SENSORLESS CONTROL OF THREE PHASE INDUCTION MOTOR

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FOR THE AWARD OF THE DEGREE

MASTER OF TECHNOLOGY

IN

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Submitted by:

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CANDIDATE'S DECLARATION

I, Anoop Sharma, Roll No. 2K18/C&I/21 student of M.Tech. (Control & Instrumentation), hereby declare that the Dissertation titled "**Sensorless Control of Three Phase Induction Motor** " which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

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CERTIFICATE

We hereby certify that the Dissertation titled "**Sensorless Control of Three Phase Induction Motor** " which is submitted by Mr. Anoop Sharma, Roll No. 2K18/C&I/21, Electrical Engineering Department, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under our supervision. To the best of our knowledge this work has not been submitted in part or full for award any Degree or Diploma to this University or elsewhere.

Prof. MADHUSUDAN SINGH

(SUPERVISOR)

ABSTRACT

In the present time most of the industrial load consists of Induction Motor drives. These drives need to be controlled for giving the desired speed. To achieve the control of these drives, various control methods are present today. Out of which, this work gives the detailed performance analysis of the MRAS based sensorless control drives for the Induction Motor . This control scheme is modeled and simulated in MATLAB SIMULINK to generate the control signal for Induction Motor under different loading conditions.

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I wish to express my deep sense of gratitude to my supervisor, counselor and advisor **Prof. Madhusudan Singh,** Department of Electrical Engineering for their constant guidance, support, motivation and encouragement during completion of this work. Their readiness for consultation at all times, educative comments, concern, and assistance have been invaluable.

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CHAPTER 1

1.1 INTRODUCTION

Induction machine generally finds robust construction that causes it to be utilized as major part of industrial applications. These applications in general include HVAC, grinding rolling pumping machine and various other tool applications.

Such uses, most of the time required controlled actions which in turn required the different kind of controller for it. The broad category for those are Scalar and Vector control, in which Vector control is further diversified as Direct field oriented controller and Indirect field oriented controller.

The basic phenomenon for the rotation of Induction Motor is rotating magnetic field. The rotating magnetic field is developed by the stationary field winding carrying the sinusoidal power supply in it. As shown in the below Figure 1. 1, when power supply is connected to stationary phase winding, the phase currents in those windings will be varying in magnitude sinusoidally, causing the resultant of magnetic flux phasor to be rotating at synchronous speed.

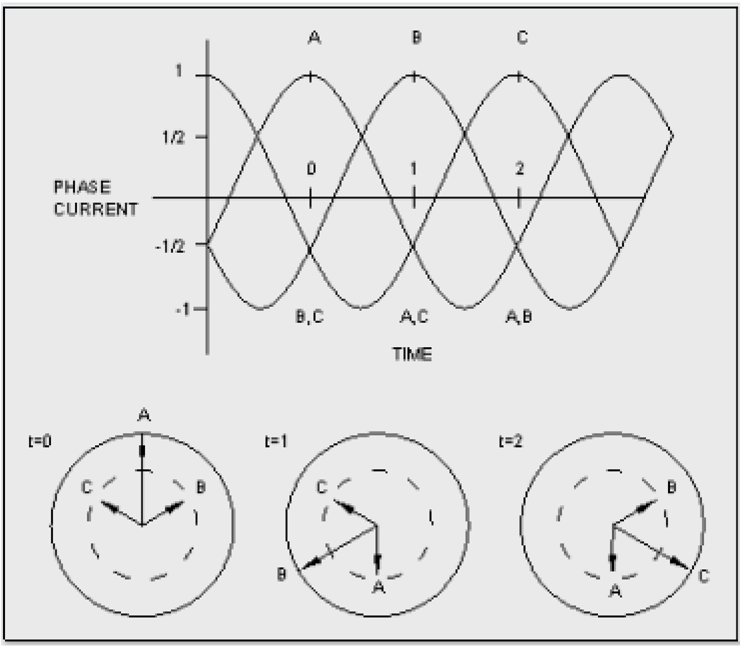


Figure 1. 1: Rotating magnetic field

As with the evolution of different industries where the working conditions are very difficult, so to increase the reliability of Induction Motor , sensorless control is found to be good controller, in which the dependence on speed sensor for precise control has been eliminated. Since speed sensors (encoder) are expensive and are very prone to failure and less reliable.

1.2 TYPES OF CONTROL

There are in general two type of controls available, first Scalar and second one is Vector control. The executional beauty of scalar control is its simplicity to implement but having some inbuilt combinational consequence. As the producing torque and flux of the motor are function of voltage and frequency of the supply, which in turn gives the sluggish response to system and because of higher order harmonics (fifth order) system is actually exposed to volatility.

Above mentioned problem can be solved by Vector or field oriented control. With the assistance of vector control enlistment, Induction Machine can be effectively controlled as an independently invigorated DC machine, the revival of elite AC drives become conceivable solely after the coming of Vector control. Since DC machine like performance can be easily achieved by the Vector control, it is also known as decoupling orthogonal or transvector control. [19]

1.3 AXIS TRANSFORMATION

For easy understanding of Vector control, some basic idea of axis transformation is required which is presented in below section.

1.4 PARKS TRANSFORMATION

With the help of Parks transformation, the time domain three phase components are transformed to the three axis- direct, quardature and zero axis components in rotating reference frame. For balance system, the zero component is equal to zero and it is also some time called as two axis rotating transformation.

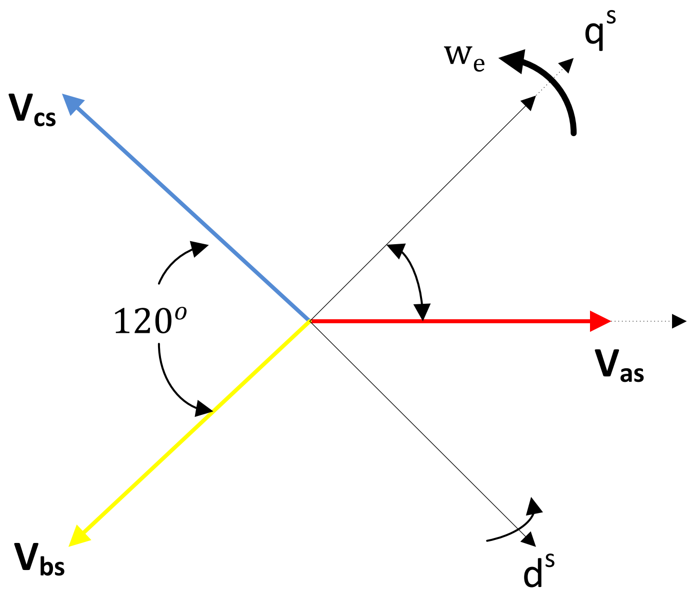


Figure 1. 2: Park Axis Transformation

$$\begin{bmatrix} Vas \\ Vbs \\ Vcs \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120°) & \sin(\theta-120°) & 1 \\ \cos(\theta+120°) & \sin(\theta+120°) & 1 \end{bmatrix} \begin{bmatrix} Vqs^s \\ Vds^s \\ Vos^s \end{bmatrix} \quad (1.1)$$

Where the above equation (1.1) presents the transformation in the matrix form, similarly corresponding inverse relation is presented by equation (1.2)

$$\begin{bmatrix} Vqs^s \\ Vds^s \\ Vos^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120°) & \cos(\theta+120°)\ 1 \\ \sin\theta & \sin(\theta-120°) & \sin(\theta+120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} Vas \\ Vbs \\ Vcs \end{bmatrix} \quad (1.2)$$

After setting theta as zero in equation (1.1) and equation (1.2) for simplicity of computation, q-axis gets lined up with the a-axis. Overlooking the zero sequence component, the transformation relations can be simplified as in the underneath equation (1.3)

$$Vas = Vqs^s$$

$$Vbs = -\frac{1}{2}Vqs^s - \frac{\sqrt{3}}{2}Vds^s \quad (1.3)$$

$$Vcs = -\frac{1}{2}Vqs^s - \frac{\sqrt{3}}{2}Vds^s$$

And inversely

$$Vqs^s = -\frac{1}{2}Vas - \frac{1}{2}Vbs - \frac{1}{2}Vcs \quad (1.4)$$

$$Vds^s = -\frac{1}{\sqrt{3}}Vbs + \frac{1}{\sqrt{3}}Vcs$$

Where the Vas, Vbs, Vcs are the corresponding phase sequences and Vqs^s, Vds^s are the quardrature axis and direct axis phases in synchronously rotating frame.

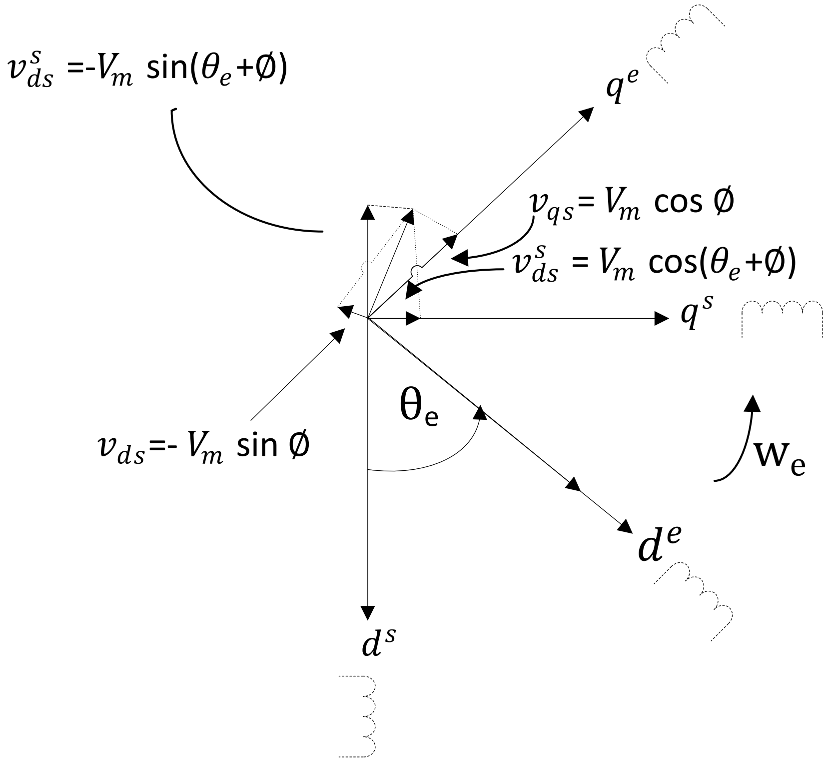


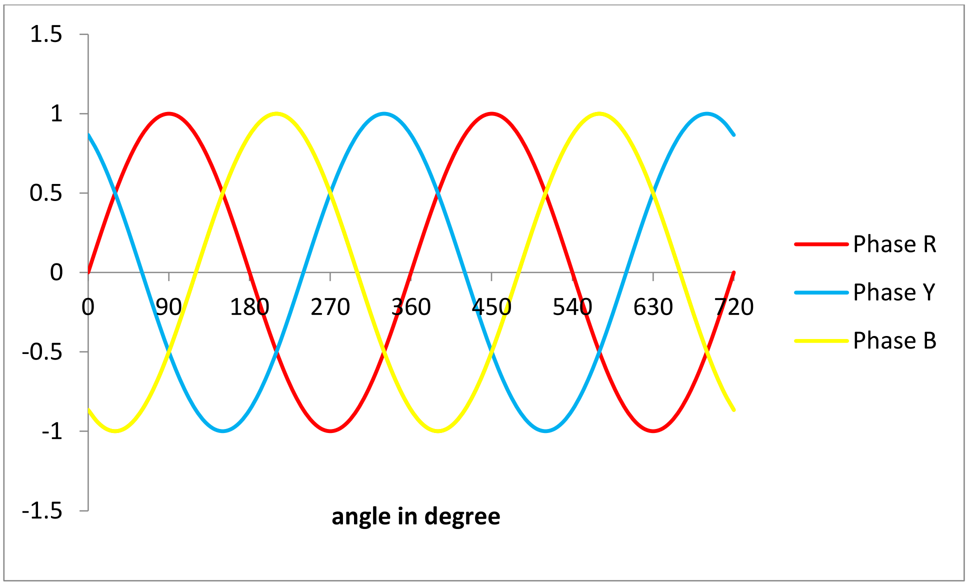
Figure 1. 3: Stationary frame d^s-q^s to synchronously rotating frame d^e-q^e

Above Figure 1. 3 shows the synchronously rotating d^e-q^e axes, which rotate at synchronous speed w_e with respect to d^s-q^s axis and the angle $\theta = w_e t$. The two phase d^s-q^s windings are transformed into hypothetical windings mounted on d^e-q^e axes. The voltages on the d^s-q^saxes can be converted into the d^e-q^e frame as follow

$$Vqs = Vqs^s \cos\theta_e - Vds^s \sin\theta_e \quad (1.5)$$

$$Vds = Vqs^s \sin\theta_e + Vds^s \cos\theta_e$$

Alignment of phase a vector with q-axis



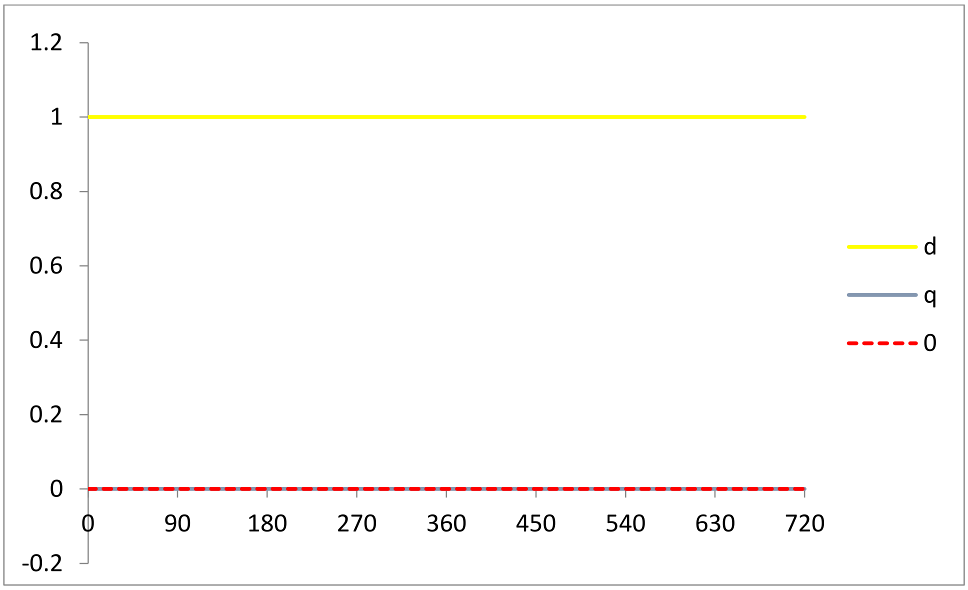


Figure 1. 4: Phasor view of Parks Transformation

1.5 CLARKS TRANSFORMATIONS

The Clarks transformation is also called as αβ transformation. In this transformation the three phases are transformed in to the two stationary αβ-axis. While transforming the three phases to two phases, no information is lost. This is the fineness of Clarks transformation that it reduces the three phase system into the two phase stationary system.

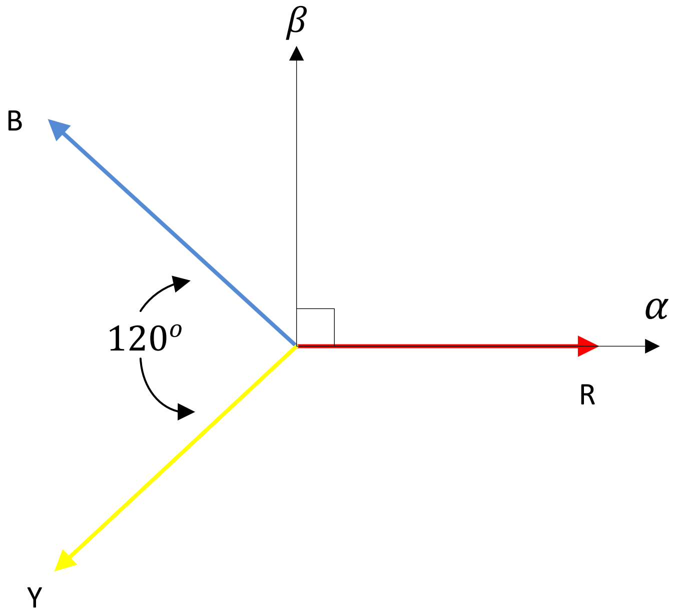


Figure 1. 5: Clarks Axis Transformation

Alignment of phase a vector with q-axis :

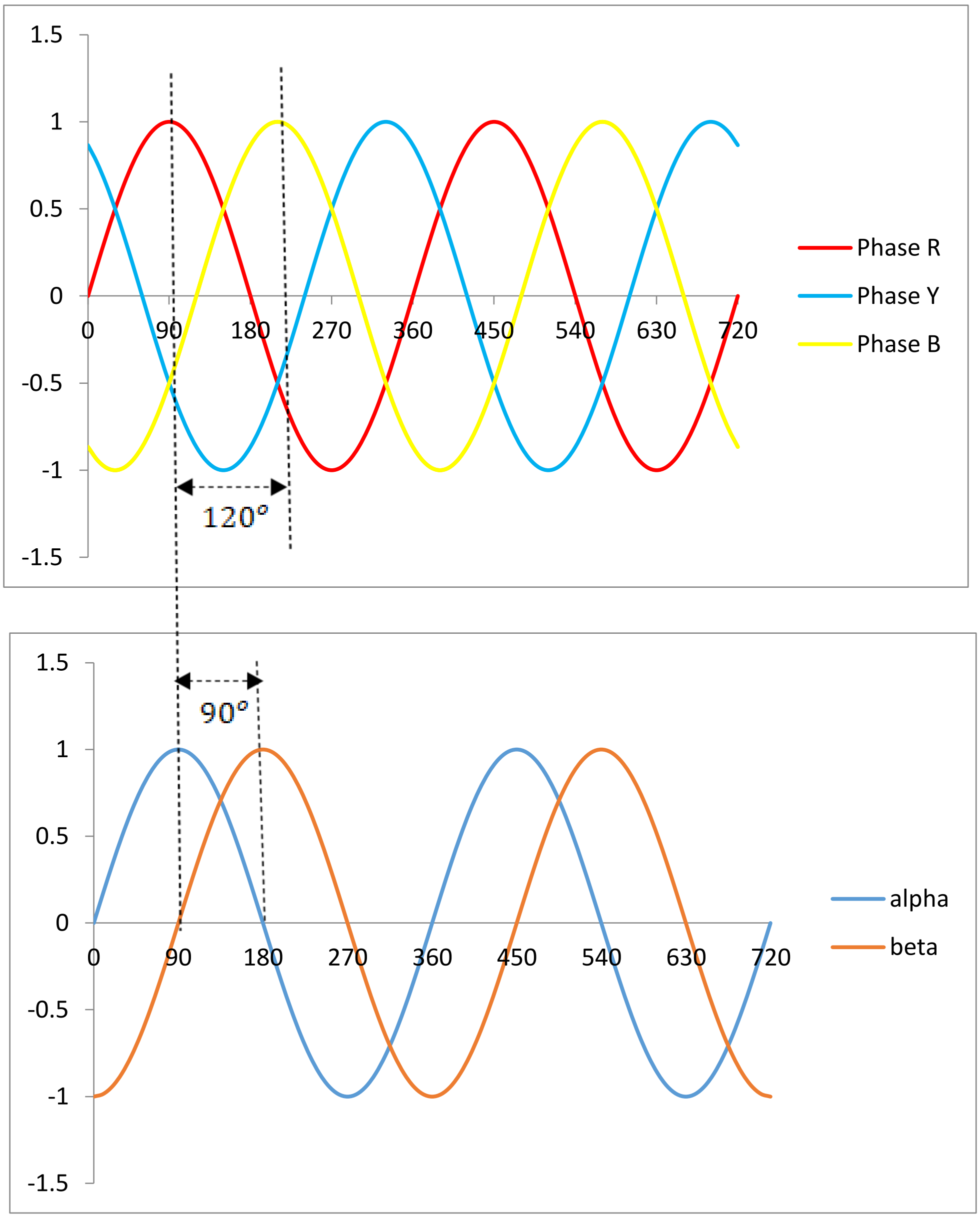


Figure 1. 6: Phasor view of Clarks Transformation

1.6 LITRATURE REVIEW

In this section we go through the work of the researchers who have worked related to the sensorless control technique. Induction Motor has been emerged out as most economical motor for particular power density (i.e., for particular power) application. Since its construction cost and robustness at the time of application makes it a very suitable motor for various line of industries. Industrial applications include the operations at various different speeds for any specified production unit. Because of requirement of different speeds of the drives, a Controlling unit is required to be installed with drive. The Controlling unit must be able to provide the controlling action which is required for variable speed industrial applications. The researchers have done commendable work to come across various types of controllers for providing the particular controlling action of Induction Motor .

Control Technique of Induction Motor

Induction Motor plays the vital role in any production or manufacturing line. So, the robust controlling action of Induction Motor around particular point of time is required. The researchers have executed the numerous experiment and invested many hours in lab for control techniques and provided the best performance for Induction Motor. In this section we go through some of the extensive review which has been presented by the researchers on subject of Induction Motor control techniques.

Colin Schauder discussed the use of estimated speed for the speed control independent of the rotational transducers. He also elaborated how to calculate the instantaneous speed, when all the motor parameters are known and with the help of measured voltage and current. [1]

Joachim Holtz executed the discussion for vector and scalar control. In vector control he showed the reference frame approach and also discussed benefits of particular controls.[2]

Kenza Bouhoune et al. discussed the ANN feed forward multilayer neural network for sensorless control of Induction Motor and represented the results for the speed and torque performance for the conventional FOC and ANN based control.[3]

Idriss Belaloui et al. discussed the vector control with the adaptation mechanism of the sliding mode controller for low speed region, however estimators in this control are not able to perform well, which can be overcome by signal injection based methods.[4]

Alberto Abbondanti and Michael B. Brennen discussed the slip calculation by the hall effect using electronic circuitry, and removed the dependency on the mechanical transducers. And the excecution shows the better results compared to the tachometer.[5]

J.W.Finch et al. discussed the summarized view of different control strategies for AC Electric Drives [6]

Abdelkarim Ammar et al. discussed the sensorless control terminology with field orientation control based by MRAS control and Fuzzy logic control.[7]

Joseph Cilia et al. discussed the rotor resistance based positional encoder for the double cage Induction Motor exploiting the use of mechanical encoder.[8]

Anitha Paladugu, Badrul H. Chowdhury discussed the control of Induction Motor for the closed loop, and discussed the results for the MRAS and Luenberger observer. [9]

Haitham Abu Rub et al. discussed the detailed analysis and design of different types of control for Induction Motor drive with MATLAB/Simulink results [10]

Razani Haron et al. discussed the control technique based on rotor flux based approach and back emf based approach for control.[11]

Marko Hinkkanen and Jorma Luomi discussed about the replacement of pure integrator with the first order low pass filter to remove the drift problem in voltage model of the speed estimation control method by MRAS[12]

Robert Joetten and Gerhard Maeder discussed the current and voltage measured quantities as a tool to close the gap between high dynamic performance drives[13]

Y.S.Lai et al. discussed, the use of commanded voltage signal instead of voltage measurement for the sensorless vector control based on stator flux oriented and rotor flux oriented control. In this control, only current measurement is required.[14]

Lazhar Ben-Brahim and Ausumu Tadakuma discussed the backpropogation neural network technique for the real time adaptive system for sensorless control.[15]

Hirokazu Tajima and Yoichi Hori discussed the flux observer-based field-oriented control and analyzed the convergence performance of the estimators.

1.6 CONCLUSION

In the above foregone discussion some of the extensive review of the published work has been presented for better understanding of the work presented in this report.

CHAPTER 2

2.1 DYNAMIC MODEL OF INDUCTION MACHINE MODEL (KRON MODEL)

The representation of three phase machine to two phase machine (Figure 2. 1) required the presentation of both stator circuit and rotor circuit and their variable in to the synchronously (d^e-q^e)rotating frame.

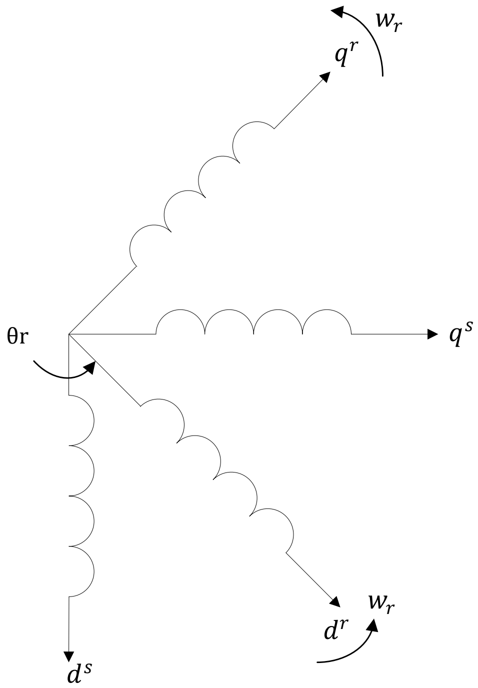


Figure 2. 1:Equivalent Two-phase Machine

$$V_{qs}^{s}=R_{s}i_{qs}^{s}+\frac{d}{dt}\psi_{qs}^{s} \qquad (2.1)$$

$$V_{ds}^{s}=R_{s}i_{ds}^{s}+\frac{d}{dt}\psi_{ds}^{s} \qquad (2.2)$$

Where ψ_{qs}^{s} and ψ_{ds}^{s} are q-axis and d-axis stator flux linkage repectively. When the above equations are converted in to d^e-q^e frame, the accompanying condition can be composed as below

$$V_{qs}=R_s i_{qs}+\frac{d}{dt}\psi_{qs}+w_e\psi_{ds} \qquad (2.3)$$

$$V_{ds}=R_s i_{ds}+\frac{d}{dt}\psi_{ds}-w_e\psi_{qs} \qquad (2.4)$$

Where all the variables are in rotating frame. Due to rotation of axis the last term in equation (2.3) and equation (2.4) can be defined as speed emf, when w_e=0, the equations revert to stationary frame.

In case rotor isn't moving, that is, w_r=0, the rotor conditions for doubly-fed machine will be as shown in Figure 2. 2

$$V_{qr}=R_r i_{qr}+\frac{d}{dt}\psi_{qr}+ \ w_e\psi_{dr} \qquad (2.5)$$

$$V_{dr}=R_r i_{dr}+\frac{d}{dt}\psi_{dr}-w_e\psi_{qr} \qquad (2.6)$$

Where all parameters are referred to the stator. As the rotor having the rotating speed of w_r, the d-q axes fixed on the rotor move at speed w_e-w_r relative to the synchronously rotating frame. Accordingly, in d^e-q^eframe, the rotor equations can be modified as

$$V_{qr}=R_s i_{qr}+\frac{d}{dt}\psi_{qr}+(\ w_e-w_r)\psi_{dr} \qquad (2.7)$$

$$V_{dr}=R_s i_{dr}+\frac{d}{dt}\psi_{dr}-(\ w_e-w_r)\psi_{qr} \qquad (2.8)$$

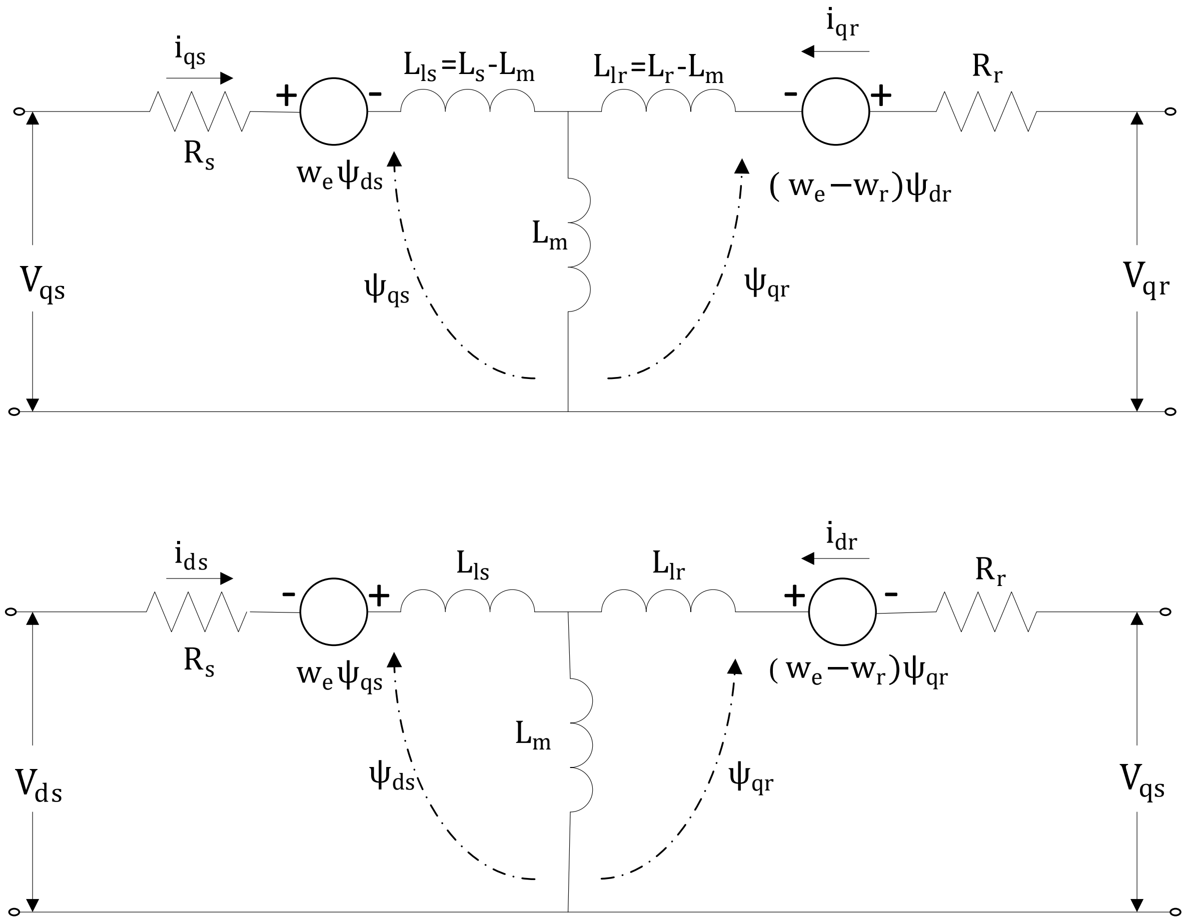


Figure 2. 2: Equivalent dynamicd^e-q^e circuits of machine (a) q^e-axis circuit, (b)d^e–axis circuit

A special amenity of synchronously rotating (d^e-q^e) dynamic model of the machine is that all the sinusoidal variables in stationary frame appear as DC quantities in synchronous frame, as talked about previously.

The flux linkage expressions can be written in terms of currents as below

$$\psi_{qs} = L_{ls}i_{qs} + L_m (i_{qs} + i_{qr}) \quad (2.9)$$

$$\psi_{qr} = L_{ls}i_{qr} + L_m (i_{qs} + i_{qr}) \quad (2.10)$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr}) \quad (2.11)$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (2.12)$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (2.13)$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr}) \quad (2.14)$$

Joining the above articulations with equation (2.5) to condition (2.8), the electrical transient model for voltages and currents can be given in network frames as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & w_e Ls & sL_m & w_e L_m \\ -w_e L_s & R_s + sL_s & w_e L_m & sL_m \\ sL_m & (w_e - w_r)Lm & R_r + sL_r & (w_e - w_r)Lr \\ -(w_e - w_r)L_m & sL_m & -(w_e - w_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (2.15)$$

The speed w_r in above equation (2.15) cannot normally be treated as a constant. It is related to torque as [18]

$$T_e = T_L + J \frac{d}{dt} w_m = T_L + \frac{2}{P} J \frac{d}{dt} w_r \quad (2.16)$$

2.2 COMPACT AND COMPLEX REPRESENTATION

In complex representation, the machine model and equivalent circuit are expressed in complex form. Multiplying equation (2.3) by –j and adding with equation (2.4) gives

$$V_{qs} - jV_{ds} = R_s(i_{qs} - ji_{ds}) + \frac{d}{dt}(\psi_{qs} - j\psi_{ds}) + jw_e(\psi_{qs} - j\psi_{ds}) \quad (2.17)$$

Or,

$$V_{qds} = R_s i_{qds} + \frac{d}{dt}\psi_{qds} + jw_e\psi_{qds} \quad (2.18)$$

Similarly, the rotor equation can be combined or compacted to represent as

$$V_{qds} = R_s i_{qds} + \frac{d}{dt}\psi_{qds} + j\,(w_e - w_r)\,\psi_{qdr} \quad (2.19)$$

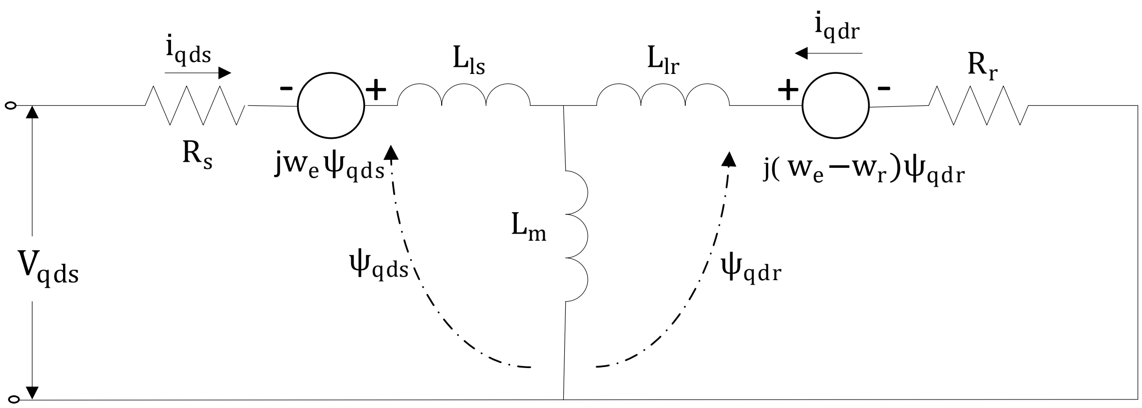


Figure 2. 3: Complex synchronous frame dqs equivalent circuit

Note, the steady state equation at any time can be inferred by surrogating the time subsidiary part to zero. In this manner the steady state condition can be derived as

$$V_s = R_s I_s + j\,w_e\psi_s \quad (2.20)$$

$$0 = \frac{R_r}{S} I_r + j\,w_e\psi_r \quad (2.21)$$

The torque can be generally expressed in vector structure as

$$T_e = \frac{3}{2}\frac{P}{2}\overline{\psi_m} \times \overline{I_r} \quad (2.22)$$

Resolving the variables into de-qe components

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{dm}i_{qr} - \psi_{qm}i_{dr}) \quad (2.23)$$

Several other torque formulations can be given easily as follows:

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{dm}i_{qs} - \psi_{qm}i_{ds}) \quad (2.24)$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds})$$

$$= \frac{3}{2}\frac{P}{2}L_m(i_{qs}i_{dr} - i_{ds}i_{qr})$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{dr}i_{qr} - \psi_{qr}i_{dr})$$

Figure 2. 4 beneath shows the square outline of the machine model alongside input voltage and yield current transformation. The three phase inputs are converted to stationary axis, afterward it is converted to synchronously rotating frame with the help of unit vector, which are deduced from the speed of the rotating field.

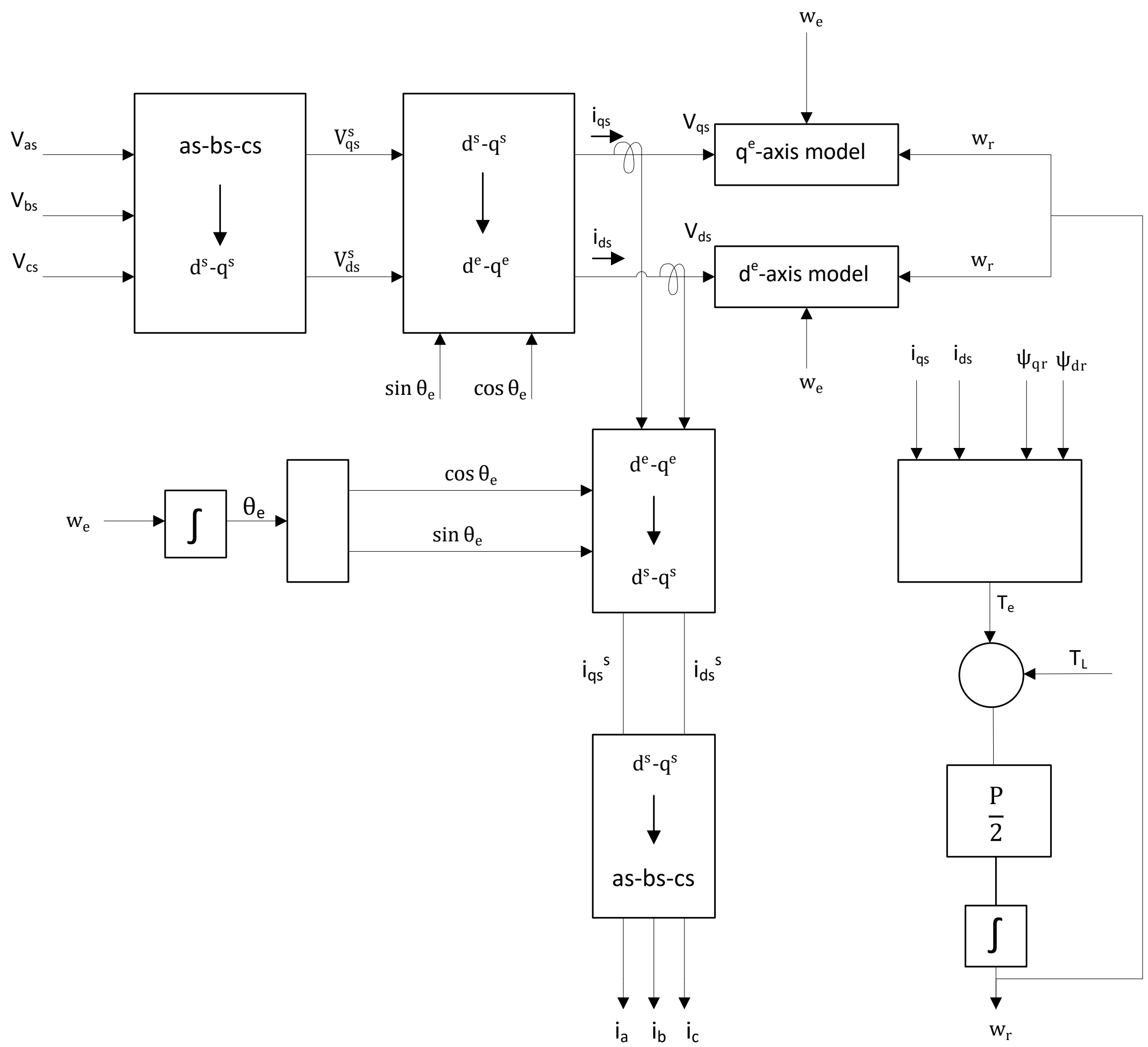


Figure 2. 4: Synchronously rotating frame machine model with input voltage and output current transformations

2.3 ESTIMATION AND CONTROL OF INDUCTION MOTOR DRIVES

Vector control gives the DC machine like performance to Induction Motor which is also called as decoupling, orthogonal, or transvector control.

2.1.1 DC DRIVE ANALOGY

Vector control provides the motor drive to be operated like a separately excited Induction Motor drive. This analogy is explained in Figure 2. 5. Figure 2. 5(a) shows the armature and decoupled field winding. Decoupled field winding is responsible for production of field in the machine. Figure 2. 5 (b) shows that the required quadrature axis control signal is fed to the vector control and after the controlled action the signals are forwarded to the inverter for controlling the motor. In DC machine after neglecting the armature reaction effect and field saturation, the developed torque is given by

$$T_e = K_t' I_a I_f \qquad (2.25)$$

Where I_a= armature current and I_f=field current. The construction of DC machine is such that, field flux produced by the current I_f is perpendicular to the armature flux ψ_a, which is delivered by armature current I_a. These space vectors are orthogonal or decoupled but stationary in nature.

This implies that when torque is constrained by controlling the current I_a, the flux ψ_f is not influenced and we get the quick transient response and high torque/ampere proportion with the evaluated ψ_f. As a result of the system is decoupled, when the field current I_f is controlled it influences the field flux ψ_f, however not the ψ_a flux.

DC machine-like analogy can be extended to the Induction Motor if machine control is considered in synchronously rotating reference frame (d^e-q^e), where the sinusoidal variables act as DC quantities in steady state.

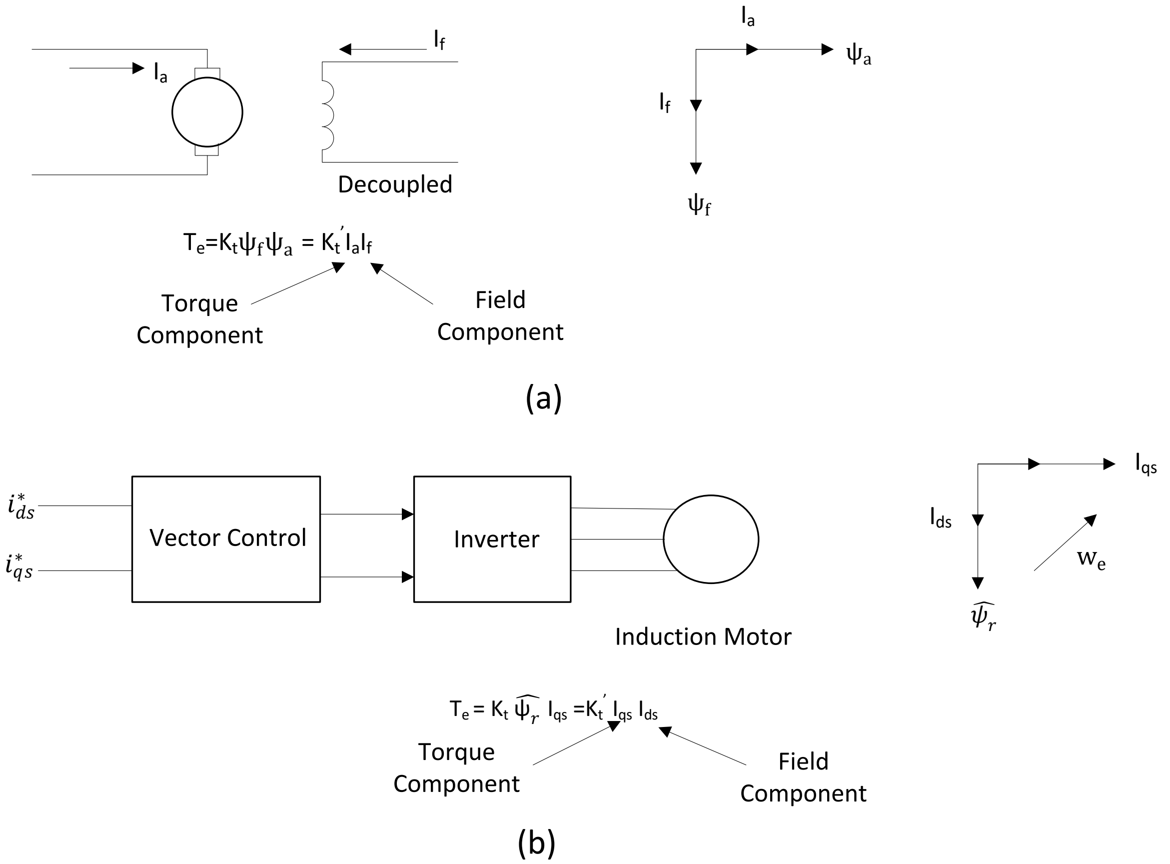


Figure 2. 5:(a) Separately excited dc motor, (b) Vector-controlled Induction Motor

2.2 GUIDELINE FOR VECTOR CONTROL

The major of vector control can be perceived by the Figure 2. 6 given underneath, where the machine model is addressed in a synchronus rotating reference frame. The inverter is precluded from the Figure 2. 6, expecting that it has a solidarity current addition, that is, it produces current i_a,i_b and i_c as dictated by the corresponding commanded currents i_a^*, $i_b^*$and i_c^* from the controller. A machine model, with inside transformations, is displayed on right side of Figure 2. 6. In Figure 2. 6 the output of inverter terminal which is omitted as mentioned above for ease of understanding the machine end terminal phase currents i_a,i_b and i_c. These phase currents i_a,i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by 3 phase to 2 phase transformation.

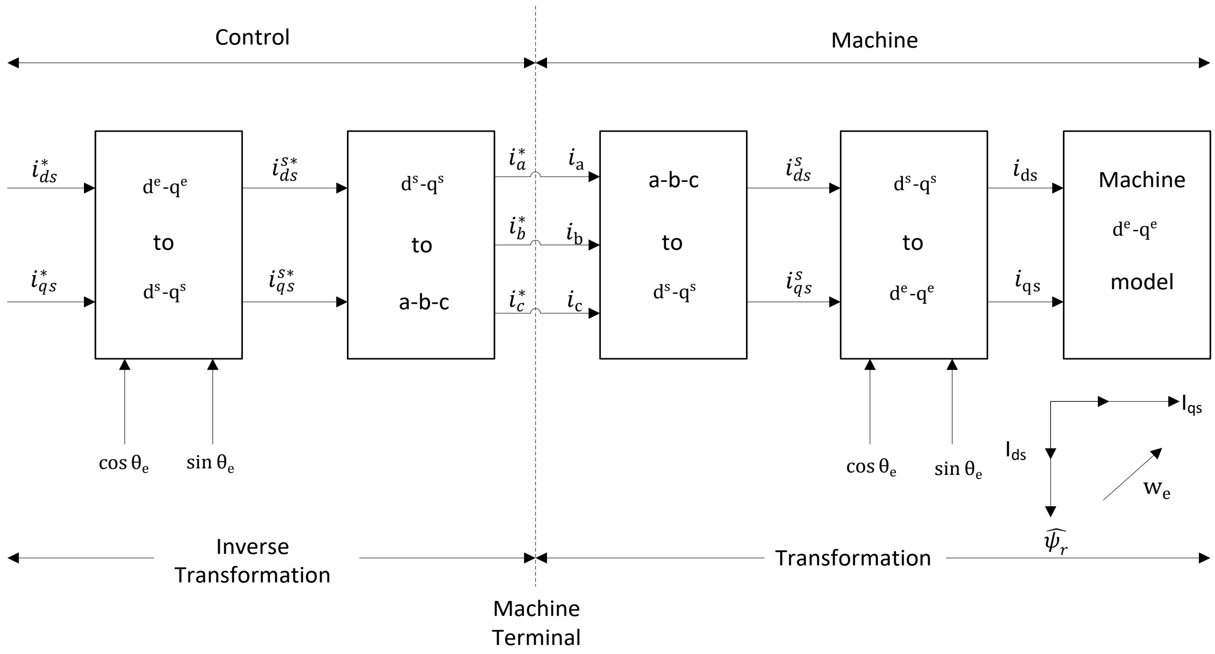


Figure 2. 6: Vector control implementation principle with machine de-qe model

The i_{ds}^s and i_{qs}^s are then changed over to synchronously rotating frame with the assistance of the unit vector parts $\cos\theta_e$ and $\sin\theta_e$, prior to applying them to the d^e-q^e machine model as displayed in Figure 2. 6. After two stages of inverse transformation in regulator, the control current i_{ds}^* and i_{qs}^* are obtained which are related to the machine current i_{ds} and i_{qs} respectively. Additionally, the unit vector guarantees right arrangement of i_{ds} current with the flux ψ_r and i_{qs} perpendicular to it. There are two general methods of vector control :

Direct or feedback method invented by Blakchke

Indirect or feed forward method invented by Hasse

Above strategies are distinctive on the basis of how the unit vectors ($\cos\theta_e$and $\sin\theta_e$) are produced for the control. The alignment of i_{ds} with rotor flux, airgap flux, or stator flux is conceivable in vector control. Nonetheless, rotor flux direction gives normal decoupling control, though airgap or stator motion direction gives a coupling impact. This coupling impact or effect must be compensated by a decoupling compensation current.

In this project we worked on direct or feedback method.

2.2.1 DIRECT OR FEEDBACK VECTOR CONTROL

In this method, the principal vector control parameters i_{ds}^* and i_{qs}^*, which are DC values in synchronously rotating frame, are converted to stationary frame (defined as vector rotation (VR)), with the help of unit vector ($\cos\theta_e$ and $\sin\theta_e$) generated from flux vector signal ψ_{dr}^s and ψ_{qr}^s. The resulting stationary frame signals are then converted to phase current commands for the inverter. The flux signals ψ_{dr}^s and ψ_{qr}^s are generated from the machine terminal voltages and currents with the help of estimator. The torque is proportional to i_{qs} (considering constant flux) and this torque producing current component is generated from the speed loop.

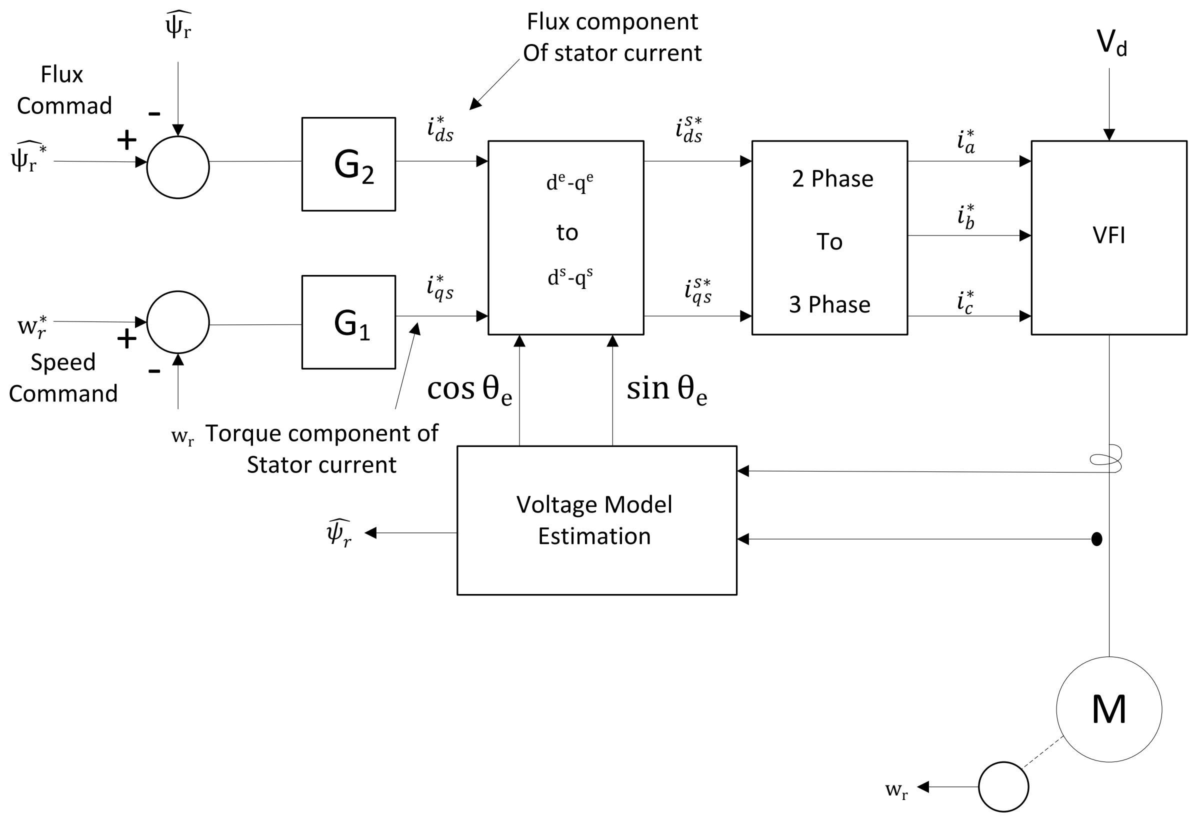
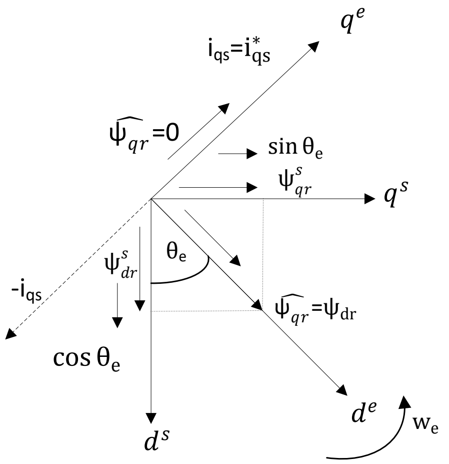
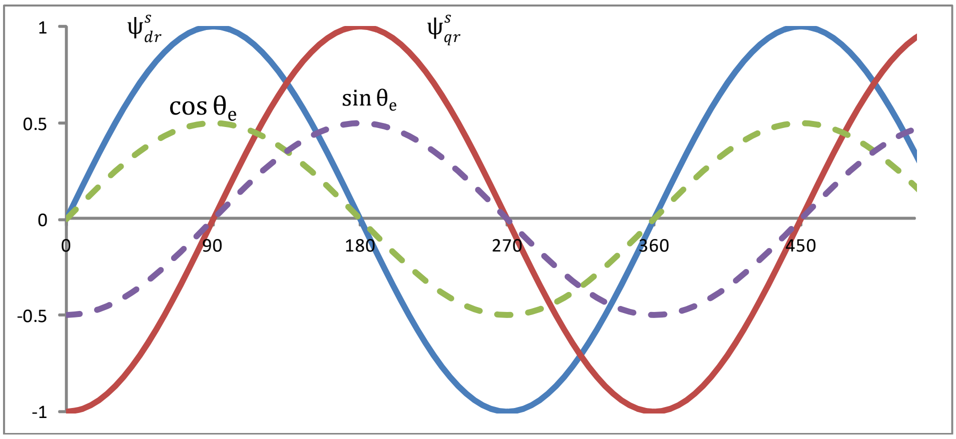


Figure 2. 7: Direct vector control block diagram with rotor flux orientation

The alignment of i_{ds} current in direction of flux and the i_{qs} current perpendicular to it are important for vector control. Such alignment, with the help of stationary frame rotor flux vectors ψ^s_{dr} and ψ^s_{qr} is explained in below Figure 2. 8. In Figure 2. 8 the d^e-q^e frame is rotating at synchronous speed w_e with respect to stationary frame d^s-q^s, and at any instant, the angular position of the d^e-axis with respect to the d^s-axis is θ_e, where $\theta_e = w_e t$. By referring the Figure 2. 8, below mentioned mathematical equations can be formed:



(a)



(b)

Figure 2. 8 : (a) d^s-q^s and d^e-q^e phasors showing correct rotor flux orientation, (b) Plot of unit vector signals in correct phase position

$$\psi_{dr}^{s} = \psi_r \cos\theta_e \qquad (2.26)$$

$$\psi_{qr}^{s} = \psi_r \sin\theta_e \qquad (2.27)$$

In other words,

$$\cos\theta_e = \frac{\psi_{dr}^{s}}{\psi_r} \qquad (2.28)$$

$$\sin\theta_e = \frac{\psi_{qr}^{s}}{\psi_r} \qquad (2.29)$$

$$\psi_r = \text{sqrt}\left(\psi_{dr}^{s^2} + \psi_{dr}^{s^2} \right) \qquad (2.30)$$

2.2.2 INDIRECT OR FEEDFORWARD VECTOR CONTROL

There is much similarity in direct vector control and indirect vector control except the control unit vector signals ($\cos\theta_e$and $\sin\theta_e$) are generated in indirect control method which is also called as feed forward method. This method is very known in modern industrial applications. Figure 2. 9 shows the prominent guideline behind indirect vector control with the assistance of phasor diagram. The stator axis (d^s-q^s) are fixed on stator, however rotor axis (d^r-q^r), which are fixed on rotor, are having the speed w_r as displayed in Figure 2. 9. The axes d^e-q^e which are rotating synchronously, are ahead of rotor axes (d^r-q^r) with positive slip angle θ_{sl} . The slip angle θ_{sl} corresponds to the slip frequency w_{sl}. Since rotor pole is directed in the d^e-axis and w_e=w_r+w_{sl}, we can write

$$\theta_e = \int w_e \, dt = \int (w_r + w_{sl}) \, dt = \theta_r + \theta_{sl}$$

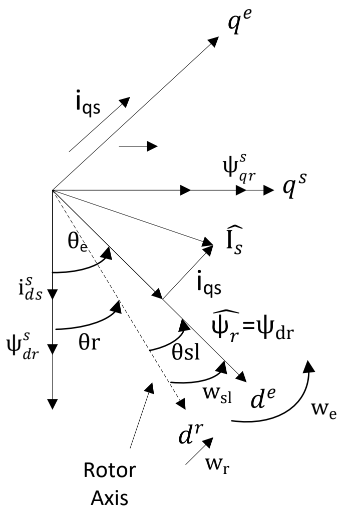


Figure 2. 9 : The Indirect vector control explaining with the phasor

Rotor pole position is falling over, with respect to the rotor at frequency of w_{sl}.

Figure 2. 9 suggests that for decoupled control, the stator flux component of current i_{ds}, is to be aligned on the direct axis d^e which is synchronously rotating and the torque component for the current i_{qs} should be on the quadrature axis q^e which is also rotating synchronously as shown.

2.3 CONCLUSION

In this chapter Induction Motor model and how it can be transformed to the DC drives terminology, is discussed. Basic vector methods of controlling the Induction Motor such as direct and indirect methods are discussed.

CHAPTER 3

3.1 FLUX VECTOR ESTIMATION

In the direct vector control method, as discussed in previous chapter, the assessment the rotor flux components ψ_{dr}^{s} and ψ_{qr}^{s} is necessary so that the unit vector ($\cos\theta_e$ and $\sin\theta_e$) and resultant rotor flux can be calculated with the aid of equation (2.30)

The two commonly used methods for the evaluation are as explained here under.

3.1.1 VOLTAGE MODEL

This method includes the machine terminal voltage and current which are sensed by the transducers. The fluxes are computed from the stationary frame (d^s-q^s) equivalent circuit.

$$i_{qs}^{s} = \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c = i_a \quad (3.1)$$

$$i_{ds}^{s} = -\frac{1}{\text{sqrt } 3} i_b + \frac{1}{\text{sqrt } 3} i_c \quad (3.2)$$

$$= -\frac{1}{\text{sqrt } 3} (i_a + 2i_b) \quad (3.3)$$

Since $i_c = -(i_a + i_b)$ for isolated neutral load

$$v_{qs}^{s} = \frac{2}{3} v_a - \frac{1}{3} v_b - \frac{1}{3} v_c \quad (3.4)$$

$$= \frac{2}{3} (v_{ab} + v_{ac}) \quad (3.5)$$

$$v_{ds}^{s} = -\frac{1}{\text{sqrt } 3} v_b + \frac{1}{\text{sqrt } 3} v_c \quad (3.6)$$

$$= - \frac{1}{\text{sqrt } 3} v_{bc} \quad (3.7)$$

$$\psi^s_{ds} = \int (v^s_{ds} - R_s i^s_{ds}) dt \quad (3.8)$$

$$\psi^s_{qs} = \int (v^s_{qs} - R_s i^s_{qs}) dt \quad (3.9)$$

$$\psi_s = \sqrt{(\psi^{s^2}_{sr} + \psi^{s^2}_{sr})} \quad (3.10)$$

$$\psi^s_{dm} = \psi^s_{ds} - L_{ls} i^s_{ds} = L_m (i^s_{ds} + i^s_{ds}) \quad (3.11)$$

$$\psi^s_{dm} = \psi^s_{ds} - L_{ls} i^s_{ds} = L_m (i^s_{ds} + i^s_{ds}) \quad (3.12)$$

$$\psi^s_{dr} = L_m i^s_{ds} + L_r i^s_{dr} \quad (3.13)$$

$$\psi^s_{qr} = L_m i^s_{qs} + L_r i^s_{qr} \quad (3.14)$$

Eliminating i^s_{dr} and i^s_{qr} from equations (3.13-3.14) with the help of equations (3.11-3.12) ,respectively, gives the following

$$\psi^s_{dr} = \frac{L_r}{L_m} (\psi^s_{dm} - L_{lr} i^s_{ds}) \quad (3.15)$$

$$\psi^s_{qr} = \frac{L_r}{L_m} (\psi^s_{ds} - L_{lr} i^s_{ds}) \quad (3.16)$$

Which can further be written as the following form given by equation (3.17) and equation (3.18) with the help of equation (3.11) and equation (3.12)

$$\psi^s_{dr} = \frac{L_r}{L_m} (\psi^s_{ds} - \sigma L_s i^s_{ds}) \quad (3.17)$$

$$\psi^{s}_{qr} = \frac{L_r}{L_m} (\psi^{s}_{qs} - \sigma L_s i^{s}_{qs}) \qquad (3.18)$$

Where $\sigma = 1 - L_m^2 / L_r L_s$

Substituting equation (3.15-3.16) in torque equation on (2.24)

$$T_e = \frac{3}{2}(\frac{P}{2}) \frac{L_m}{L_r} (\psi^{s}_{dr} i^{s}_{qs} - \psi^{s}_{qr} i^{s}_{ds}) \qquad (3.20)$$

3.1.2 CURRENT MODEL

The component of rotor flux can more easily be formulated with the aid of speed and current signals. The rotor circuit equation of d^s-q^s equivalent circuits can be given as

$$\frac{d\psi^{s}_{dr}}{dt} + R_r i^{s}_{dr} + w_r \psi^{s}_{qr} = 0 \qquad (3.21)$$

$$\frac{d\psi^{s}_{qr}}{dt} + R_r i^{s}_{qr} - w_r \psi^{s}_{dr} = 0 \qquad (3.22)$$

Adding terms $(L_m R_r / L_r) i^{s}_{ds}$ and $(L_m R_r / L_r) i^{s}_{qs}$, on both sides respectively, of the above equation (3.21) and equation (3.22), we get

$$\frac{d\psi^{s}_{dr}}{dt} = \frac{R_r}{L_r} (L_m i^{s}_{ds} + L_r i^{s}_{dr}) + w_r \psi^{s}_{qr} = \frac{L_m R_r}{L_r} i^{s}_{ds} \qquad (3.23)$$

$$\frac{d\psi^{s}_{qr}}{dt} = \frac{R_r}{L_r} (L_m i^{s}_{qs} + L_r i^{s}_{qr}) - w_r \psi^{s}_{dr} = \frac{L_m R_r}{L_r} i^{s}_{qs} \qquad (3.24)$$

Substituting equation (3.13-3.14) respectively, and simplifying, we get

$$\frac{d\psi_{dr}^s}{dt} = \frac{L_m}{T_r} i_{ds}^s - w_r \psi_{qr}^s - \frac{1}{T_r} \psi_{dr}^s \quad (3.25)$$

$$\frac{d\psi_{qr}^s}{dt} = \frac{L_m}{T_r} i_{qs}^s + w_r \psi_{dr}^s - \frac{1}{T_r} \psi_{qr}^s \quad (3.26)$$

Where $T_r = L_m/R_r$ is the time constant of the rotor. Above two equations (3.25) and (3.26) give the rotor flux as function of stator current and speed. Hence, knowing these signals, the fluxes and corresponding unit vector signals can be estimated. Equation (3.25) and equation (3.26) are defined as the current model for flux estimation.

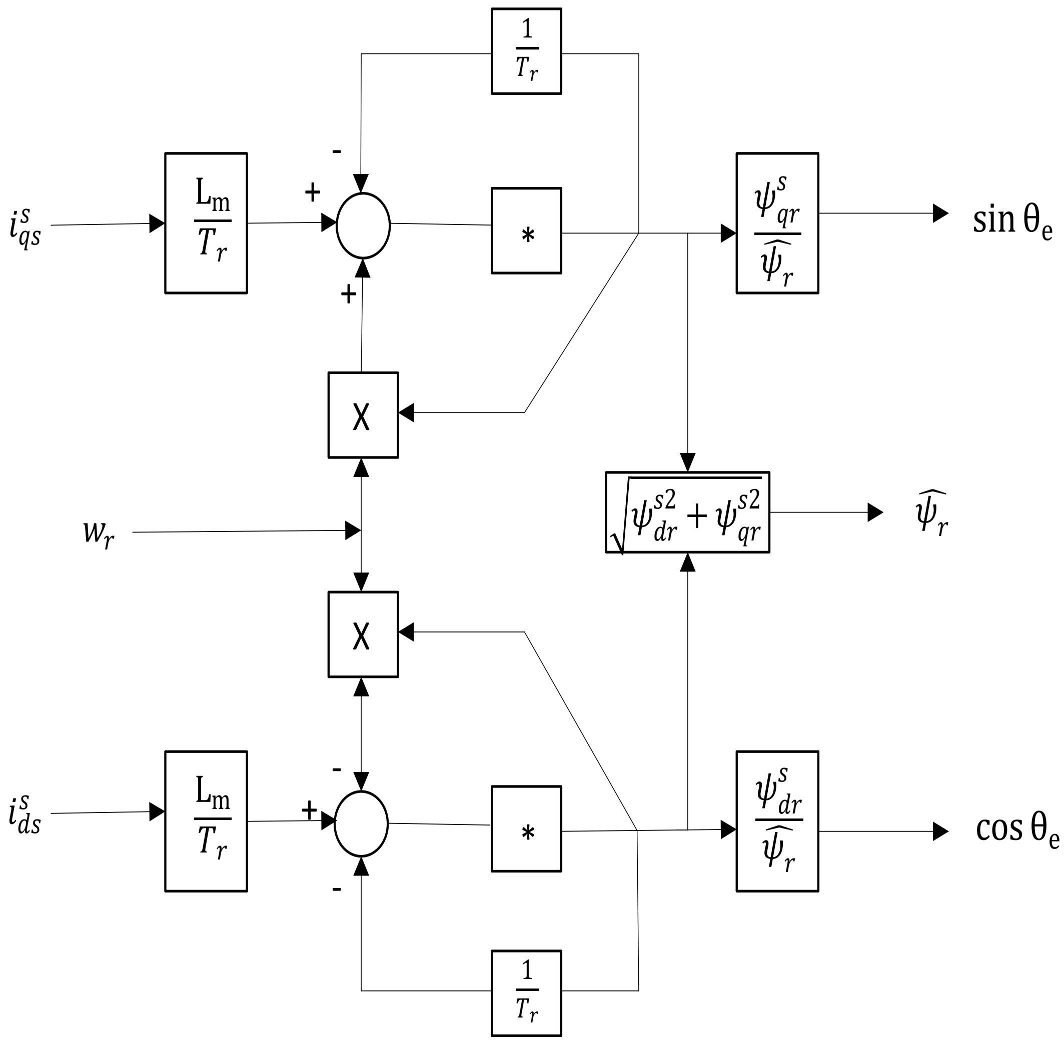


Figure 3. 1: Current model flux estimation

3.2 SENSORLESS VECTOR CONTROL

As the name suggests, this scheme eliminate sensor for speed and position tracking but we need both of them for precise control of motor. So instead of sensor we use the estimator for the calculation of speed. There are various type of speed estimators for speed estimation as given below :

- Slip calculation
- Direct synthesis from state equations
- Model referencing adaptive system (MRAS)
- Speed adaptive flux observer (Luenberger Observer)
- Extended Kalman filter (EKF)
- Slot harmonics
- Injection of auxiliary signal on Silent Rotor

In this project we focus in the Model reference adaptive system.

Model Referencing Adaptive System (MRAS)

This estimation technique was proposed by Schauder. In this method of speed estimation output of the reference model is compared with the output of adjustable model, and try to make the error to zero with the aid of gains. Figure 3. 1 shows the block for the model reference based adaptive system. The voltage model for the estimator uses the equation (3.15) and equation (3.16) with aid of equation (3.8) and equation (3.9) to calculate the rotor flux vector signals, as can be visualized from the Figure 3. 2. In the similar fashion the adaptive model uses the current model equation (3.25) and equation (3.26) to calculate the rotor flux vector signals. But this adaptive model can calculate the flux vector signal from the current signal but only if the rotor speed w_r is known, as shown in equation (3.25) and equation (3.26). This model having the current equation, which is called adaptive because of the speed term. The error term produced from the two models is fed again in to the adaptive model with gains, to acquire the required speed.[1]

A block diagram for speed estimation by the MRAS technique is shown in Figure 3. 2. Consider the voltage model's stator –side equations, which are defined as a reference model. When the measured values of stator voltage and current signals are given to the reference model, it generates the rotor flux vector signals, as shown in

Figure 3. 2. The current model equations are also termed as adaptive model equations.

Designing the adaptation mechanism requires that the overall stability of the system should be maintained. And the estimated speed should also be converging to required speed with adequate dynamic performance.

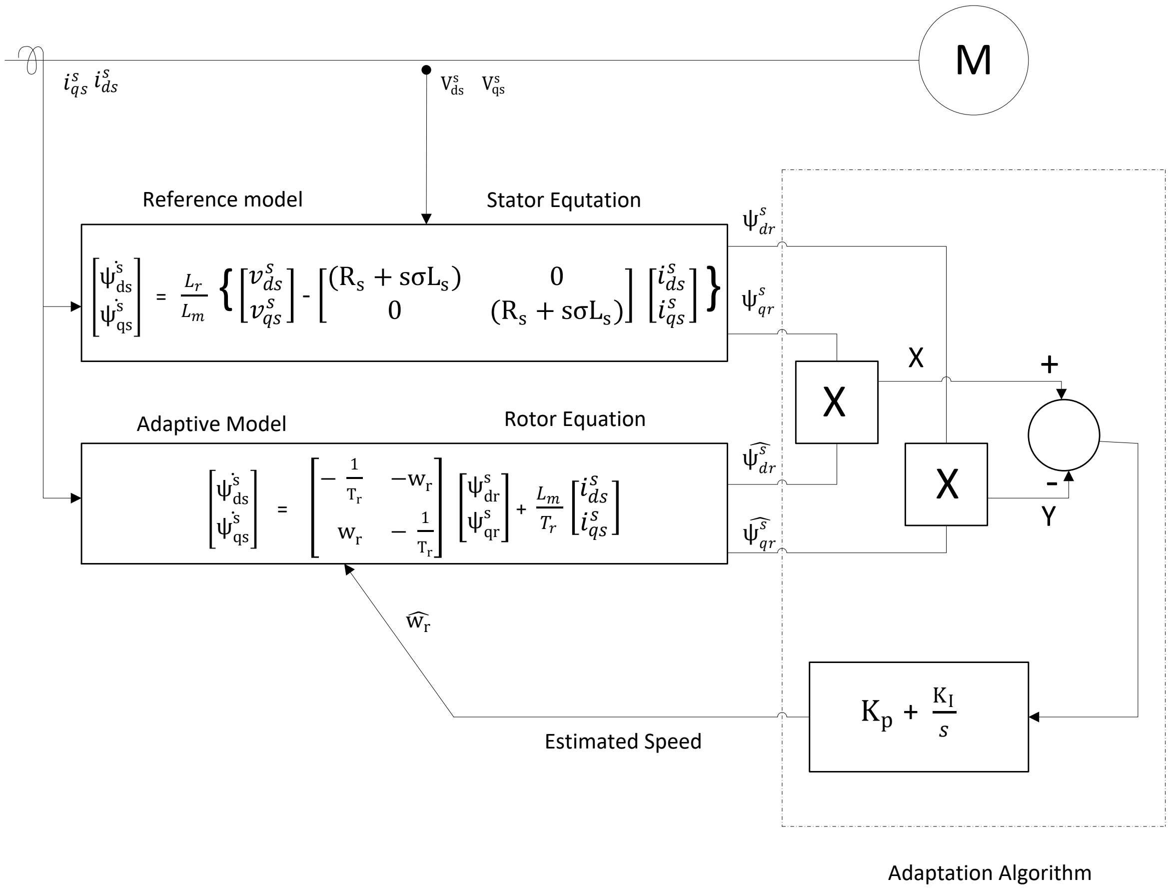


Figure 3. 2: Model of MRAS (Model reference Adaptive System)

3.3 CONCLUSION

In this chapter, flux estimation methods are discussed to calculate the unit vector for controlling action. Voltage and current models for the calculation of fluxes are also discussed with the MRAS controlling technique.

CHAPTER 4

4.1 MODELLING OF PROPOSED SYSTEM IN MATLAB/SIMULINK

In this chapter simulation of all the components of project is shown. Analysis under different load conditions is done.

This chapter includes the result and comparison of sensorless motor control with speed sensor feedback. The simulink is executed under different load conditions.

In the first part of this chapter, estimator simulation is shown. Afterwards the controller simulation is shown with three PI controllers, which are used in the controlling action.

4.2 MODEL REFERENCE ADAPTIVE SYSYTEM ESTIMATOR

The Figure 4. 1 shows the simulation of the estimator. As shown in Figure 4. 1, first block shows the axis transformation from three phases to two phases. Line voltages and current are converted in to the two axis transformation with the help of equation 3.5, 3.6 and 3.1, 3.2 respectively. Afterwards, block diagram in Figure 4. 2 is implemented along with adaptive mechanism.

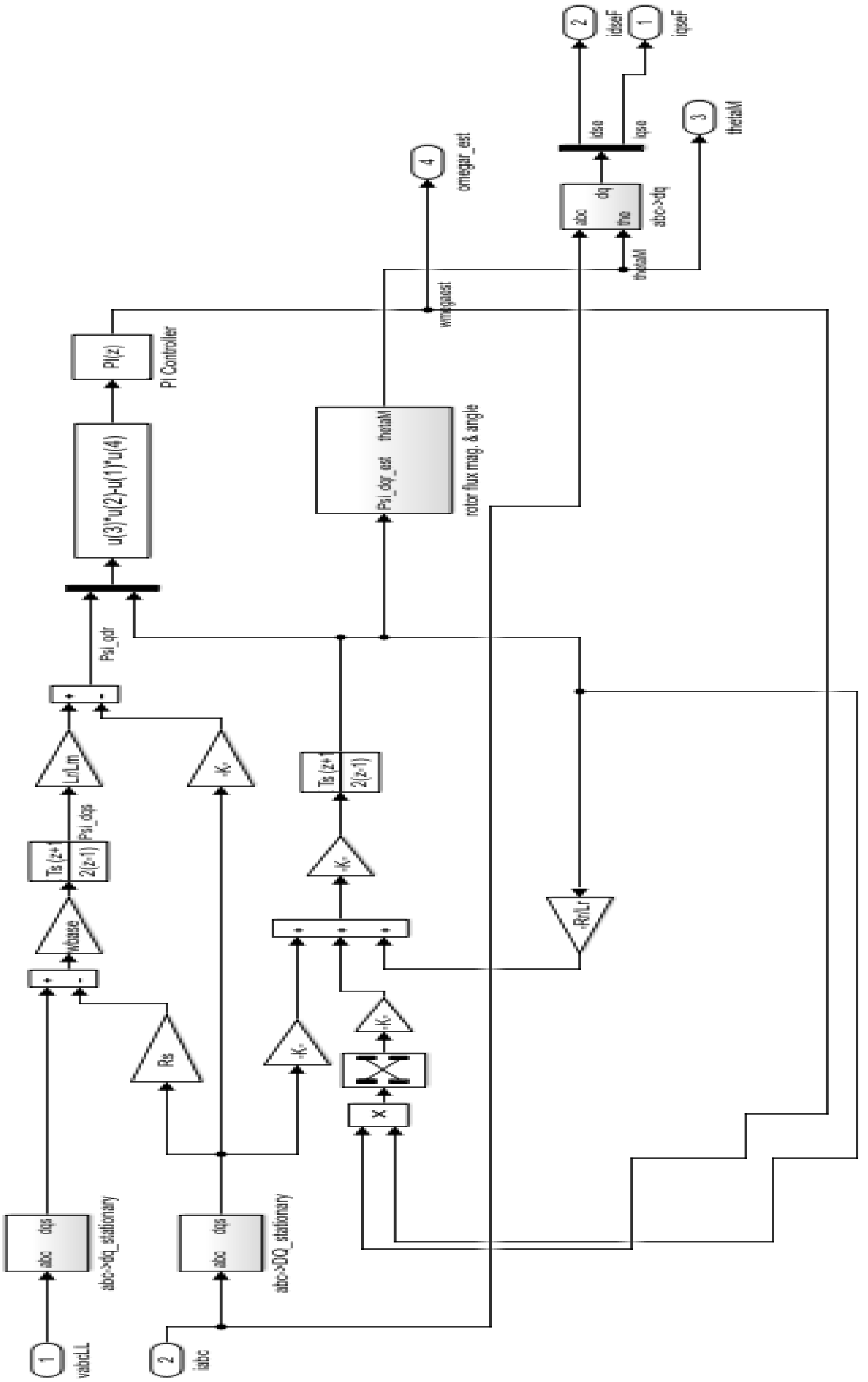


Figure 4. 1:Simulink Model of Model Reference Adaptive System (MRAS) Estimator

4.3 CONTROL SIMULINK

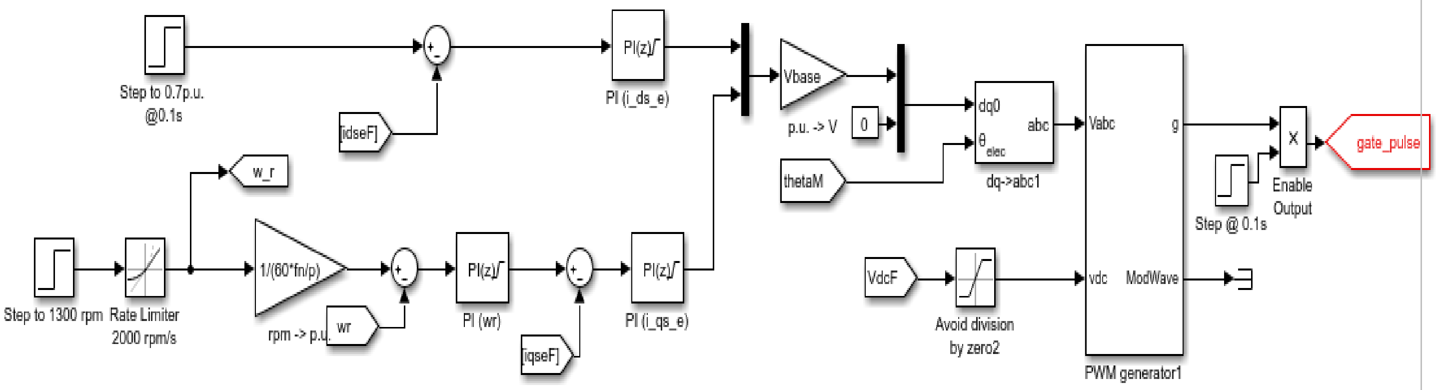


Figure 4. 2: Simulink Model of sensorless control

The above Figure 4. 2 shows the overall control setup for generating the gate signals for sensorless control. As shown in the Figure 4. 2, three PI controllers are used. One PI controller is used in flux control loop and remaining two are used in speed control loop. In speed control loop, first PI controller (PI(w_r)) is for the control of speed and the second is for the torque control. All the calculations in above control system are in per unit system.

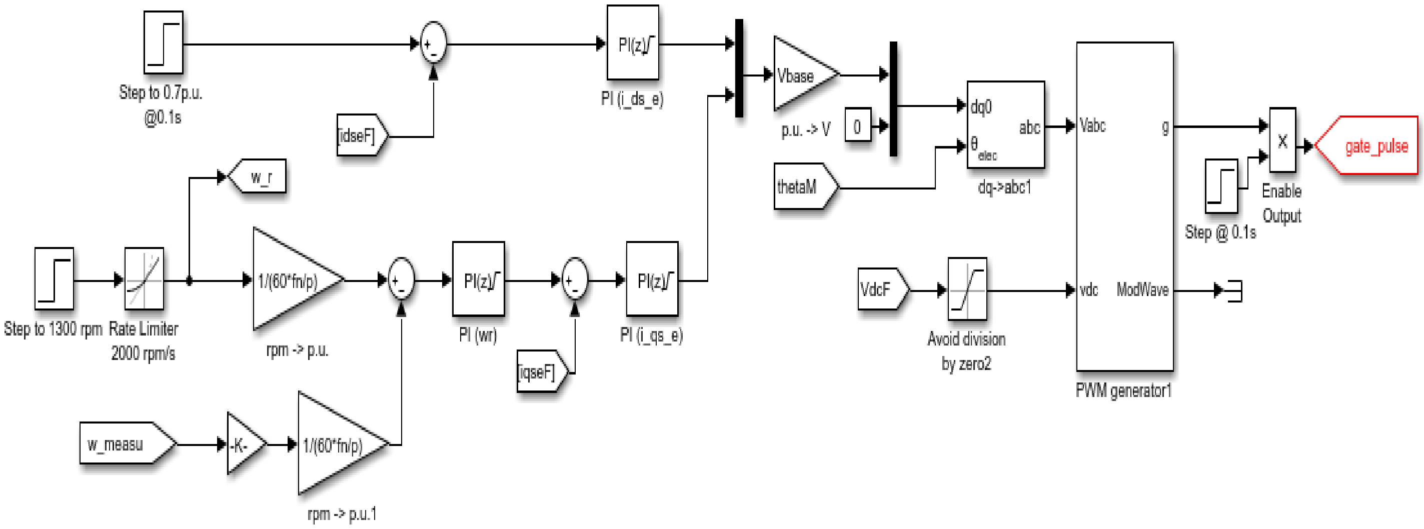


Figure 4. 3: Simulink Model of Control action with sensor feedback

Figure 4. 3 shows the same control action as shown by the Figure 4. 2 except that it uses speed feedback (w_measu) FROM block in MATLAB. Speed is converted to per unit value and then used for speed error calculation before PI controller in speed control loop.

4.4 SIMULINK INDUCTION MOTOR

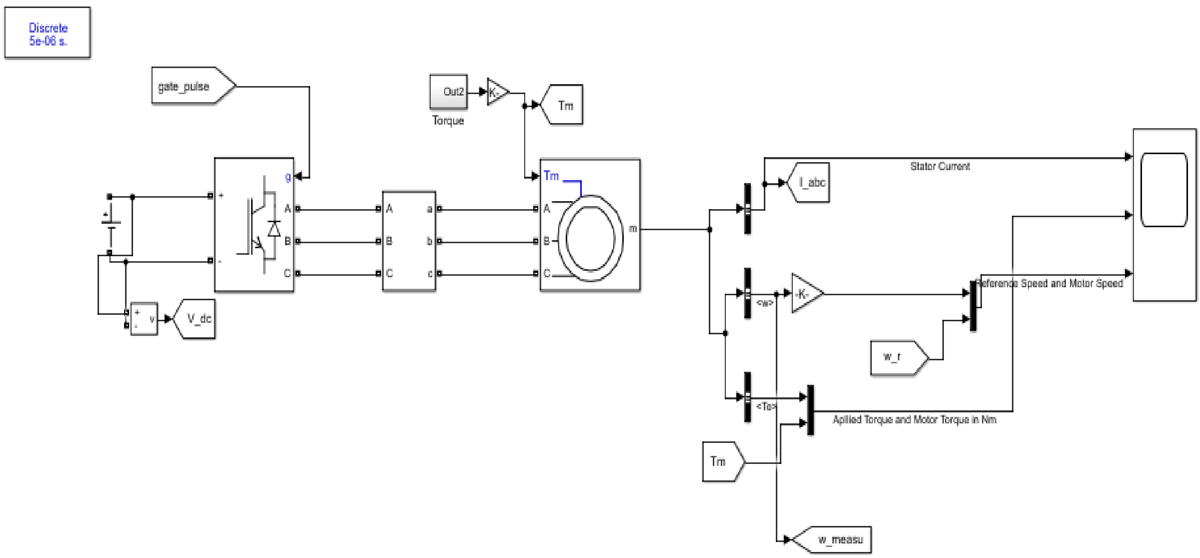


Figure 4. 4: Simulink model of Induction Motor with Inverter

Above Figure 4. 4 shows the main Simulink block for the motor control. In this Induction Motor block diagram, VI measurement block and IGBT inverter block are shown. Current, speed and torque outputs of Induction Motor are sent to the scope.

4.5 MOTOR PARAMETERS

The squirrel type Induction Motor used in the modeling is 4kW rated. The technical parameters, for the Induction Motor on which the test is carried out for both sensorless and speed feedback in the MATLAB, are given in the Table 1 shown below.

Table 1 : Parameters considered for the Induction Motor

Power (W)	4000
Rated Voltage (Volts)	400
Rated Current (Ampere)	5.44
Rated Speed (Rpm)	1430
Pole Pairs	2
Stator Resistance (Ohm)	1.405
Stator Leakage Reactance (Henry)	0.005839
Rotor Resistance Referred To The Stator Side (Ohm)	1.395
Rotor Leakage Reactance Referred To The Stator Side (Henry)	0.005839
Magnetizing Reactance (Henry)	0.1722
Inertia (Kg.Meter^2)	0.0131
Rated Frequency (Hz)	50

4.6 CONCLUSION

In this chapter the simulink models for the sensorless control and speed feedback control for Induction Motor, are shown. Simulink model for the MRAS control is also shown in this chapter.

CHAPTER 5

5.1 RESULT AND DISCUSSION

In this chapter, results for the speed control of Induction Motor for sensorless and speed feedback are discussed.

5.1.1 DYNAMIC PERFORMANCE OF INDUCTION MOTOR FOR NO LOAD AT RATED SPEED

Figure 5. 1 shows the speed performance of Induction Motor at rated speed of 1430 rpm. Top View of scope in Figure 5. 1 shows the current response , bottom left shows the speed response and bottom right shows the torque response of Induction Motor for MRAS control of Induction Motor . Step response of speed (1430 rpm) is given with a rate limiter to the controller. Overall rise time for the step response is around 0.25 second afterward current gets settled. Specific values of phase currents are Ia=-3.4 Amp, Ib=7 Amp and Ic=-3.8 Amp at 0.085 sec after the start up, sum of which shows that the system is balanced also. Bottom left of Figure 5. 1 shows the speed response of the controller corresponding to the reference speed and it can be observed that the response is quite good for tracking the reference speed. Bottom right of Figure 5. 1, shows that the motor torque gets settled after approximately 0.25 seconds and oscillates around it (zero load torque) with maximum and minimum value of it around the 3 Nm, giving the zero average value as required torque (as shown by blue line).

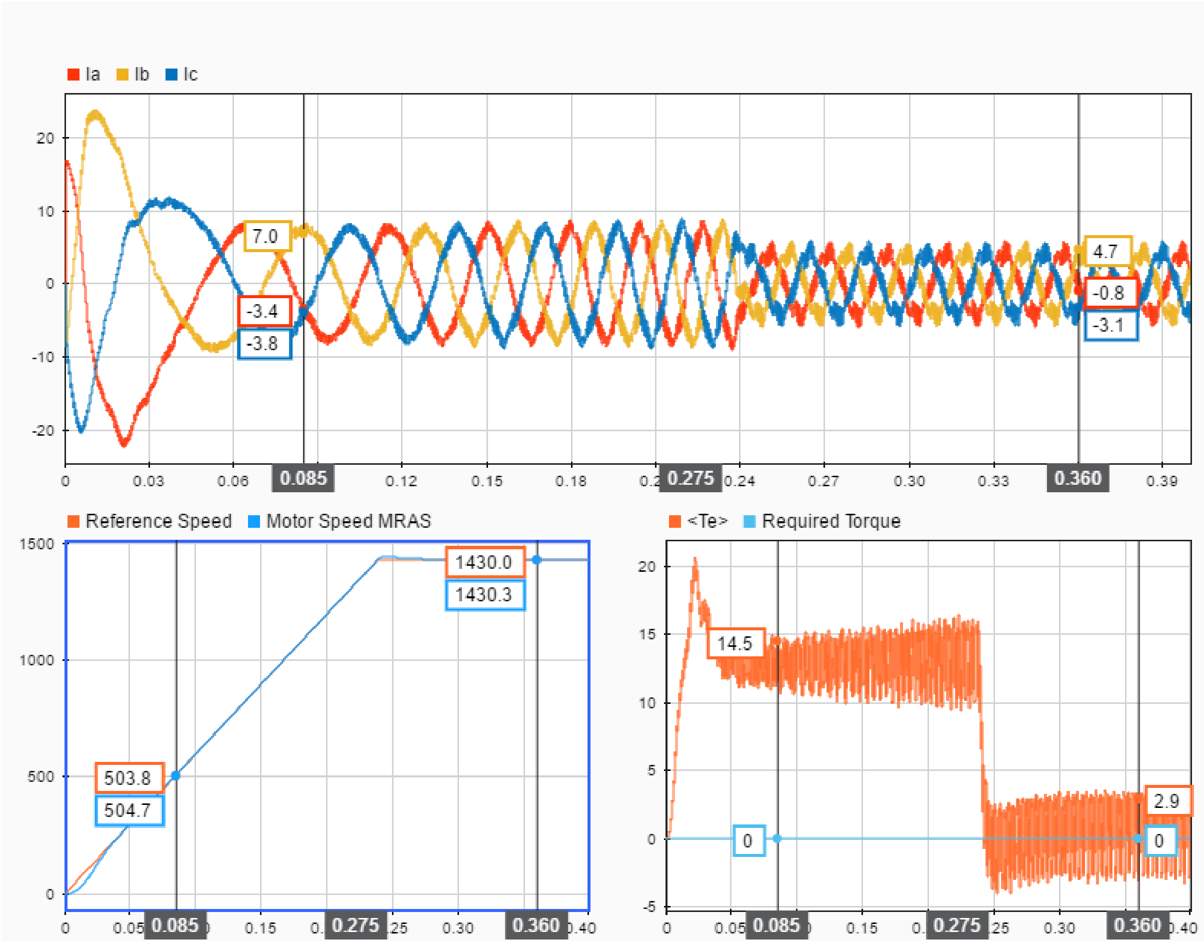


Figure 5. 1: Dynamic performance of IM for sensorless control at rated speed for no load

Figure 5. 2 shows the response of Induction Motor control for the rated speed of 1430 rpm for speed feedback remaining all the condition as before. Controlling action shows the good response as the motor tracks the specified speed of 1430 rpm very accurately as shown in the bottom left of Figure 5. 2. While rising for the rated speed, current is calculated at 0.085 second and the sum up of all three phase currents is approximately zero, showing the balanced system. Further, at 0.360 seconds the sum up of current is approx to zero. Again when the speed settles, current is measured at 0.360 seconds as shown, it shows the balance system and torque is also zero as shown in bottom right of the Figure 5. 2. On comparing the Figure 5. 1 and Figure 5. 2 we can observe that the response for the sensorless control is as good as for the speed feed back at no load condition.

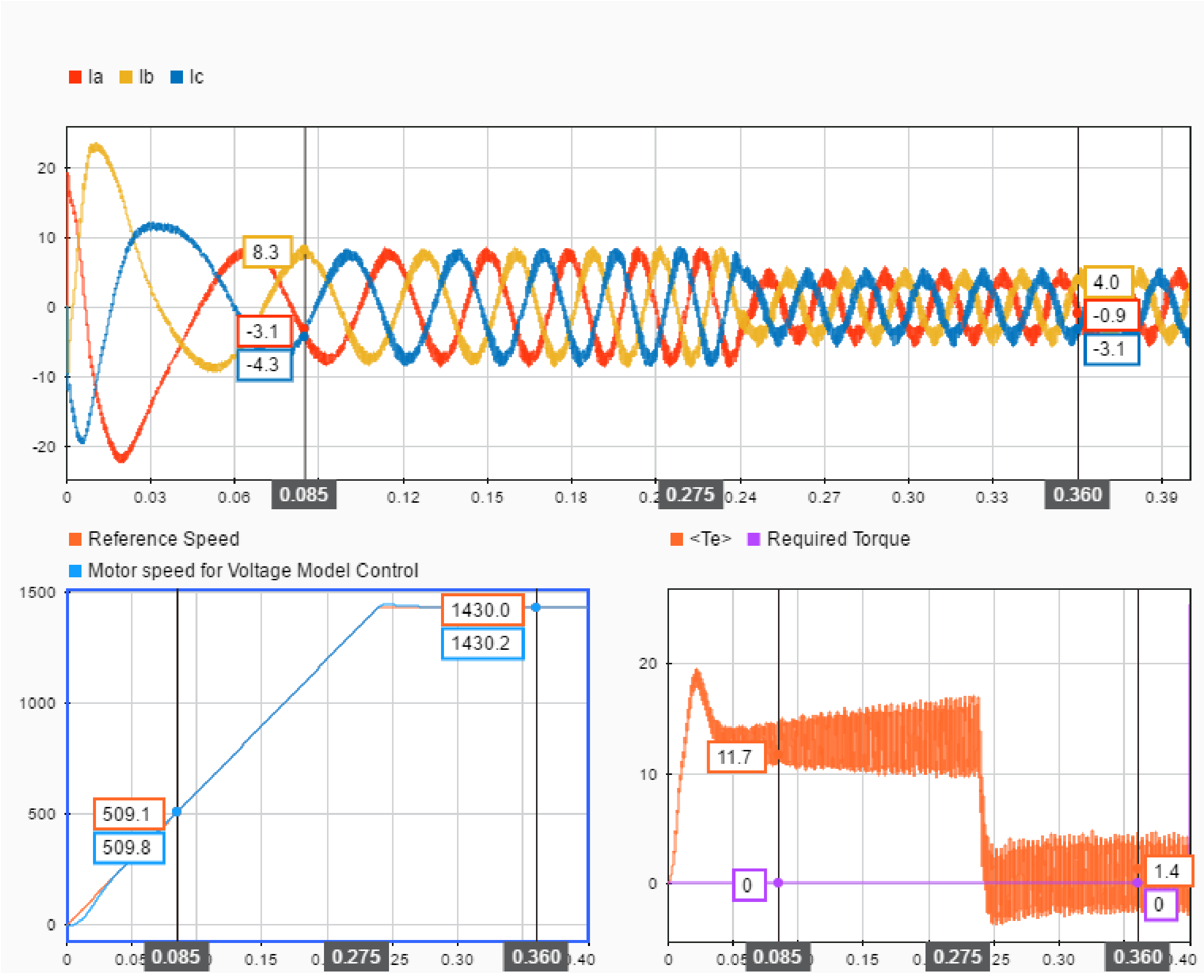


Figure 5. 2 : Dynamic performance of IM for speed feedback at no load

5.1.2 DYNAMIC PERFORMANCE OF INDUCTION MOTOR FOR RATED LOAD RATED SPEED

Figure 5. 3 shows the performance for the Induction Motor for the rated load at rated speed for sensorless control. As shown in the bottom right of Figure 5. 3, the full load of 25.5 Nm is given at 0.3 seconds after motor has attained the rated speed at approx 0.25 second. The mentioned figure shows that the motor is providing the rated torque. The torque is oscillating around the given torque with in confined boundaries, averaging up in the full load torque.

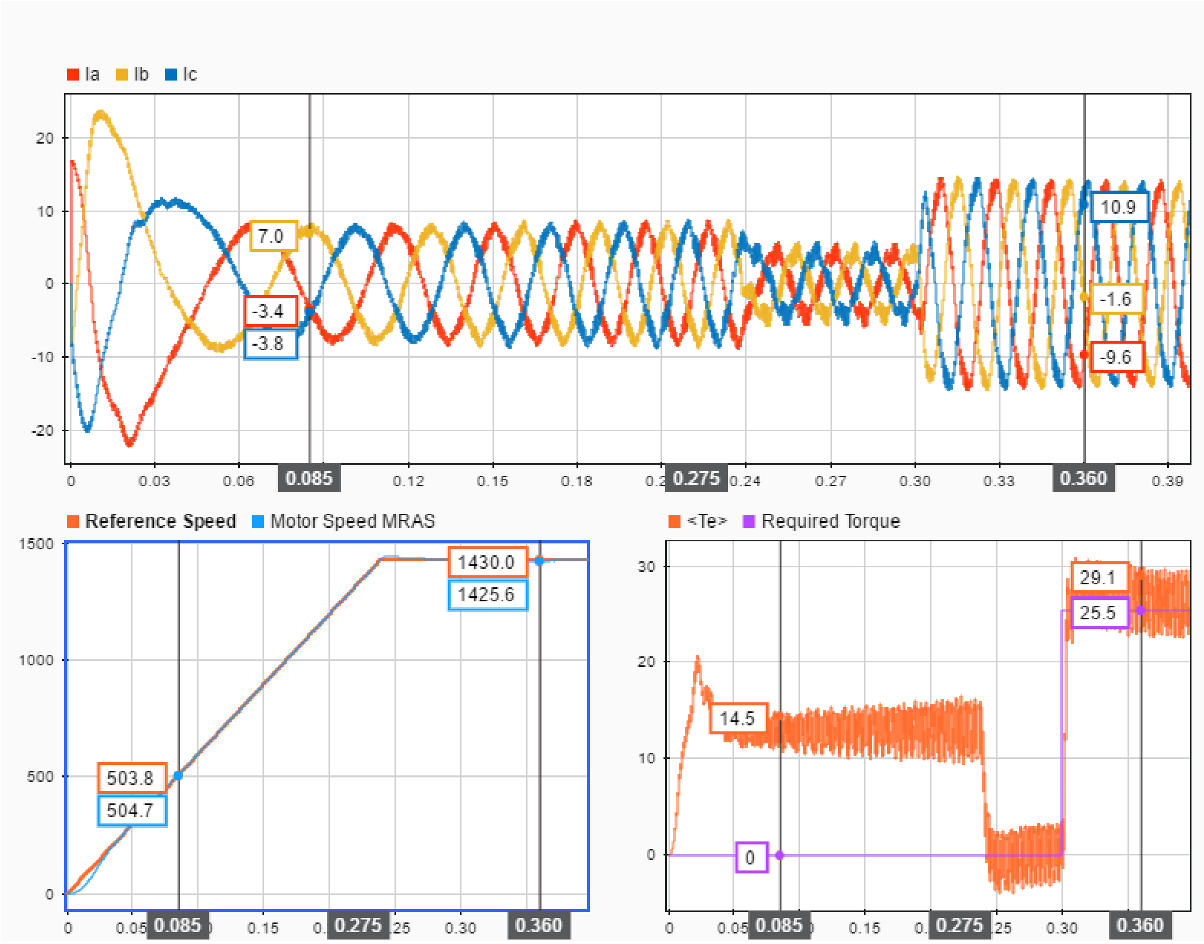


Figure 5. 3: Dynamic performance of IM for sensorless control at rated speed for full load

Figure 5. 4 shows the motor current in top, bottom left shows the speed and the bottom right shows the motor torque along with the given load torque for the speed feedback control. The motor attains the rated torque quite well as shown in figure.

On comparing the results for both sensorless and speed feedback control for the rated load, we get that the motor performance for sensorless is quite well.

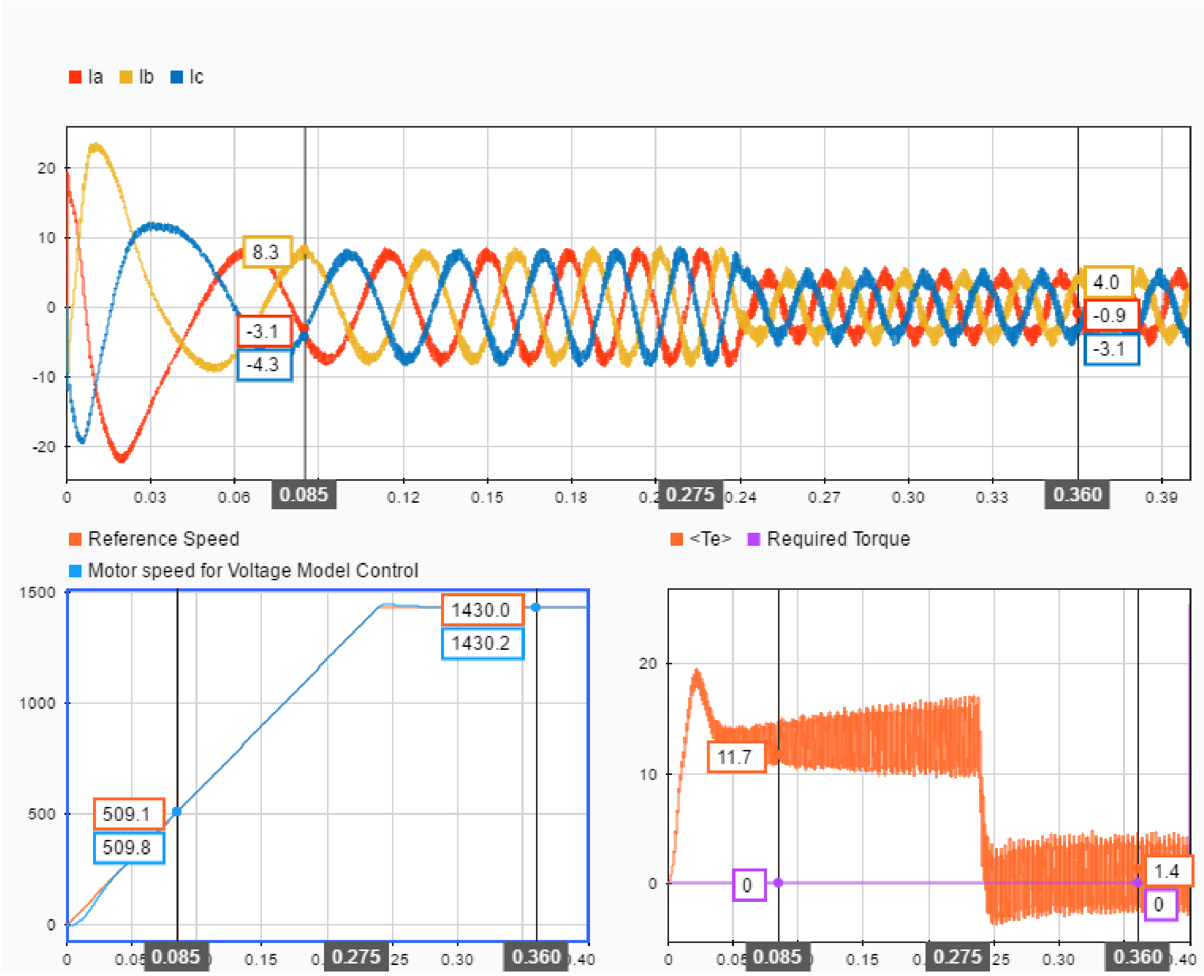


Figure 5. 4: Dynamic performance of the IM at full load for speed feedback

5.1.3 DYNAMIC PERFORMANCE OF INDUCTION MOTOR FOR STEP CHANGED IN LOAD AT RATED SPEED

Figure 5. 5 shows the response of the MRAS control Induction Motor at rated speed for step change in load, firstly the full load torque is applied at 0.3 second to the motor than gradually the torque reduces to half of the full load at 0.5 second. Afterwards the torque reduced to zero. At 0.85 second 75% of the load torque is given and it is found that the motor is continuously able to provide the required speed within the stability limit.

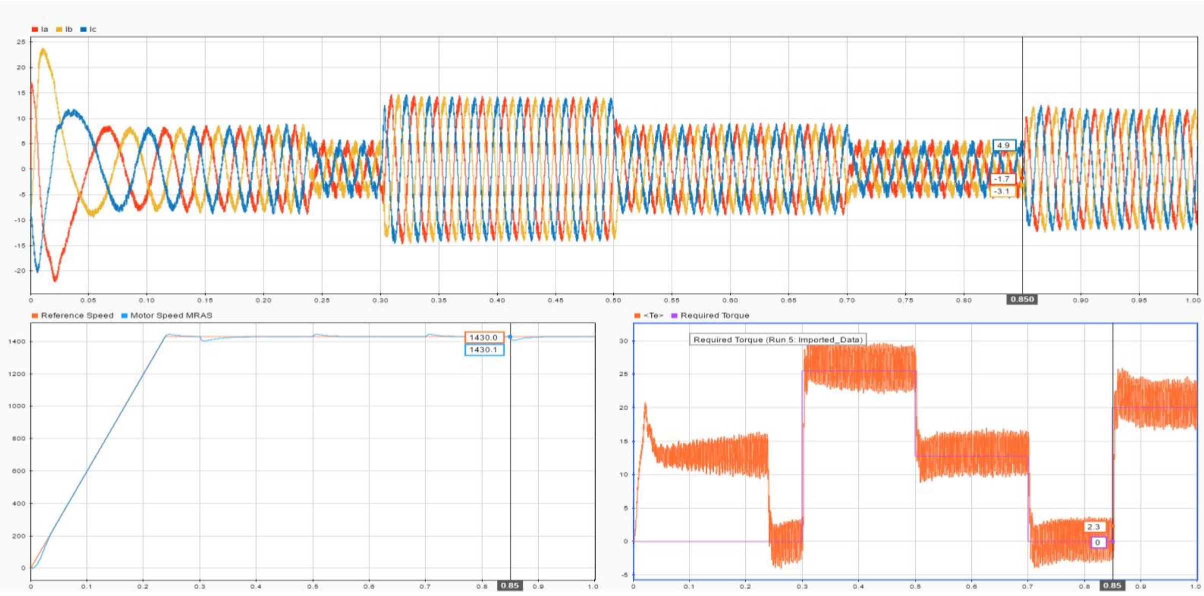


Figure 5. 5: Dynamic performance of IM for sensorless control at step change in load for rated speed

Similarly Figure 5. 6 shows the response for the speed feedback control at rated speed and its performance is quite well for tracking the speed at different load conditions. At 0.3 second 100% load is given, then it is reduced to 50% at 0.5 second, afterwards it reduces to zero. Again at 0.85 seconds 75% of full load is given and the output speed of motor is traced for the reference speed and the result is good. While on comparing the result of Figure 5. 6 and Figure 5. 5 we can observe that the sensorless control is showing the good performance.

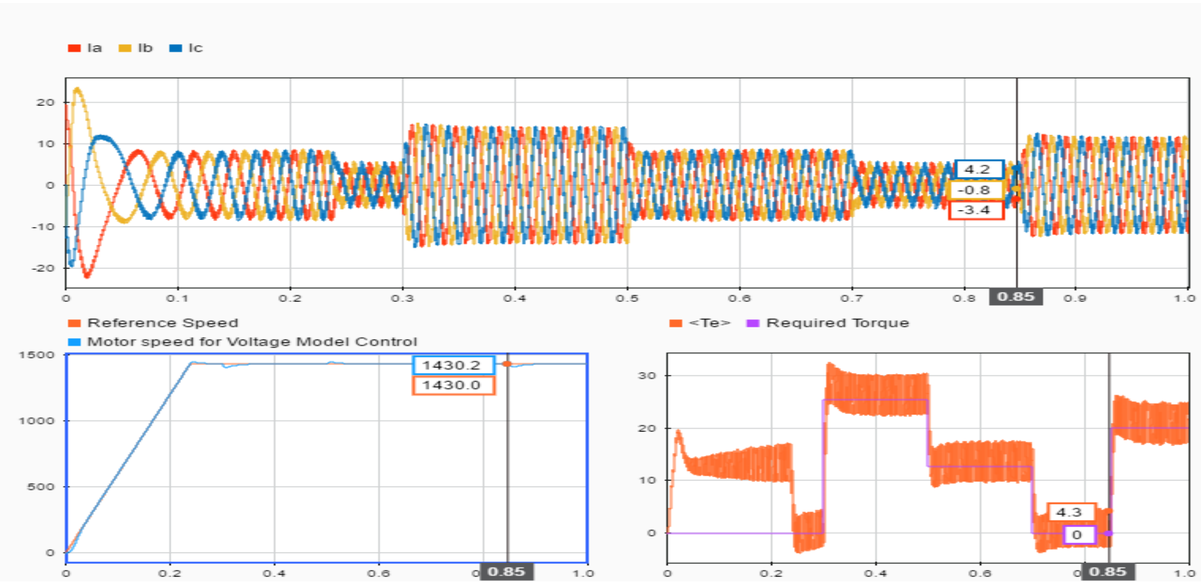


Figure 5. 6: Dynamic performance of IM at step change in load for speed feedback control

5.1.4 DYNAMIC PERFORMANCE OF INDUCTION MOTOR FOR STEP CHANGED IN LOAD AT 150 RPM

Bottom left of Figure 5. 7 shows the speed response for sensorless control at 150 rpm (which is approximately 10.5% of the rated) with the torque response at step change in load on the bottom right. Change in load is given at 0.3 second, 0.5 second, 0.7 second and 0.85 second with the corresponding changes in the speed. The speed response shows the noise at the mentioned specified time, but the controller is able to track the speed well at low speed. Figure 5. 7 shows the measured current at 0.465 second which is found to be -7.5amp for R phase, -5.6amp for the B phase and 13.4amp for the Y phases respectively. On summing the above phases currents we can say the controller is providing almost the balanced supply to the Induction Motor.

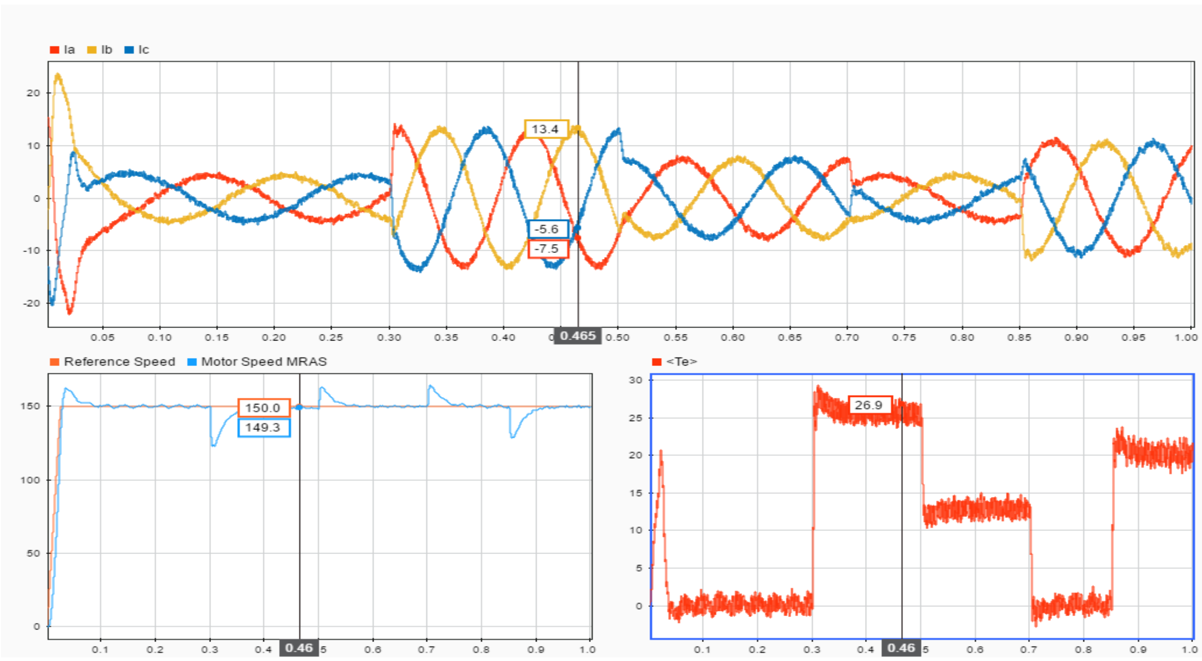


Figure 5. 7: Dynamic performance of IM at 150 rpm for sensorless control

Figure 5. 8 shows the speed and torque response along with the current in the phases for speed feedback control of Induction Motor . The response is for step changes in load as for the sensorless control. The noise at the 0.3 second, 0.5 second, 0.7 second and 0.85 second is almost same as for the sensorless control. But closer view of the speed response as shown in Figure 5. 9, tells that the response for the sensorlees control is having more noises as compared to the speed feedback control.

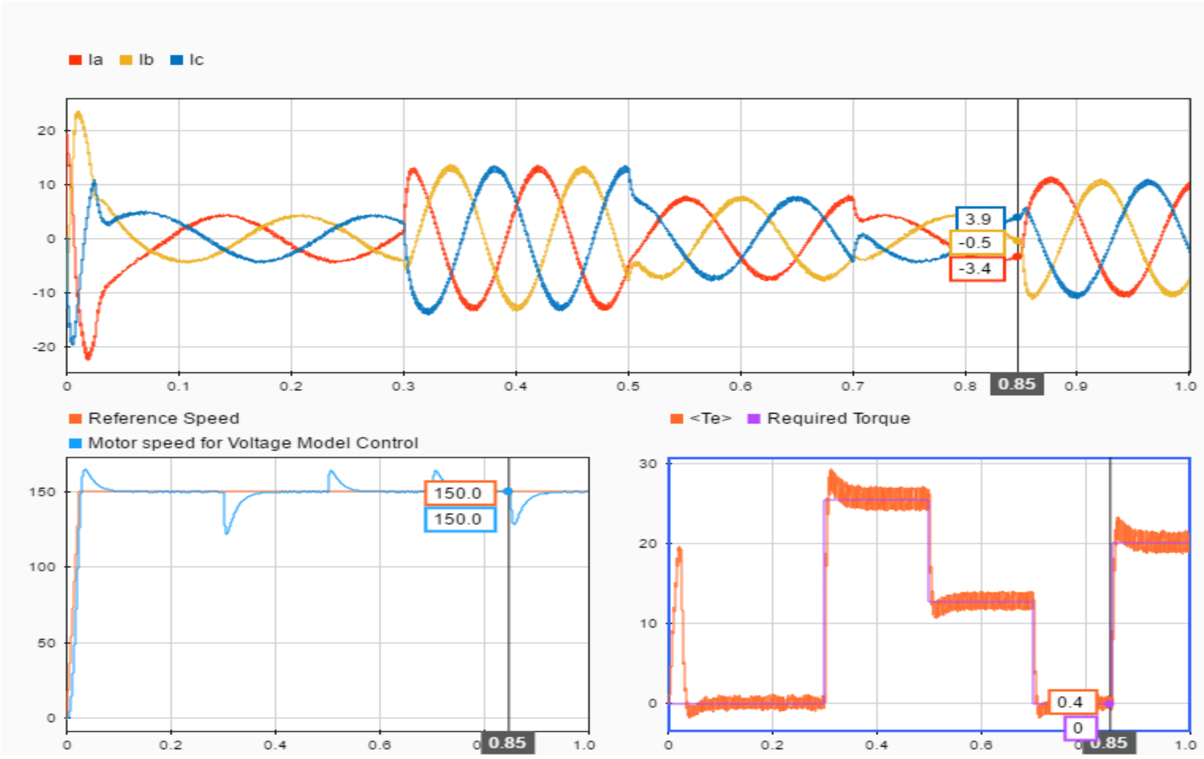


Figure 5. 8: Dynamic performance of IM at 150 rpm for speed feedback control

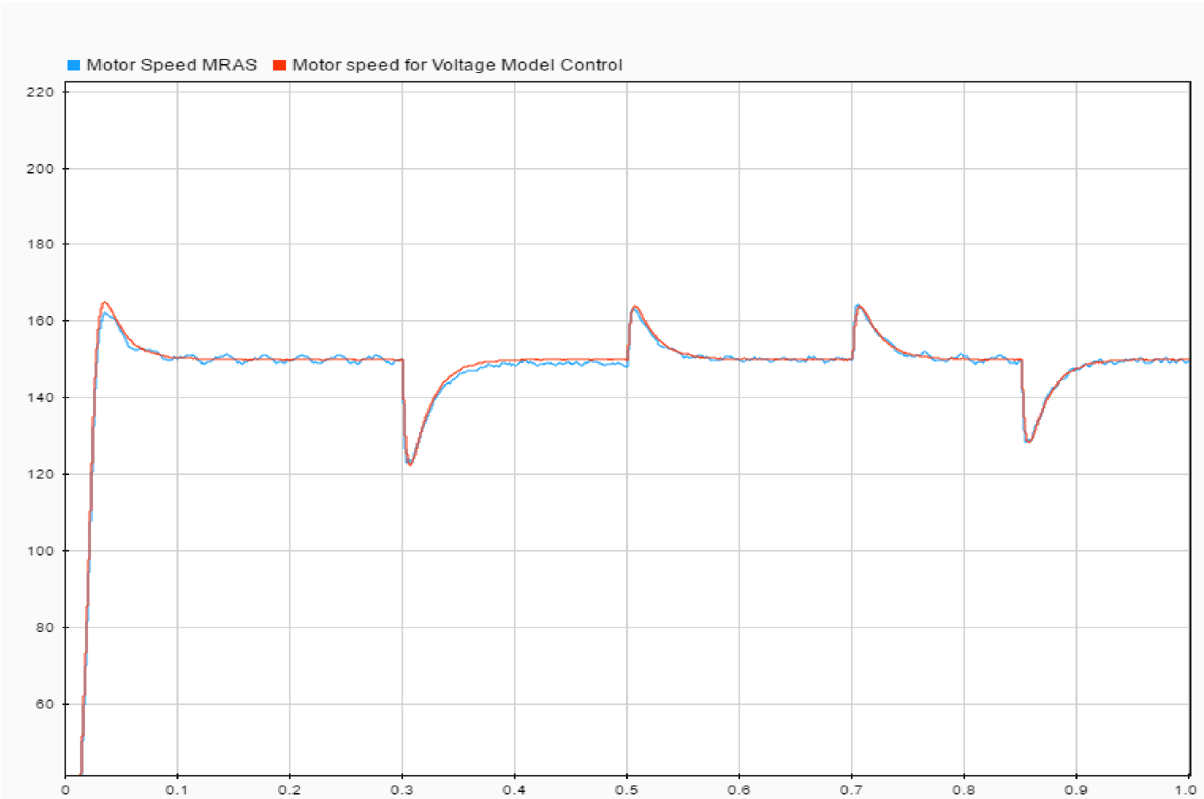


Figure 5. 9: Speed comparison at 150 rpm

As the speed goes down, approximately below 10% of the rated speed, speed tracking by the sensorless control does not show the satisfactory result and the output speed contain more noises as shown in the above Figure 5. 9 for the 150 rpm (which is 10.5% approximately). The sensorless control shows the good control over the wide range of speed but below 12% of the rated speed, the performance is not up to the mark but over all for the wide range the performance is satisfactory.

5.2 CONCLUSION

In this chapter the result is presented for the sensorless and speed feedback control. It is found that the sensorless control provides the better speed control for wide range of speeds but below 12% of rated speed the MRAS based sensorless control is not quite effective.

CHAPTER 6

6.1 MAIN CONCLUSION

Simulink modeling of sensorless based control of Induction Motor drive using PI control is done in MATLAB. The Simulink is made for the speed feedback and without speed feedback and anticipated output is obtained. The speed of Induction Motor traces the reference speed with change in load.

It is observed that overall performance of Induction Motor is good with sensorless control. Speed is found to be following the reference speed in all loading conditions.

6.2 FUTURE SCOPE

Some workable recommendations for future work to the work carried out in this dissertation are given below:

The experimental execution of Induction Motor drive can be carried in PSCAD.

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APPENDIX

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%% Induction machine parameters



Pn =4000;     % W, nominal power
Vn = 400;     % V, rms phase-to-phase, rated voltage
fn = 50;      % Hz, rated frequency


p = 2;        % pole pairs

%for base value calculation

Vbase = Vn/sqrt(3)*sqrt(2);  % V, base voltage, peak, line-to-neutral
Ibase = Pn/(1.5*Vbase);      % A, base current, peak
Zbase = Vbase/Ibase;         % ohm, base resistance
wbase = 2*pi*fn;             % rad/s, base elec. radial frequency
Tbase = Pn/(wbase/p);        % N*m, base torque
Lb=Zbase/wbase               % Henery, Base inductance



% Motor Nominal Parameters

Rss    = 1.405;       % ohm, stator resistance
Lss    = 0.005839;    % henery, stator leakage reactance
Rrr    = 1.395;       % ohm, rotor resistance, referred to the stator side
Lrr    = 0.005839;    % henery, rotor leakage reactance, referred to the stator side

Lmutual = 0.1722;     % henery, magnetizing reactance

H=0.0131;             % Kg.metersqare

%For pu calculation

Rs  = Rss/Zbase;      % pu, stator resistance
Lls = Lss/Lb;         % pu, stator leakage inductance
Rr  = Rrr/Zbase;      % pu, rotor resistance, referred to the stator side
Llr = Lrr/Lb;         % pu, rotor leakage inductance, referred to the stator side
Lm  = Lmutual/Lb;     % pu, magnetizing inductance
Lr = Llr+Lm;          % pu, rotor inductance
Ls = Lls+Lm;          % pu, stator inductance

sigma=1-(Lm*Lm)/(Ls*Lr);
```