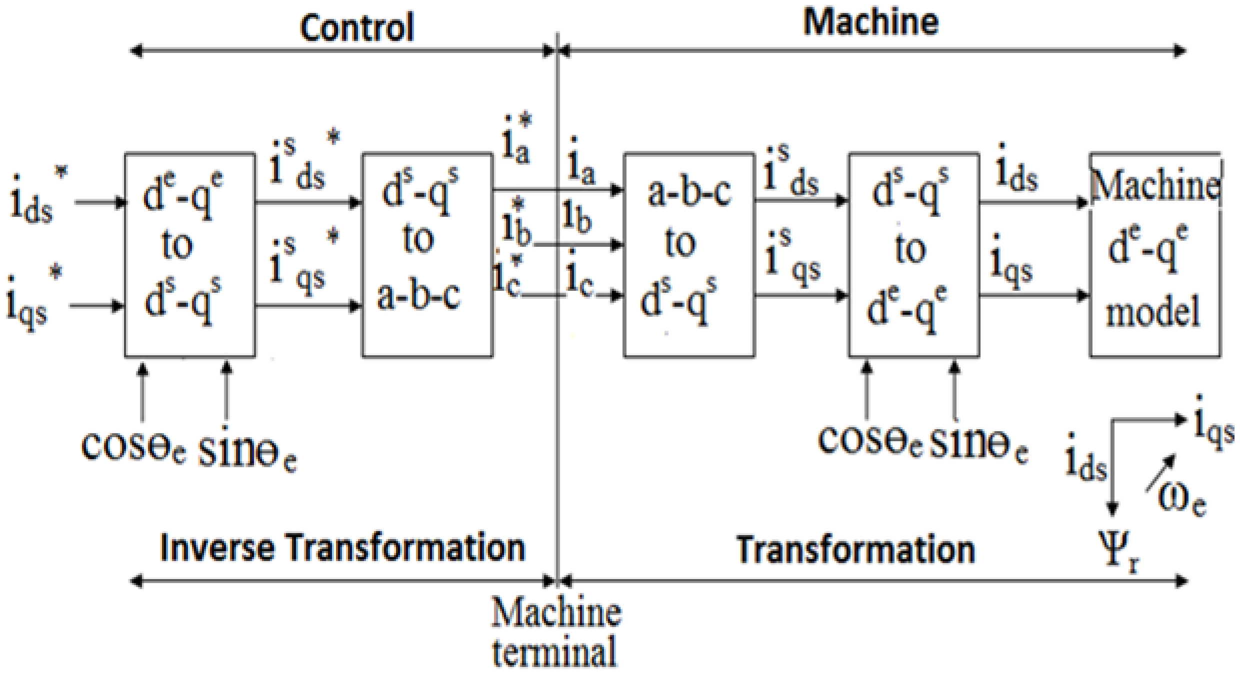


Figure 2.5: vector control implementation principles with machine de-qe model

vector control in the whole speed range and in direct vector control for the low speed range, including the zero speed start up operation.

- Controlled induction motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability.
- Drives operating in hostile environments or in high speed drives speed sensors cant be mounted. To replace the sensor the information on the rotor speed is extracted from measured stator voltages and currents at the motor terminals.
- The Schematic diagram of control strategy of induction motor with Sensorless control is shown in figure 2.6.Sensorless controlled induction motor drive essentially means vector control without any speed sensor .
- The inherent coupling of motor is eliminated by controlling the motor by vector control,like in the case of as a separately excited motor.
- The inverter provides switching pulses for the control of the motor.The flux and speed estimator are used to estimate the flux and speed respectively.These signals then compared with reference values and controlled by using the PI controller.

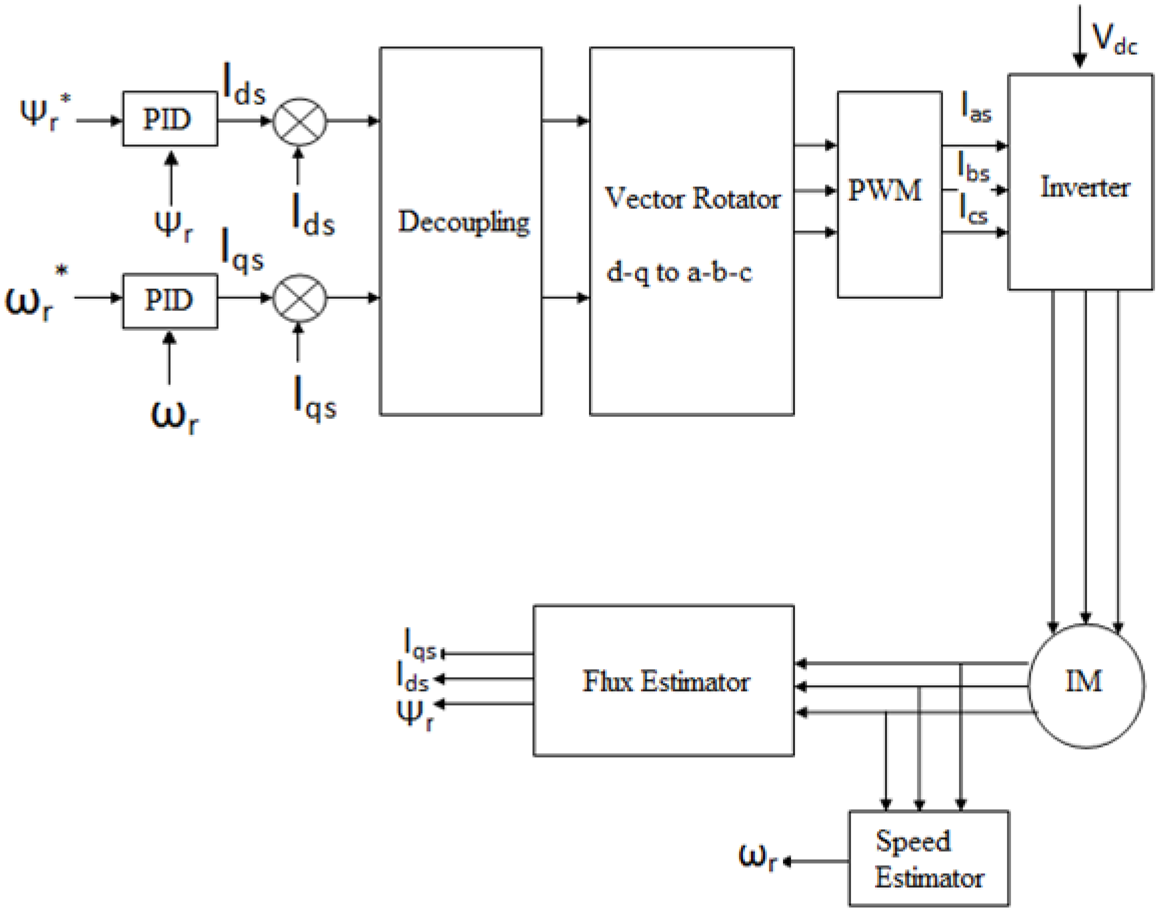


Figure 2.6: Basic block diagram of Sensorless control of induction motor

Chapter 3

Methods of Estimation of Rotor Resistance

For the high-performance sensor-less vector control of an induction motor, the accuracy of the motor parameters has an important impact on the performance of the whole system. The parameters of equivalent circuit of Induction Machines are crucial when considering advanced control techniques (i.e. Vector Control). Accidentally these are also uncertain parameters when the machine is released from production. The most common ways, to manually determine induction motor parameters, are to test motor under no-load and locked rotor conditions.

3.1 Conventional Methods:

1 **NO-LOAD TEST** The no-load test, similar to the open circuit test on a transformer, gives data about energizing present and rotational misfortunes. The test is performed by applying adjusted appraised voltage on the stator windings at the evaluated recurrence. The little power gave to the machine is because of center misfortunes, grating and winding loses.Machine will turn at verging on nonconcurrent speed, which makes slip almost zero. This test is spoken to with an equal circuit in Figure 3.1 .Values measured amid this test are present and it s point concerning know voltage. From this we can figure all out force supplied to the machine. Expecting that Rc is much greater than Rs and Xlr we can ascertain Rc and Lm from the proportional circuit.

2 **LOCKED ROTOR TEST** The locked rotor test, similar to short out test on a transformer, gives the data about spillage impedances and rotor resistance. Rotor is at the stop, while low voltage is connected to stator

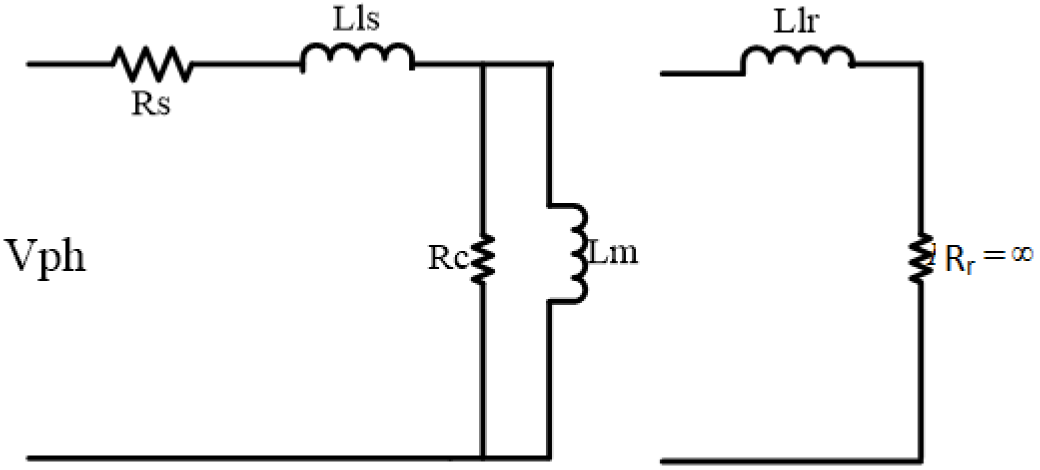


Figure 3.1: Equivalent Circuit for No-Load Test

windings to circle evaluated current. Measure the voltage and energy to the stage. Since there is no turn slip, s=1 which gives us taking after proportionate circuit. Note that Rr is a great deal not exactly Rc so that part of the circuit is overlooked.

3 **DC Measurement** DC Measurement test is used to determine the stator resistance (RS).This test consists of applying a DC voltage to one stator winding. The DC voltage and current are measured, and the RS value is computed by dividing both measurements.

3.2 Drawbacks of the conventional methods

- It is usually realized that the information required for figuring the execution of an IM under burden operation can be acquired from the aftereffects of a no-heap test, a blocked rotor test, and estimations of the dc resistances of the stator windings. So as to perform these tests, two challenges are confronted: i) it is hard to obstruct the rotor when the engine is fused inside a framework, ii) the no-heap test is commonly difficult to perform practically speaking, in light of fan and rigging misfortunes or basically on the grounds that the machine can't turn without burden.

- The another fundamental hindrance of this strategy is that the engine must be bolted mechanically and tests must be done by gifted administrators. Also, most minimal effort applications require an inverter which

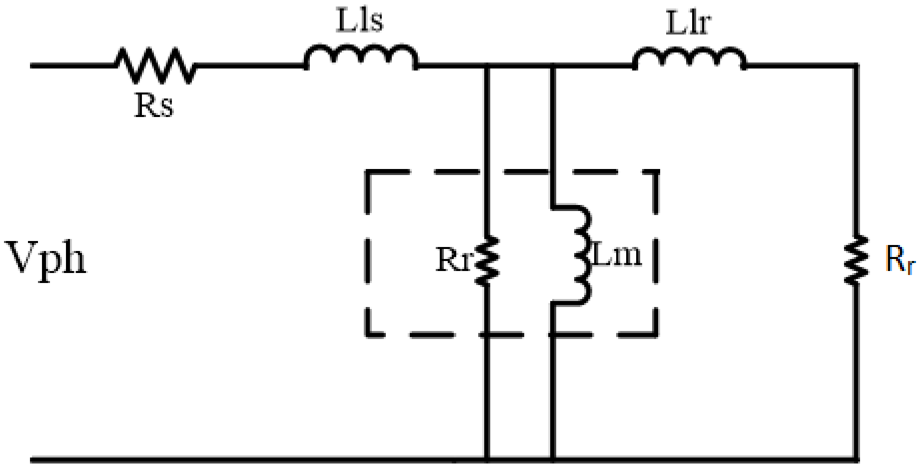


Figure 3.2: Equivalent Circuit for Locked Rotor Test

can be rapidly set up by the plant engineer and each establishment requires the tuning to various engines with various parameters.

- The mechanical obstructing of the machine can be excluded by substituting the three-stage blocked-rotor test by a solitary stage test. No torque is then created and the electric conduct of the machine is practically the same as on account of three stage excitation .When working inside the straight range there is no serious distinction identified with the electric conduct of the machine at three-and single-stage excitation. Be that as it may, in the immersion range at the three-stage excitation, the charging inductance is marginally bigger than that on account of single stage excitation. This impact is because of third request music, which show up at three-stage excitation in the winding voltages. These music counterwork the wellsprings of immersion and as an outcome the successful polarizing inductance is marginally bigger than on account of single-stage excitation, where such music can not happen.

- The no-load test also can be omitted and substituted with the single-phase test. If making several single-phase tests, for various frequencies at a constant stator-flux level, the locus curve of the stator current can be drawn.

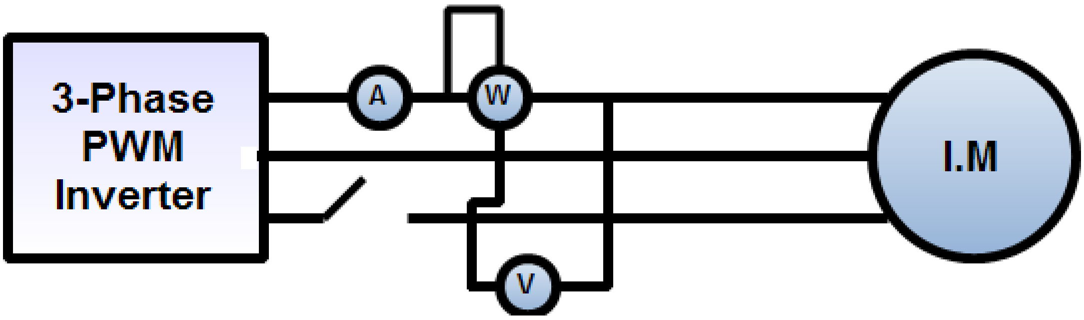


Figure 3.3: Circuit diagram for the single-phase test

3.3 Single Phase Test

To permit a simple execution of the proposed strategy utilizing a microchip, the ECP ought to be computed in light of an arrangement of conditions utilizing the single-stage test results at two estimations of the essential recurrence. Actually, the two qualities (fl, f2) if the recurrence ought to be close to stay away from the way that rotor parameters may fluctuate as a component of recurrence. The single-stage test is performed utilizing the circuit outline appeared as a part of Fig. 1 in which the connections between three-stage and the single-stage engine variables can be communicated as takes after,

$$E_{3p} = \sqrt{\frac{3}{2}} * E_{1p} \tag{3.1}$$

$$P_{3p} = \sqrt{\frac{3}{2}} * P_{1p} \tag{3.2}$$

where E and P designate the voltage and the power respectively.
The most commonly used IM models in motor drives and control applications are the

1 T-form circuit

2 Inverse T circuit

3 τ form circuit

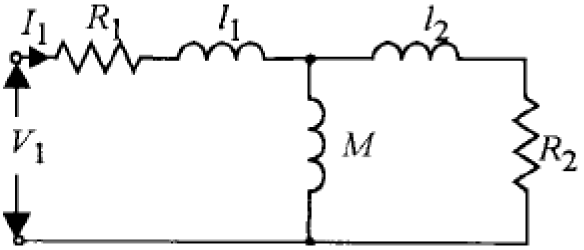


Figure 3.4: T-form circuit

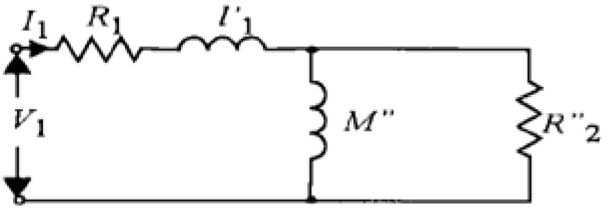


Figure 3.5: Inverse T circuit

The parameters of the τ-and the inverseT form circuits can be expressed in terms of the T-form circuits parameters as follows.

$$M' = L_2 = I_2 + M \tag{3.3}$$

$$I_2 = \frac{L_2}{M} * I_1 + \sqrt{(\frac{L_2}{M})} * I_2 \tag{3.4}$$

$$R_2' = \sqrt{(\frac{L_2}{M})} * R_2 \tag{3.5}$$

$$M'' = \frac{M^2}{L_2} \tag{3.6}$$

$$I' = I_1 + M - \frac{M^2}{L_2} \tag{3.7}$$

$$R_2' = \sqrt{(\frac{M}{L_2})} * R_2 \tag{3.8}$$

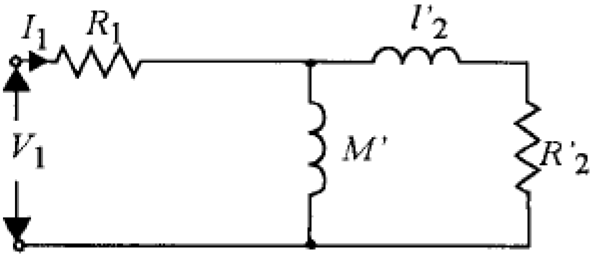


Figure 3.6: τ form circuit

3.4 Equivalent Circuit Parameters Calculation

1 T-form circuit

According to fig 3.4,the equivalent impedance is calculated as follows.

$$Z_{eq} = R_1 + jX_1 + jX_m\frac{(R_2 + jX_2)}{R_2} + j(X_m + X_2) = R_{eq} + jX_{eq} \quad (3.9)$$

Considering that the stator leakage inductance l1 is equal to the rotor leakage Inductance l2,the equivalent circuit impedance can be expressed as

$$Z_{eq} = \frac{V_1}{I_1} = R_{eq} + jX_{eq} \quad (3.10)$$

$$R_{eq} = \frac{V_1}{I_1 cos\phi} = R_1 + \frac{R_2 X_m^2}{R_2^2 + (X_m + X_2)^2} \quad (3.11)$$

$$X_{eq} = \frac{V_1}{I_1 sin\phi} = X_2 + (X_m R_2^2 + \frac{X_m X_2 (X_m + X_2)}{R_2^2} + (X_m + X_2)^2) \quad (3.12)$$

Where,
$cos\phi = \frac{P_{3p}}{3V_1 I_1}$
$sin\phi = \sqrt{1 - cos\phi^2}$

Considering R2eq=Req-R1,X2=wl2,Xm=wM and L2=l2+M,and assuming that ,for two angular frequencies w1,w2 the motor parameters remain unchanged,the motor parameters at any angular frequency can be expressed as follows :

$$R_2 = (R_{2eq}(w_2) * X_{eq}(w_1) - R_{2eq}(w_1) * w_1/w_2)/(X_{eq}(w_1)/X_{eq}(w_1) - w_1/w_2) \tag{3.13}$$

$I_2 = L_2$ - M

$$L_2 = \frac{X_{eq}(w1)}{R_2 - R_{2eq}(w_1)} \times \frac{R_2}{w_1} \tag{3.14}$$

$$M = \frac{1}{w1} \times \sqrt{\frac{R_{2eq}(w1) * (R_2^2) + (w_1 L_2)^2}{R_2}} \tag{3.15}$$

2 τ - form circuit

According to Fig.3.6 the equivalent circuit impedance takes the following expression:

$$Z_{eq} = R_1 + \frac{jX'_m(R'_2 + jX'_2)}{R'_2 + j(X'_m) + X_2} = \frac{V_1}{I_1} = R_{eq} + jX_{eq} \tag{3.16}$$

$$R_{eq} = \frac{|V_1|}{|I_1|} cos\phi = R_1 + \frac{R'_2 X'^2_m}{R'^2_2 + (X'_m + X'_2)^2} \tag{3.17}$$

$$X_{eq} = \frac{|V1|}{|I1|} sin\phi = \frac{X'_m R'^2_2 + X'_m X'_2(X'_m + X'_2)}{R'^2_2 + (X'_m + X'_2)^2} \tag{3.18}$$

Considering X2=wl2, Xm=wM and L2=l2+M, and assuming that ,for two angular frequencies w1 and w2, the motor parameters remain unchanged , the motor parameters at any frequency can be expressed as follows.

$$M' = \frac{R_{2eq}(w_1) \times \frac{X_{eq}(w_2)}{w_2} - R_{2eq}(w2) \times \frac{X_{eq}(w_1)}{w_1}}{R_{2eq}(w_1) - R_{2eq}(w_2)} \tag{3.19}$$

$$R'_2 = \frac{(w_1 M')^2 * R_{2eq}(w_1)}{R^2_{2eq}(w_1) + (w_1 M' - X_{eq}(w_1))^2} \tag{3.20}$$

$$I'_2 = \frac{w_1 M' - X_{eq}(w_1)}{w_1 R_{2eq}(w_1)} R'_2 - M' \tag{3.21}$$

3 Inverse τ-form circuit
According to Fig.3.5 the equivalent circuit impedance takes the following expression:

$$Z_{eq} = R_1 + jX_1^{'} + \frac{jX_m^{''}R_2^{''}}{R_2^{''} + X_m^{''}} = \frac{V_1}{I_1} = R_{eq} + jX_{eq} \tag{3.22}$$

$$R_{eq} = \frac{|V_1|}{|I_1|} cos\phi = R_1 + \frac{R_2^{''}X_m^{''2}}{R_2^{''2} + X_m^{''2}} \tag{3.23}$$

$$X_{eq} = \frac{|V1|}{|I1|} sin\phi = X_1^{'} + \frac{X_m^{''}R_2^{''2}}{R_2^{''2} + X_m^{''2}} \tag{3.24}$$

Considering X1 =wl1,X=wM,and assuming that for two angular frequencies w1 and w2,the motor parameters remain unchanged ,the motor parameters at any frequency can be expressed as follows.

$$R_2^{''} = \frac{R2eq(w2) \times R2eq(w1) \times (w_1^2 - w_2^2)}{R2eq(w2) \times w_1^2 - R2eq(w1) \times w_2^2} \tag{3.25}$$

$$M^{''} = \frac{R_2^{''}}{w_1} \times \sqrt{|\frac{R_{2eq}(w_1)}{R_{2eq}(w_1) - R_2^{''}}|} \tag{3.26}$$

$$I_1^{'} = \frac{X_{eq}(w_1)}{w_1} - \frac{M^{''}R_2^{''2}}{R_2^{''2} + (w_1M^{''})^2} \tag{3.27}$$

a. ALGORITHM FOR ECP IDENTIFICATION

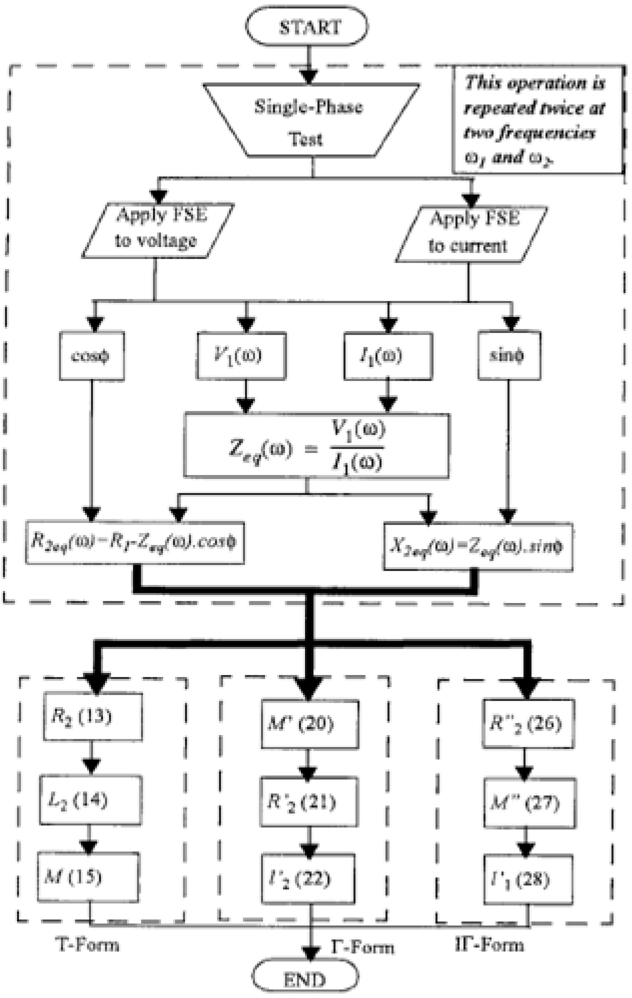


Figure 3.7: Algorithm for computing motor parameters

The stator resistance Rs is measured using the inverter as a chopper and the remaining parameters are determined based on the results of the single-phase test. Fig. 3.7 shows the flowchart of the algorithm for computing motor parameters for the three equivalent circuits described above. The single-phase test is performed at two different angular frequencies w1 and w2 of the voltage supply. For each frequency, the rms values of the voltage V1(w) and the current I1(w) as well as the sine and cosine value of their phase angle (ϕ)are calculated using the Fourier Series Expansion (FSE) method.The real part and the imaginary part of the equivalent impedance are then calculated.Finally, the equivalent circuit parameters of all three models are calculated using the set of equations given in section. The same procedure can be repeated for different sets of angular frequencies w1 and w2 which makes it possible to determine their effect on motor parameters. This routine along with the FSE routine are incorporated in the V/f PWM control program. The advantages of using such a PWM control algorithm are its simplicity and the easy implementation of the FSE method for the calculation of the voltage and current fundamental components.

3.5 The Modified DC Test

In the programmed DC Test ,the inverter needs to assume the part of an extra DC power supply for measuring stator of winding resistance. Fig 3.8 is the Connection of the Inverter and the three stator windings.In this altered DC test , the same control signs are connected to the stage b and stage c legs of inverter. Along these lines stage b leg of inverter is equally shorted to the stage c.The inverter Phase a yield current is sent into the stage a winding and is shared by stage b and stage c.The current in the stage a winding is conformed to appraised value,and the voltage between the terminals is measured .The current in the stator winding is changed in accordance with warmth the windings to temperature they would have amid ordinary operation.The identical circuit is appeared in Fig. 3.8 and stator winding resistance can be found.

$$R_s = 2V_{ab}/3I_a \tag{3.28}$$

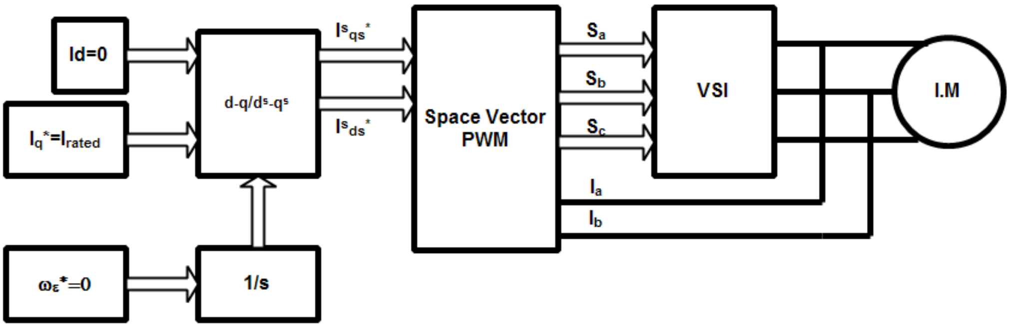


Figure 3.8: Block Diagram for modified DC test

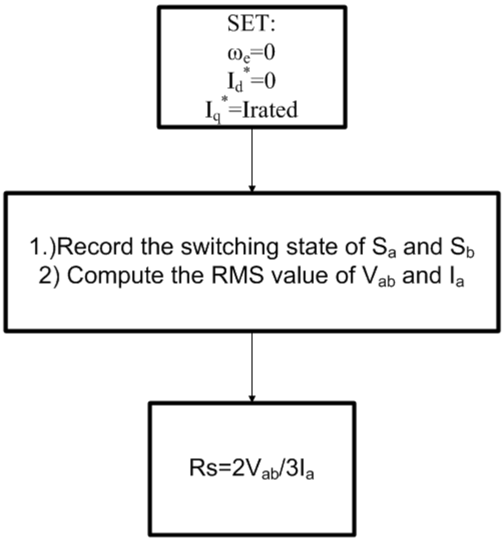


Figure 3.9: Flow chart

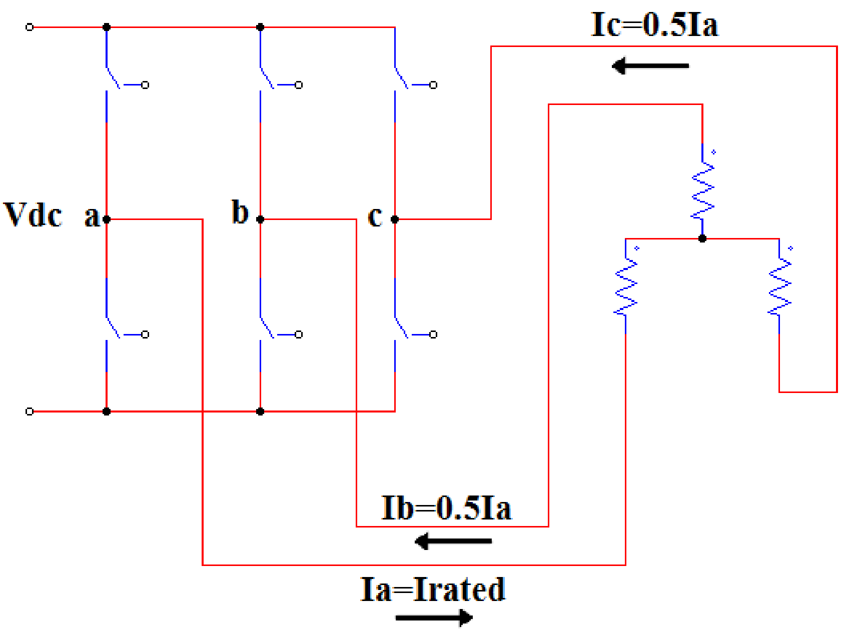


Figure 3.10: Inverter-motor connection

3.6 No-Load Test

The conventional no-load test provides the information about the magnetization induction Lm and magnetization current.The test setup for the conventional no-load is shown in figure.Two wattmeters,a voltmeter,and three ammeters are used.

$$|Z_{eq}| = V/I_{nl} = X_{ls} + X_m \tag{3.29}$$

$$|R_{eq}| = (p_1 + p_2)/(3 * I_{nl}) \tag{3.30}$$

$$|X_{eq}| = \sqrt{Z_{eq}^2 - R_{eq}^2} \tag{3.31}$$

$$L_m + L_{ls} = X_{eq}/W_e \tag{3.32}$$

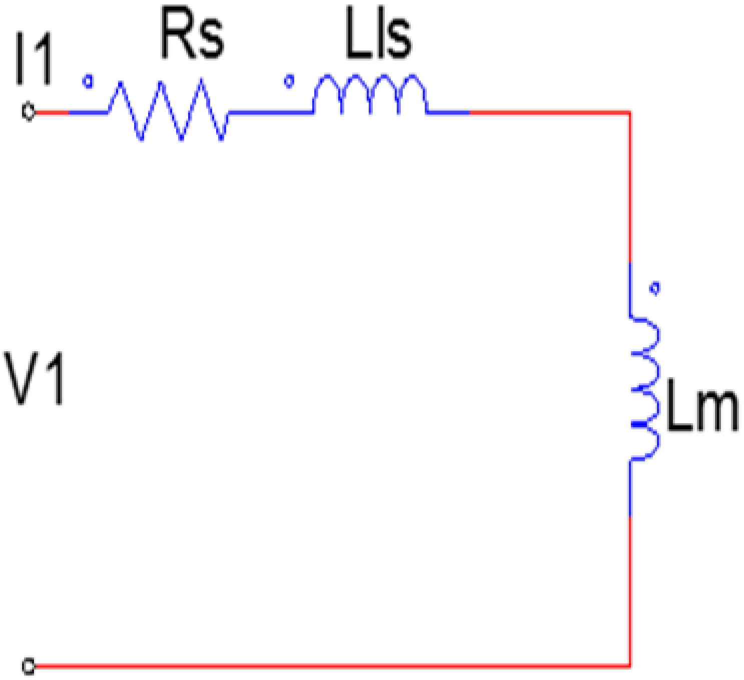


Figure 3.11: Equivalent circuit

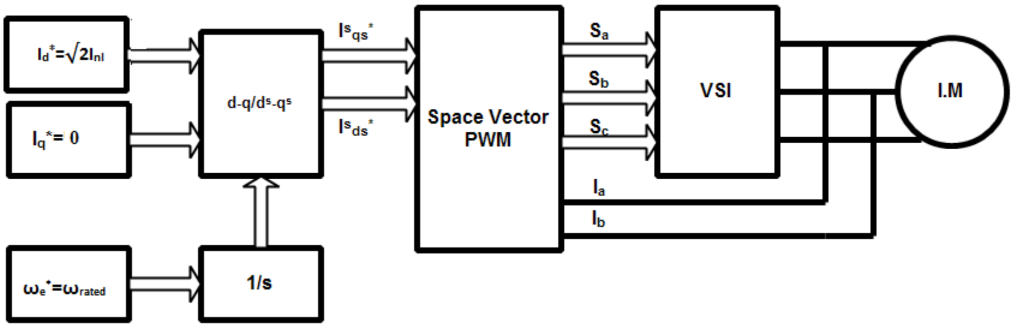


Figure 3.12: Block diagram for no load test

Three commands Id*,Iq*,and e* are modified in the proposed automatic no-load test. Initially, e*=rated,Iq*=0,and Id*=Irated. During the test,Id* is gradually adjusted down to an appropriate no load value. Before Id* reaches its no-load value the three phase inverter output voltage will be unbalanced.The complete control flow for the no-load test is shown in flow chart.

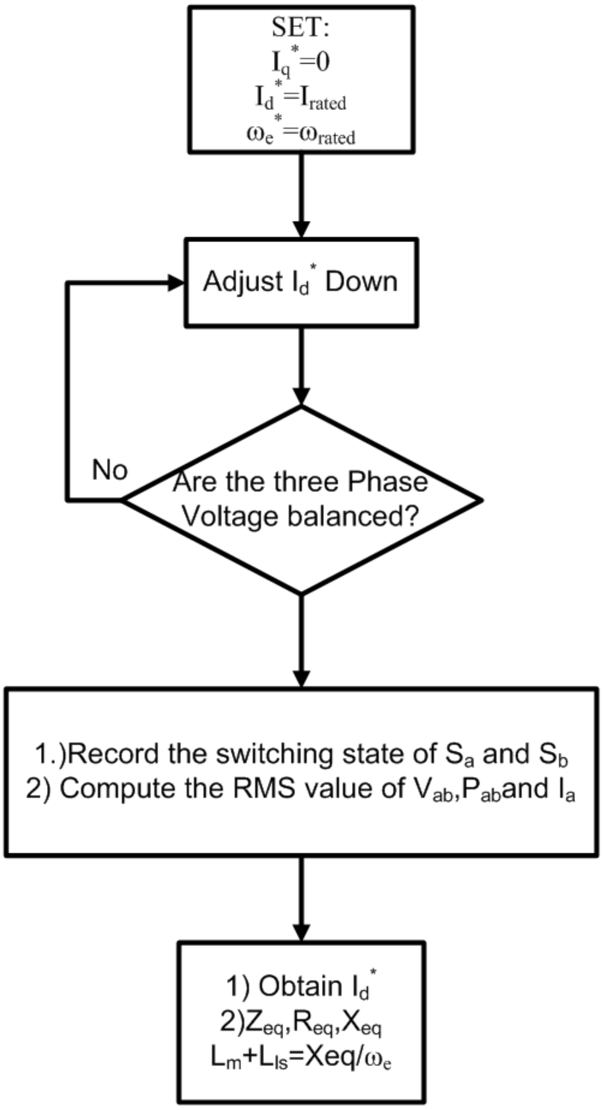


Figure 3.13: Flow chart

3.7 Advanced Locked Rotor Test

To perform the locked rotor test, the rotor has to remain stationary. Conventionally, the rotor shaft has to be locked mechanically during this test. For Fully automatic locked rotor test,the mechanical locking is removed and the rotor stands still during test. The automatic pseudo locked rotor test can be performed under sensorless FOC.Three commands are modified,Id*=0,Iq*=Irated,and e*=0.25 rated.The normal operating frequency of rotor is not same as the stator.A typical compromise is to use a frequency 25% or less of rated frequency.Here inverter pattern has been changed.Three phase inverter has been switched as a single phase inverter.For this siwtch s1 of a phase A and switches s6 and s2 of phase B and C accordingly hase been switched at a time.

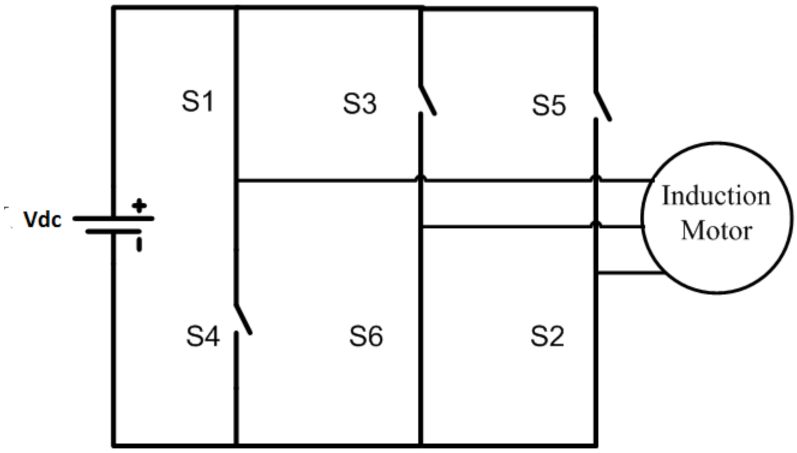


Figure 3.14: Switching of Inverter

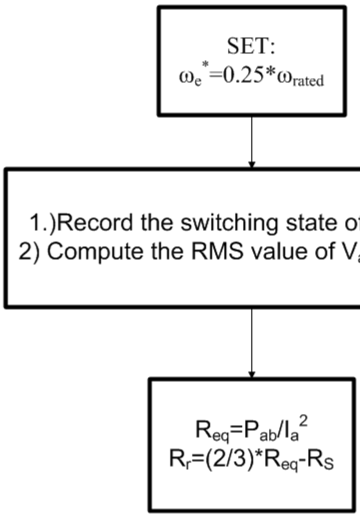


Figure 3.15: Flow chart

Chapter 4

Simulation and Hardware Results

4.1 Simulation Results

The simulation is carried out with two different Scheme in Power Sim.

I The first Scheme is based on voltage generation.In this method current feedback is taken and according to the required rated current of motor ,the voltage is generated.For this scheme the waveform of rated current(Ir),Voltage(V),Power Factor,Rotor resistance(Rr) is shown in following figures, i.e Fig(4.1) to Fig(4.5).The disadvantage of this scheme is that ,current and voltage will become stable approximately after 1.73 second. And we will get erroneous results.

II The disadvantage of first scheme is overcome in this scheme.In the second Scheme, the current feedback is taken ,and with the help of PI error current is found.And with the use of error current the required voltage for rated current is generated.For this scheme the waveform of rated current(Ir),Voltage(V),Power Factor,Rotor resistance(Rr) is shown in following figures, i.e Fig(4.6) to Fig(4.10).

III In this scheme,Current of phase R is taken as feedback.Then it is compared with the reference current, which gives error.Then this error is processed through the PI controller. Output Of the PI controller is processed through moving average filter,which takes previous eight sample and take the average of the same.In this scheme first full (100%) current is taken.Now second time half(50%) current reference is taken.Now difference between Voltage required for 100% current reference and voltage required for 50% current reference gives losses.Then it is deducted from voltage required for 50% current reference which gives actual losses.Then is is this deducted from voltage required for 100% current reference,which gives actual volage required for 100% current reference.Then power is calculated and then rotor resistance is calculated.

IV In the fourth scheme ,Current of phase R is taken as feedback.Then it is compared with the reference current, which gives error.Then this error is processed through the controller.Output Of the PI controller is processed through moving average filter,which takes previous eight sample and take the average of the same.Due to which ,Error signal maintains as sine wave. Deadband of 3.2s is applied between two switches of inverter. In this scheme instantaneous power is calculated and then rotor resistance is calculated.Waveform of this scheme is shown below.

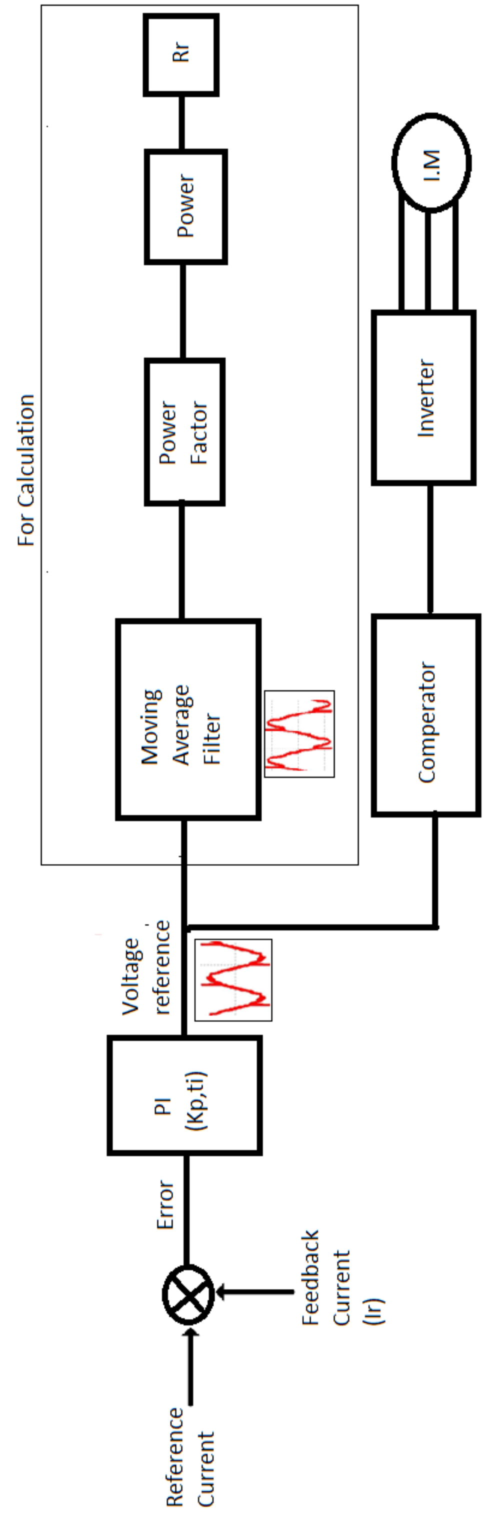


Figure 4.1: Block diagram of simultaion

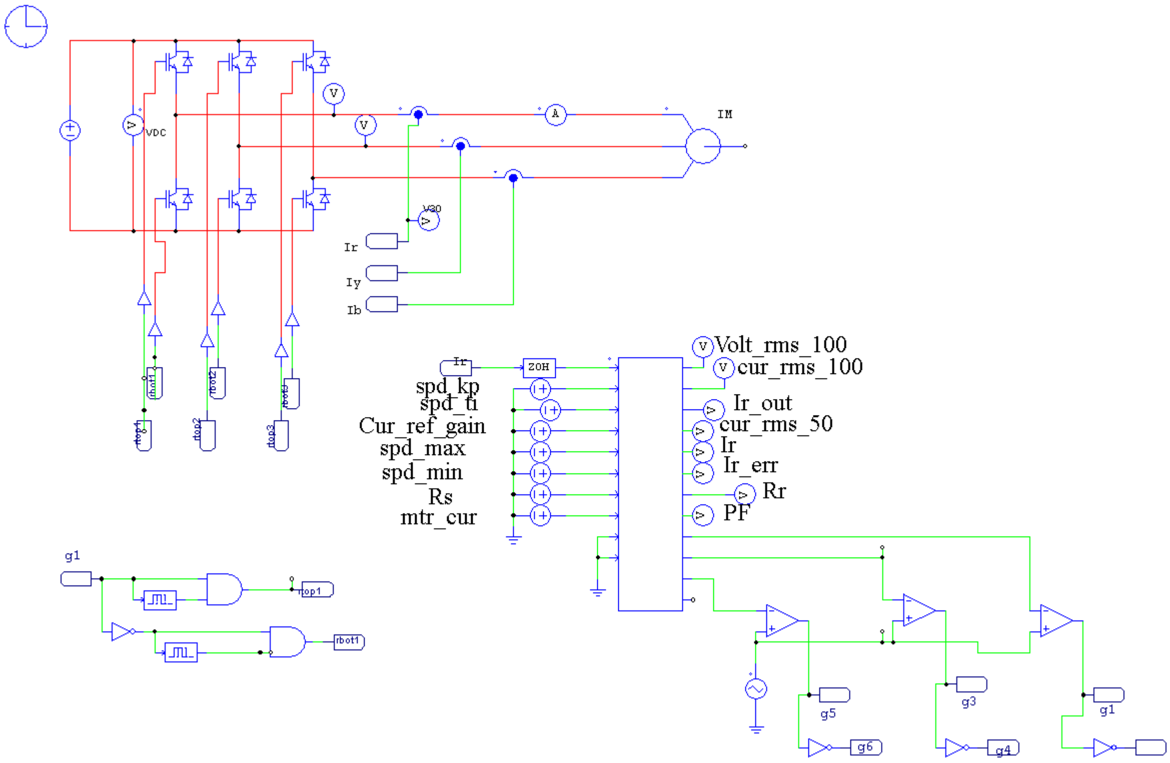


Figure 4.2: simultaion diagram

1. Results based on the scheme(I) of simulation

- R-phase Current waveform(Ir)

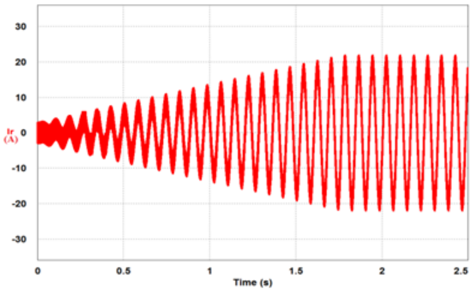


Figure 4.3: current Waveform;X-axis= 0.5 s/div ;Y-axis:=10 A/div

- Voltage waveform(V)

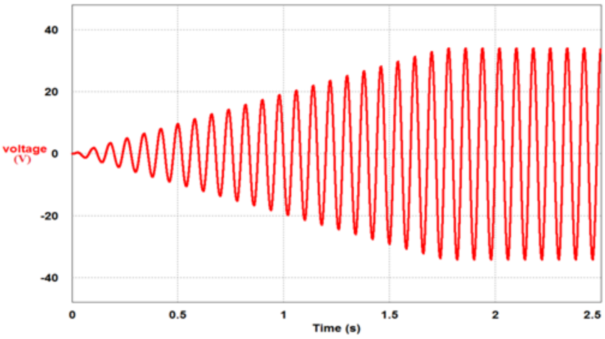


Figure 4.4: Voltage Waveform;X-axis =0.5 s/div:Y-axis=20 V/div

- Voltage (V) and Current(Ir)

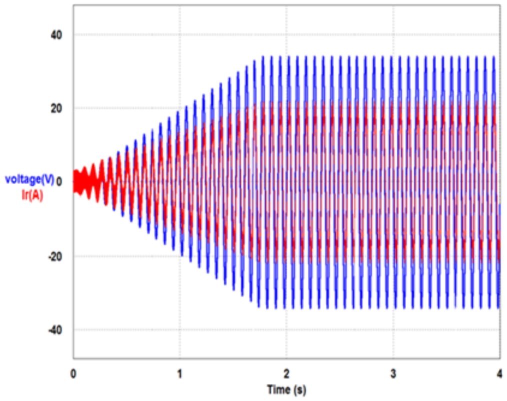


Figure 4.5: Voltage And current Waveform-axis =0.5 s/div:Y-axis=20 V/div X-axis= 0.5 s/div ;Y-axis:=10 A/div

- Power Factor

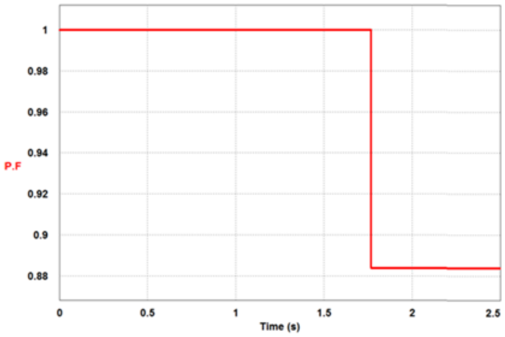


Figure 4.6: Power Factor;X-axis= 0.5 s/div ;Y-axis:=10 /div

- Rotor Resistance(Rr)

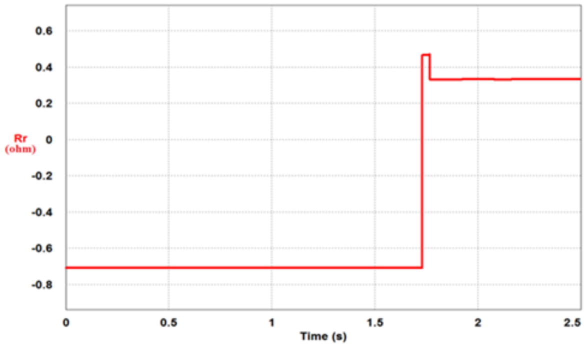


Figure 4.7: X-axis=0.5 s/div;Y-axis=0.2 ohm/div

1. Results based on scheme(II) of simulation

- R-phase Current(Ir)

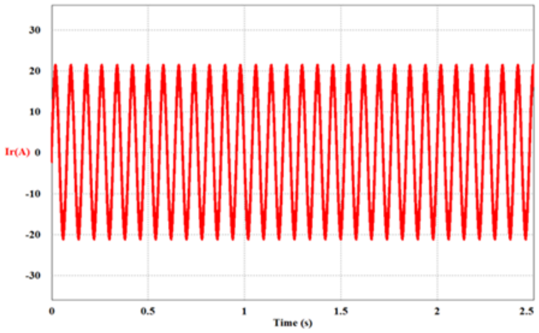


Figure 4.8: RMS Current X-axis= 0.5 s/div ;Y-axis:=10 A/div

- Voltage(V)

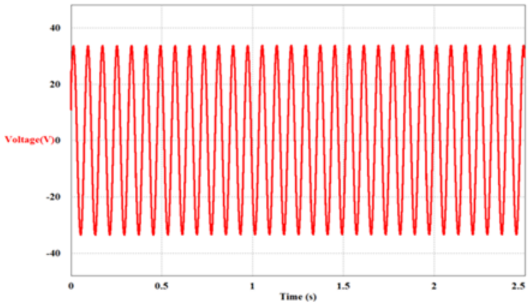


Figure 4.9: RMS Voltage;X-axis =0.5 s/div:Y-axis=20 V/div

- Voltage (V) and Current(Ir)

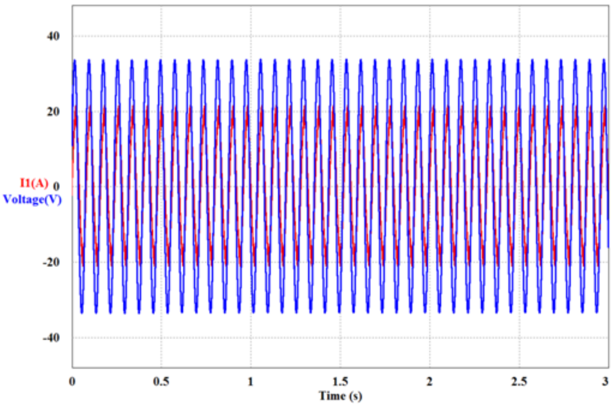


Figure 4.10: RMS current And Voltage;X-axis =0.5 s/div:Y-axis=20 V/div X-axis= 0.5 s/div ;Y-axis:=10 A/div

- Power Factor

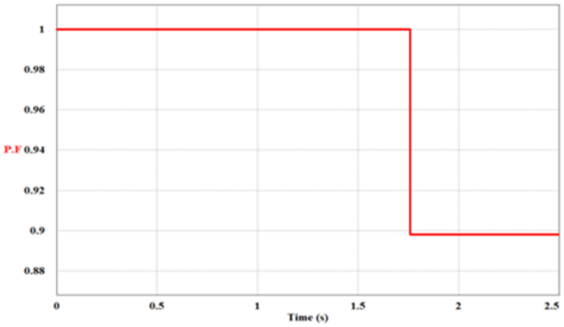


Figure 4.11: Power Factor;X-axis=0.5 s/div

- Rotor Resistance (Rr)

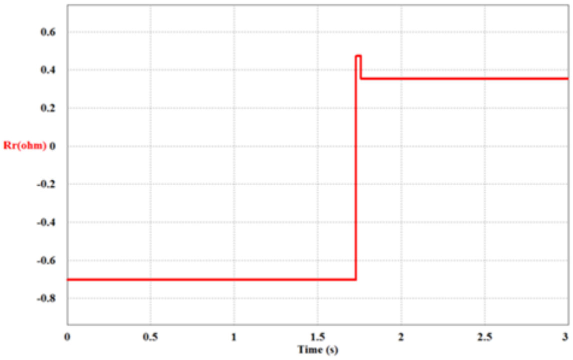


Figure 4.12: Rotor Resistance ;X-axis=0.5 s/div;Y-axis=0.2 ohm/div

- Observation Table from Simulation:

Table 4.1: values of parameter using first scheme

Parameters	Power Rating(HP)					
	2	10	20	40	60	100
Vrms(V)	34.97	24.02	28.45	26.28	21.9	20.8
Irms(A)	3.44	13.63	30.82	56.26	86.08	123.17
Power(W)	106.6853	290.885	610.9893	979.4418	1035.7526	1485.1649
Power Factor	0.8838	0.8838	0.6962	0.6616	0.5494	0.5494
Req(Ω)	9.0018	1.5617	0.6441	0.3091	0.14	0.0881
Rs(Ω)	4.615	0.7021	0.3252	0.1733	0.0779	0.0441
Rr(Ω)	1.3827	0.3335	0.104	0.0326	0.0152	0.0145
Actual Rr(Ω)	1.667	0.3783	0.1333	0.0463	0.024	0.0185
Error(%)	17.50%	11.84%	21.98%	29.58%	36.67%	21.62%

Table 4.2: values of parameter using second scheme

Parameters	Power Rating(HP)					
	2	10	20	40	60	100
Vrms(V)	34.22	23.69	27.38	25.3	20.7	16.55
Irms(A)	3.36	13.42	29.65	54.29	81.47	122.73
Power(W)	108.9907	285.7405	714.0782	1192.6226	991.9464	1388.1116
Power Factor	0.9591	0.8981	0.8943	0.6848	0.5881	0.5754
Req(Ω)	9.1244	1.585	0.6631	0.3191	0.1494	0.0921
Rs(Ω)	4.651	0.7021	0.3252	0.1733	0.0779	0.0441
Rr(Ω)	1.4661	0.3544	0.1168	0.0394	0.0216	0.0173
Actual Rr(Ω)	1.667	0.3783	0.1333	0.0463	0.024	0.0185
Error(%)	12.05%	6.31%	12.37%	14.90%	10.00%	6.48%

3. Results based on the scheme(III) of simulation

- R-phase Current waveform(Ir)

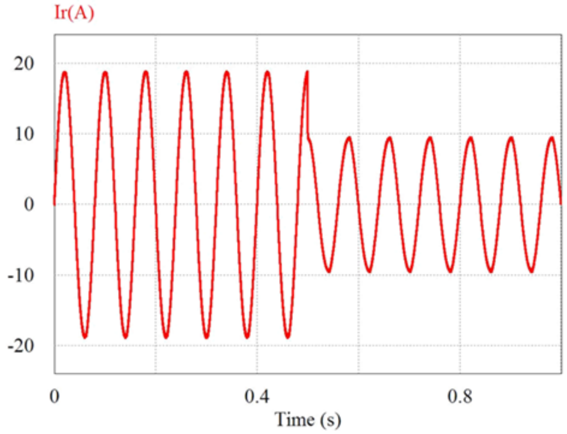


Figure 4.13: current Waveform;X-axis= 0.2 s/div ;Y-axis:=10 A/div

- Output of PI and Moving average filter

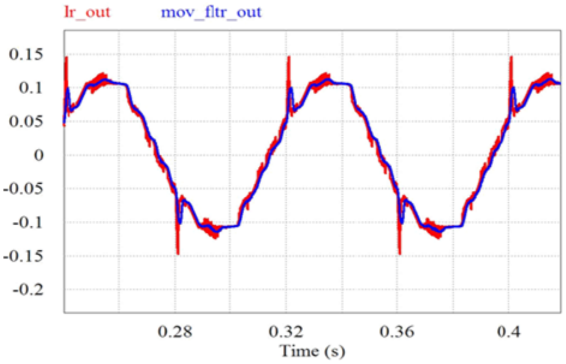


Figure 4.14: Output of PI and moving average filter;X-axis =0.14 s/div:Y-axis=0.05 A/div

- Output of PI

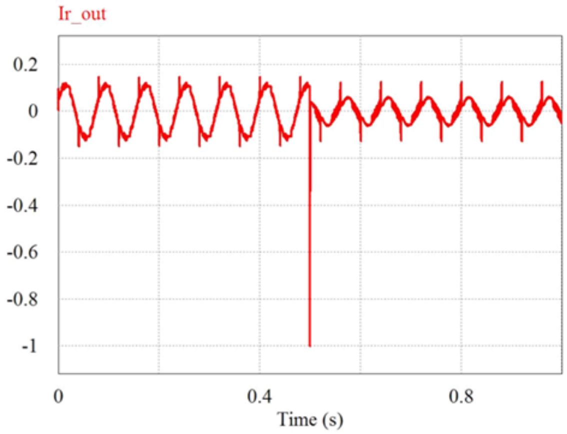


Figure 4.15: Output of PI; X-axis =0.2 s/div:Y-axis=0.2 A/div

  - Output of Moving average Filter

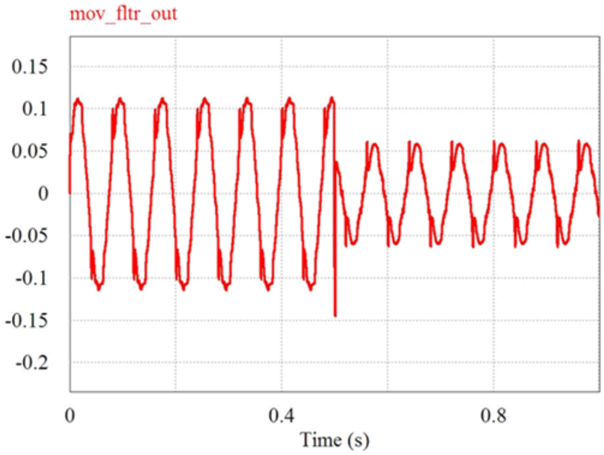


Figure 4.16: Output of Moving average Filter;X-axis= 0.2 s/div ;Y-axis:=0.05 A/div

- Power factor

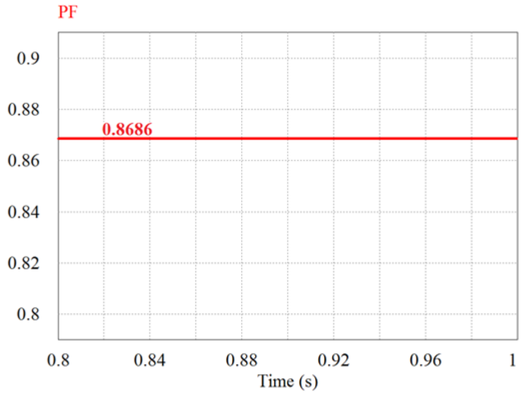


Figure 4.17: Waveform of Power factor; X-axis =0.2 s/div

- Power

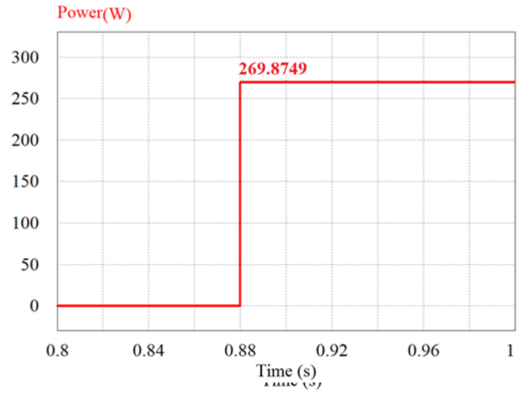
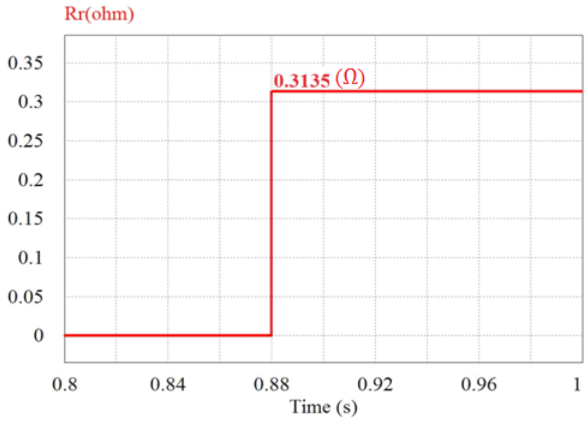


Figure 4.18: Power; X-axis =0.2 s/div:Y-axis=50 W/div

- Rotor Resistance



4. Results based on the scheme(IV) of simulation

- R-Phase current

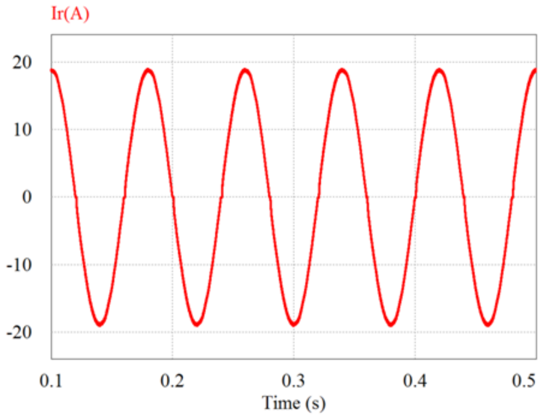


Figure 4.20: R-phase current;X-axis =0.1 s/div:Y-axis=10 A/div

Power(W)

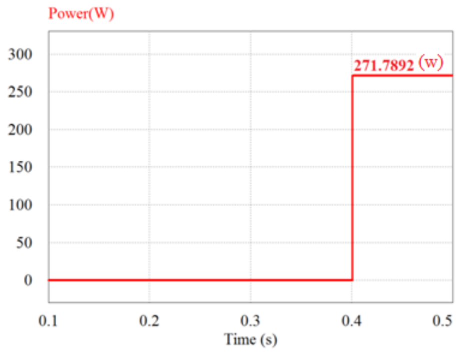
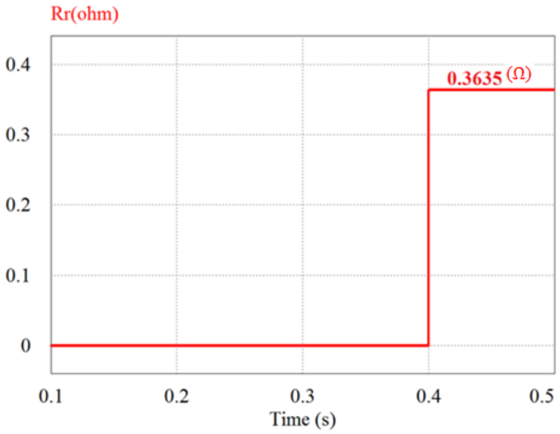


Figure 4.21: Power;X-axis =0.1 s/div:Y-axis=50 W/div

Rotor Resistance



- Observation Table from Simulation:

Table 4.3: Values of parameters using third scheme

Parameters	HP				
	2	10	20	60	100
Vrms(V)_100	46.93	37.34	39.03	32.80	31.16
Vrms(V)_50	30.09	25.67	27.35	22.31	21.66
Irms(A)_100	3.35	13.30	29.87	82.26	123.89
Irms(A)_50	1.67	6.65	14.92	41.40	62.54
Power(W)	101.4653	269.8740	493.7670	1036.2124	1353.6724
Power Factor	0.8980	0.8686	0.7071	0.6129	0.5750
Rr()	1.3991	0.3135	0.0434	0.0241	0.0146
Actual Rr()	1.6670	0.3783	0.1333	0.0240	0.0185
Error(%)	16.07	17.13	67.44	-0.33	21.08

Table 4.4: Values of parameters using forth scheme

Parameters	HP						
	2	10	20	40	60	100	420
Vrms(V)	33.42	23.89	27.12	24.90	21.29	20.02	23.99
Irms(A)	3.35	13.31	29.82	54.60	82.03	123.60	537.86
Power(W)	99..9810	283.4446	589.7728	961.5351	1058.9326	1359.1927	6570.9263
Power Factor	0.8910	0.8910	0.7289	0.7071	0.6004	0.5490	0.5090
Rr()	1.2977	0.3639	0.1167	0.0416	0.0268	0.0151	0.0038
Actual Rr()	1.6670	0.3783	0.1333	0.0463	0.0240	0.0158	0.0040
Error(%)	22.15	3.80	12.45	10.15	-11.66	4.43	6.86

4.2 Hardware Results

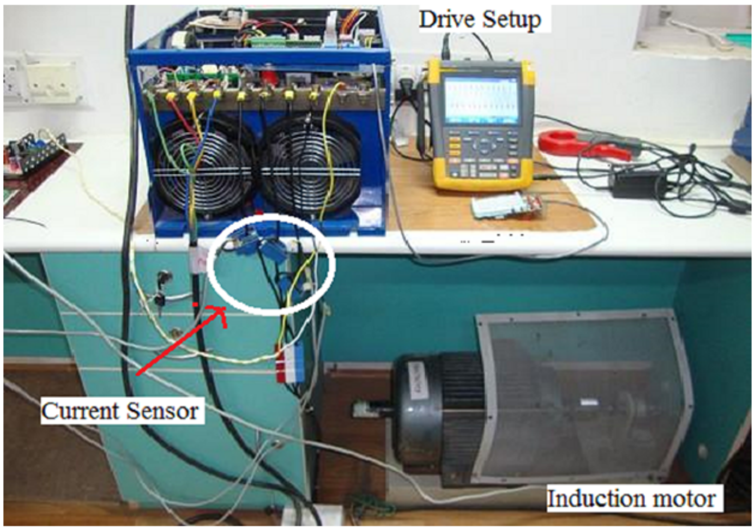


Figure 4.23: Complete set of 10HP induction motor drive

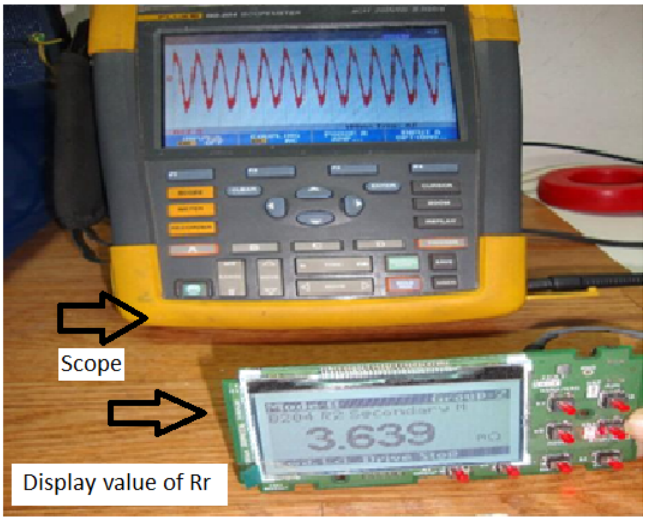


Figure 4.24: waveform of current captured in scope and Value of Rr in display

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Advanced locked rotor test has been simulated for low-rating motor ,medium rating motor and high-rating motor. The test has been performed practically on 10 HP motor in which rotor resistance has been estimated successfully.There are still some minor errors in high rating motors which is due to the effect of deadband. Deadband leads to error in rms calculations of votltage and current.

5.2 Future Scope

An accurate method for deadband compensation is needed,which will eliminate the rms calculation of voltage.

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