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Model Reference Adaptive System (MRAS) Based Speed Sensorless Vector Control of Induction Motor Drive

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Abstract - This paper presents a Model Reference Adaptive System (MRAS) based speed sensorless estimation of vector controlled Induction Motor Drive. MRAS based techniques are one of the best methods to estimate the rotor speed due to its performance and straightforward stability approach. Depending on the type of tuning signal driving the adaptation mechanism, MRAS estimators are classified into rotor flux based MRAS, back e.m.f based MRAS, reactive power based MRAS and artificial neural network based MRAS. In this paper, the performance of the rotor flux based MRAS for estimating the rotor speed was studied. Overview on the IM mathematical model is briefly summarized to establish a physical basis for the sensorless scheme used. Further, the theoretical basis of indirect field oriented vector control is explained in detail and it is implemented in MATLAB/SIMULINK.

Keywords - Model Reference Adaptive System (MRAS), Sensorless Control, Vector Control, Indirect Field Oriented Control.

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I. INTRODUCTION

Induction motors are rugged and inexpensive machines, therefore much attention is taken while implementing the drive system for various applications with different control requirements [1]. An induction machine has many advantages, especially cage rotor induction machine, when compared with DC machine [2]. However, an induction machine requires more complex control schemes than DC motors because of its highly nonlinear and coupled dynamic structure [3]. Conventional open-loop control of variable frequency induction motor drives may provide a satisfactory solution under limited conditions. However, these methods are unsatisfactory when high performance dynamic operation is required. [4]. Therefore, highly developed control schemes are needed to improve the performance of the induction motor drive comparable with DC motors [5]. Recent evolutions in the area of control systems, power electronics, powerful and cheap microcontrollers, DC motors are replaced by an induction motor in the industry.

Variable speed IM drives use mainly PWM techniques to generate a polyphase supply of a given frequency [6, 7]. Most of these induction motor drives are based on keeping a constant voltage/frequency (V/f) ratio in order to maintain a constant flux in the machine. Although the control of V/f drives is relatively simple, the torque and flux dynamic performance is extremely poor [7]. As a consequence, a great quantity of industrial applications that require good torque, speed or position control still use DC machines [8, 9].

Over the past few decades a great deal of work has been done into techniques such as Field Oriented Control, Direct Torque Control and Space Vector Pulse Width Modulation [10]. Field oriented control (FOC) or vector control (VC) was introduced by Hasse and Blaschke from Germany, in 1969 and 1971 respectively [6]. On the contrary to the scalar control, the development of FOC control scheme is based on dynamic model of the IM where the voltages, currents and fluxes are expressed in space vector forms [11].

The representation of the motor's quantities using space vectors valid under both steady state and transient conditions hence with FOC, excellent transient response can be achieved. The rotor flux FOC scheme is based on the frame transformation of all quantities to a rotating frame fixed to the rotor flux. In this rotating rotor flux frame, all quantities rotating at synchronous speed will appear as DC quantities [12]. If the flux is aligned to the d axis of this reference frame, then the d component of the stator current represent the flux and q component of the stator current represent torque component. This means that utilizing FOC, the control of IM is transformed to a simple control scheme similar to the DC motor control where the torque and flux components are decoupled.

The way the rotor flux position is obtained determines the type of FOC as either direct FOC or indirect FOC. In indirect FOC, the flux position is obtained by adding the slip position to the measured rotor position, where as in direct FOC it is calculated (or can also be measured) based on the terminal variables and rotor speed [13].

Another emerging area of research involves the sensorless control of drive system which is different from conventional methods because it doesn’t require speed or position sensors. Removing these sensors gives a number of advantages such as increased reliability, lower production costs, reduced size and removal of excess cabling. Sensorless drives require less maintenance and are also more suitable for harsh inaccessible environments [14].

The study of speed sensorless control of the IM has undergone through maturing years when new techniques came into introduction to improve the previous techniques. The motivation is to find one method that can cater the entire problem related to speed sensorless IM. Among them, MRAS based techniques have been proven to be one of the best methods being proposed by the researchers due to its good high performance ability and straight-forward stability approach. The method was first proposed in [15] followed by [16] which consists of a reference model (RM), an adjustable model (AM) and an adaptation mechanism. RM is independent of the rotor speed whereas AM requires the rotor speed information. Through Landau’s idea of comparing the outputs of RM and of AM, the error between the two models can be minimized using the adaptation mechanism [17].

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The paper has been organized as follows: section II briefly explains the mathematical modeling of induction motor, section III demonstrate the indirect Field Oriented Control of the induction motor drive, section IV describes the Rotor Flux based MRAS Speed Observer, and the results of implemented Matlab models are shown in section V.

II. MATHEMATICAL MODELLING

The dynamic behavior of an induction motor is complex due to the coupling effect between the stator and rotor phases. Fig. 1 shows the dynamic d-q equivalent circuits of an induction machine.

The dynamic model of induction motor represented in terms of voltages and currents can be given in matrix form as [6]:

$$\begin{bmatrix} V_{qs}^c \\ V_{ds}^c \\ V_{qr}^c \\ V_{dr}^c \end{bmatrix} = \begin{bmatrix} R_s + L_s Þ & \omega_c L_s & L_m Þ & \omega_c L_m \\ -\omega_c L_s & R_s + L_s Þ & -\omega_c L_m & L_m Þ \\ L_m Þ & (\omega_c - \omega_r) L_m & R_r + L_r Þ & (\omega_c - \omega_r) L_s \\ -(\omega_c - \omega_r) L_m & L_m Þ & -(\omega_c - \omega_r) L_r & R_r + L_r Þ \end{bmatrix} \cdot \begin{bmatrix} i_{qs}^c \\ i_{ds}^c \\ i_{qr}^c \\ i_{dr}^c \end{bmatrix}$$

These equations are expressed in general reference frame denoted by the superscript ‘c’ and ‘Þ’ represents the derivative operator, d/dt. The dynamic model of the induction motor can also be rearranged with the stator and rotor flux linkages as the state variables [6].

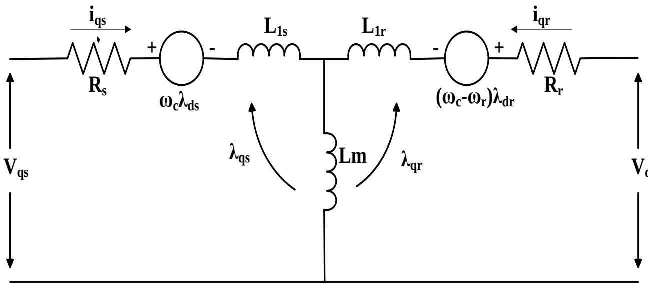
$$\begin{bmatrix} \dot{\Psi}_{qs}^c \\ \dot{\Psi}_{ds}^c \\ \dot{\Psi}_{qr}^c \\ \dot{\Psi}_{dr}^c \end{bmatrix} = \begin{bmatrix} \frac{-1}{\tau_s'} & -\omega_c & \frac{K_r}{\tau_s'} & 0 \\ \omega_c & \frac{-1}{\tau_s'} & 0 & \frac{K_r}{\tau_s'} \\ \frac{K_s}{\tau_r'} & 0 & \frac{-1}{\tau_r'} & -(\omega_c - \omega_r) \\ 0 & \frac{K_s}{\tau_r'} & (\omega_c - \omega_r) & \frac{-1}{\tau_r'} \end{bmatrix} \begin{bmatrix} \Psi_{qs}^c \\ \Psi_{ds}^c \\ \Psi_{qr}^c \\ \Psi_{dr}^c \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{qs}^c \\ V_{ds}^c \end{bmatrix} \quad (2)$$

Where $\tau_s' = \sigma \frac{L_s}{R_s}$, $\tau_r' = \sigma \frac{L_r}{R_r}$, $K_s = \frac{L_m}{L_s}$, $K_r = \frac{L_m}{L_r}$, $\sigma = 1 - K_s K_r$

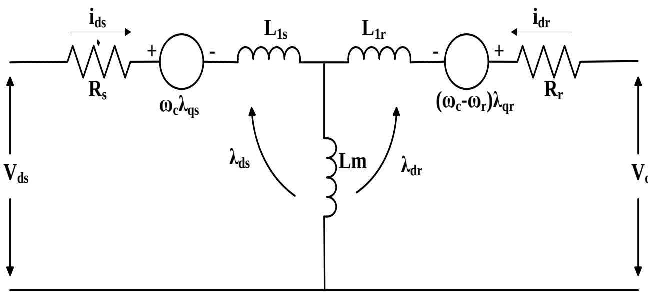
The speed ω_r in the above equations is related to the torque by the following mechanical dynamic equation,

$$T_e - T_L = J \frac{d\omega_r}{dt} + B\omega_r \quad (3)$$

$$T_e = \frac{3P}{4}\left(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}\right) \quad (4)$$



(a) q-axis circuit



(b) d-axis circuit

Fig. 1 Dynamic d-q equivalent circuits of an IM

III. INDIRECT FIELD ORIENTED CONTROL

A. *Principle of Vector Control*

To explain principle of vector control, an assumption is made that the position of rotor flux linkages phasor, Ψ_r is known. Ψ_r is at θ_f from a stationary reference, θ_f is referred to as field angle hereafter, and the three stator currents can be transformed into q and d axes currents in the synchronous reference frame by using the park’s transformation given below [7].

$$\begin{bmatrix} I_{qs}^e \\ I_{ds}^e \\ I_{os}^e \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta_f) & \cos\left(\theta_f - \frac{2\pi}{3}\right) & \cos\left(\theta_f + \frac{2\pi}{3}\right) \\ \sin(\theta_f) & \sin\left(\theta_f - \frac{2\pi}{3}\right) & \sin\left(\theta_f + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} \quad (5)$$

Stator current phasor, Is can be derived as

$$I_s = \sqrt{\left(I_{qs}^e\right)^2 + \left(I_{ds}^e\right)^2} \quad (6)$$

And stator phase angle is $\theta_s = \tan^{-1} \frac{I_{qs}^e}{I_{ds}^e}$ (7)

where I^e_{qs} and I^e_{ds} are the q and d axes currents in the synchronous reference frames that are obtained by projecting the stator current phasor on q and d axes, respectively. That the current phasor magnitude remains same regardless of the reference frame chosen to view it is evident from Fig. 2.

The current phasor I_s produces the rotor flux ψ_r and torque T_e. The component of current producing rotor flux phasor has to be in phase with ψ_r. Therefore resolving stator current phasor along ψ_r reveals the component i_f is the field producing component and i_t is the torque producing component perpendicular to it. By writing rotor flux linkages and torque in terms of these components

$$\Psi_r \propto i_f \quad (8)$$

$$T_e \propto \Psi_r i_t \propto i_f i_t \quad (9)$$

For vector control operation of the induction motor, the arbitrary reference frame must be aligned along the rotor flux linkage space phasor at every instant. It is therefore essential that the position of the rotor flux linkage space phasor θ_f, be accurately known at every instant. From the Fig. 2, the instantaneous rotor flux phasor position, θ_f can be written as

$$\theta_f = \theta_r + \theta_{sl} \quad (10)$$

Where θ_r is the rotor position and θ_{sl} is the slip angle. In terms of the speeds and time, the field angle is written as

$$\theta_f = \int (\omega_r + \omega_{sl})dt = \int \omega_s dt \quad (11)$$

This knowledge of rotor flux linkage space phasor position can be acquired either by measuring the flux directly or by estimating the flux from terminal variables i.e. by indirect means. This leads to two possible control techniques of induction motor namely: Direct field oriented control and Indirect field oriented control.

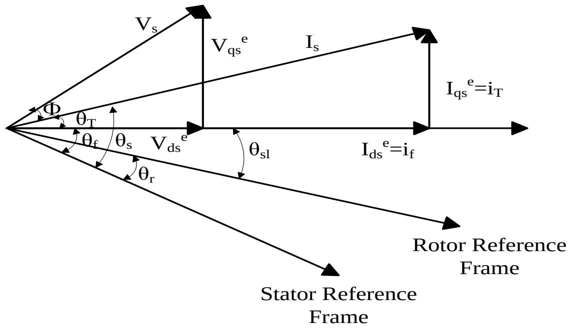


Fig. 2 Phase diagram of vector control

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B. Indirect Field Oriented Control

In an Indirect Field Oriented Control (IFOC) a flux estimator is used to estimate the required flux linkage space phasor magnitude and angular position θ_f as shown in Fig. 3. The shaft position is usually needed for estimating flux linkage space phasor position. This gives a more adaptable drive system, but this method would generally result in a more complex control system [18]. Since it is generally desirable to have a scheme which is applicable for all induction motors, the indirect field oriented has emerged as the more popular method. In the indirect field orientated control method the flux linkage space phasor is estimated from the motor model and which is sensitive to variations in machine parameter like the stator time constant or rotor time constant. In the rotor flux oriented control, the indirect rotor flux estimator is sensitive to the rotor time constant τ_r, of the motor. In stator flux oriented control, the indirect stator flux estimator is sensitive to the stator time constant of the motor. In the air gap flux oriented control, the indirect air gap flux estimator is sensitive to both the stator and the rotor time constants. Therefore, if the value of the motor parameter varies, the desired decoupled of the flux and the torque components of the stator current space phasor is not achieved and this leads to reduce the performance of the dynamic behavior of the drive system. In this paper, only rotor field orientation control is considered.

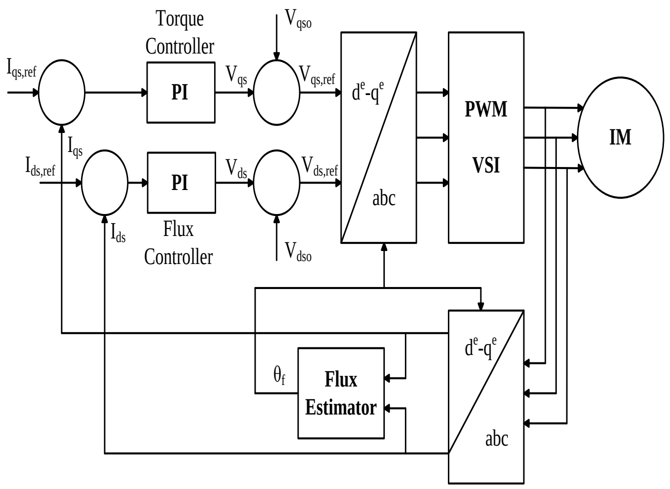

Fig. 3 Block diagram for Indirect Field Oriented Control

C. Rotor Flux Linkage Estimator

For indirect field oriented control, it is essential to estimate the flux linkage space phasor position. Therefore it is necessary to model the rotor flux linkages for rotor field orientation technique.

From the induction motor modeling Fig. 1, by eliminating the rotor currents

$$\frac{d\Psi_{dr}}{dt} + \frac{R_r}{L_r}\Psi_{dr} - \frac{L_m}{L_r}R_r i_{ds} - \omega_{sl}\Psi_{qr} = 0 \qquad (12)$$

$$\frac{d\Psi_{qr}}{dt} + \frac{R_r}{L_r}\Psi_{qr} - \frac{L_m}{L_r}R_r i_{qs} - \omega_{sl}\Psi_{dr} = 0 \qquad (13)$$

where $\omega_{sl} = \omega_e - \omega_r$

For decoupling control, it is desirable that

$$\Psi_{qr} = 0 \qquad (14)$$

that is, $\frac{d\Psi_{qr}}{dt} = 0$ (15)

So that the total rotor flux is $\hat{\Psi}_r$ directed on the d^e axis. Substituting the above conditions in the eqns. 12 & 13, we get

$$\frac{L_r}{R_r}\frac{d\Psi_r}{dt} + \Psi_r = L_m i_{ds} \qquad (16)$$

$$\Psi_r = L_m \frac{i_{ds}}{1+\tau_r \text{þ}} \qquad (17)$$

defining an equivalent rotor magnetizing current, i_{mr} as

$$i_{mr} = \frac{\Psi_r}{L_m} \qquad (18)$$

$$i_{ds} = i_{mr} + \tau_r \text{þ} i_{mr} \qquad (19)$$

From the above equation, the equivalent rotor magnetizing current i_{mr} is obtained by passing the direct axis component of the stator current i_{ds} through a first order low pass filter having time constant τ_r .The position of the rotor flux linkage space phasor ρ is obtained by integrating ω_e which is given by the sum of the electrical rotor speed ω_r and the slip speed ω_{sl}.

If rotor flux $\hat{\Psi}_r$= constant, which is usually the case, then from eqn. 16

$$\Psi_r = L_m i_{ds} \qquad (20)$$

In other words, the rotor flux is directly proportional to current i_{ds} in steady state.

Where ω_{sl} is given by $\omega_{sl} = \frac{L_m i_{qs}}{\tau_r \Psi_r}$ (21)

From eqn. 21, $\omega_{sl} = \frac{i_{qs}}{\tau_r i_{ds}}$ (22)

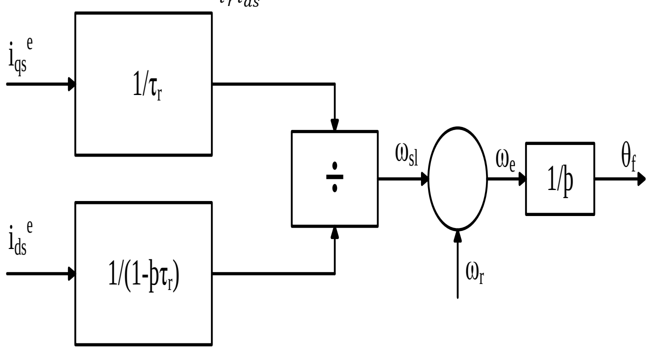

Fig. 4 Rotor Flux Estimator

IV. MODEL REFERENCE ADAPTIVE SYSTEMS (MRAS)

MRAS is one of the most popular adaptive control method used in motor control applications for tracking and observing system parameters and states. There are different model reference adaptive control methods such as series model, parallel model, direct model and indirect model etc. are available [14] [15].

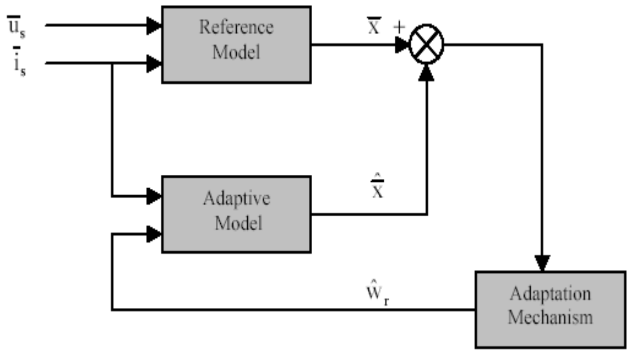

Fig. 5 Generalized model reference adaptive system

MRAS estimators consist of *reference model* and *adjustable model* as shown in Fig. 5.The speed-adaptation laws adjusts the estimate speed based on the outputs of reference and adjustable models. MRAS used in this model compares both the outputs of a reference and adaptive models, and processes the error between these two based on the appropriate adaptive laws that do not disturb the stability of the applied system [16]. In the MRAS technique, the desired process response to a command signal is specified by means of a parametrically defined *reference model*. An *adaptation mechanism* keeps track of the process output and the model output and calculates a suitable parameter setting such that difference between these outputs tends to zero [17].

An important issue in MRAS is the design of adaptive laws. The first examples of adaptive law designs made use of sensitivity models, and later the stability theory of Lyapunov, and Popov`s hyper stability theory, served as standard design methods, yielding a guaranteed stable adaptive system. In this paper, the detail of the adaptation mechanism design is not elaborated since it has been clearly discussed in [16] and [17].

A. Rotor Flux MRAS Estimator

In this MRAS scheme the rotor flux linkage (Ψ_r) is used as speed tuning signal. The motor voltages and currents are measured in a stationary frame of reference. It is also convenient to express these equations in that stationary frame. The speed can be calculated by the model referencing adaptive system (MRAS), where the output of the reference model is compared with the output of an adjustable model until errors between the two models vanish to zero. A block diagram for speed estimation by this MRAS technique is shown in the Fig. 6. Consider the voltage model's stator side equations (23) and (24) which are defined as a reference model.

The model receives the machine stator voltage and current signals and calculates the rotor flux vector signals, as indicated. From the stator voltage equations in the stationary frame, the Reference model equations can be obtained as:

<u>*Reference model equations*</u>

$$\dot{\Psi}_{dr} = \frac{L_r}{L_m} v_{ds} - \frac{L_r}{L_m}(R_s + \sigma L_s \frac{d}{dt}) i_{ds} \quad (23)$$

$$\dot{\Psi}_{qr} = \frac{L_r}{L_m} v_{qs} - \frac{L_r}{L_m}(R_s + \sigma L_s \frac{d}{dt}) i_{qs} \quad (24)$$

Where Ψ is flux linkage, L_r, L_m, L_s are inductances, R_s is resistance and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is motor leakage coefficient. The subscripts r and s denotes the rotor and stator values, respectively, referred to the stator and subscripts d and q denote d-axis and q-axis components in the stationary reference frame

The current model flux equations (25) and (26) are defined as an adaptive model in the Fig. 6. This model can calculate fluxes form the input stator currents only if the speed signal ω_r is known. With the correct speed signal, ideally, the fluxes calculated from the reference model and those calculated from the adaptive model will match, that is, $\Psi_{dr} = \widehat{\Psi}_{dr}$ and $\Psi_{qr} = \widehat{\Psi}_{qr}$, where $\widehat{\Psi}_{dr}$ and $\widehat{\Psi}_{qr}$ are the adaptive model outputs. An adaptation algorithm with P-I control, as indicated, can be used to tune the speed $\widehat{\omega}_r$ so that the error $\xi = 0$.

<u>*Adaptive model equations*</u>

$$\widehat{\Psi}_{dr} = \int \left(\frac{L_m}{T_r} i_{ds} - \omega_r \widehat{\Psi}_{qr} - \frac{1}{T_r} \widehat{\Psi}_{dr} \right) \quad (25)$$

$$\widehat{\Psi}_{qr} = \int \left(\frac{L_m}{T_r} i_{qs} + \omega_r \widehat{\Psi}_{dr} - \frac{1}{T_r} \widehat{\Psi}_{qr} \right) \quad (26)$$

where ω_r is rotor electrical speed and $T_r = \frac{L_r}{R_r}$ is the rotor time constant.

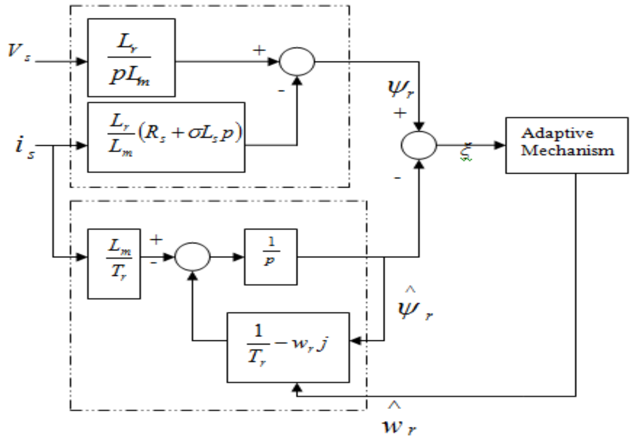

Fig. 6 MRAS based on rotor flux estimation

In designing the adaptation algorithm for the MRAS, it is important to take account of the overall stability of the system and to ensure that the estimated speed will converge to the desired value with satisfactory dynamic characteristics. Using Popov's criteria for hyper stability for a globally asymptotically stable system, we can derive the following relation for speed estimation:

$$\omega_r = \xi \left(K_p + \frac{K_i}{S} \right) \quad (27)$$

where $\xi = X - Y = \widehat{\Psi}_{dr} \Psi_{qr} - \widehat{\Psi}_{qr} \Psi_{dr}$ (28)

In steady state $\xi = 0$, Balancing the fluxes; in other words, $\Psi_{dr} = \widehat{\Psi}_{dr}$ and $\Psi_{qr} = \widehat{\Psi}_{qr}$. The MRAS in the Fig. 6 can be interpreted as a vector PLL in which the output flux vector from the reference model is the reference vector and the adjustable model is a vector phase shifter controlled by $\widehat{\omega}_r$.

V. SIMULATION RESULTS

The following induction motor parameters are chosen for the simulation studies:

$R_s = 0.855\Omega, R_r = 1.15\Omega, L_s = 0.10432H, L_r = 0.10432H$
$L_m = 0.1004\ H, f = 50\ Hz, J = 0.06\ kg - m^2, P = 6.$

Fig. 7 shows the complete Simulink model of induction motor, Fig. 8 shows the Simulink Model of Rotor Flux based MRAS Speed estimator and Fig. 9 shows the complete Simulink Model of sensorless indirect field oriented control of induction motor with Rotor Flux MRAS speed Observer.

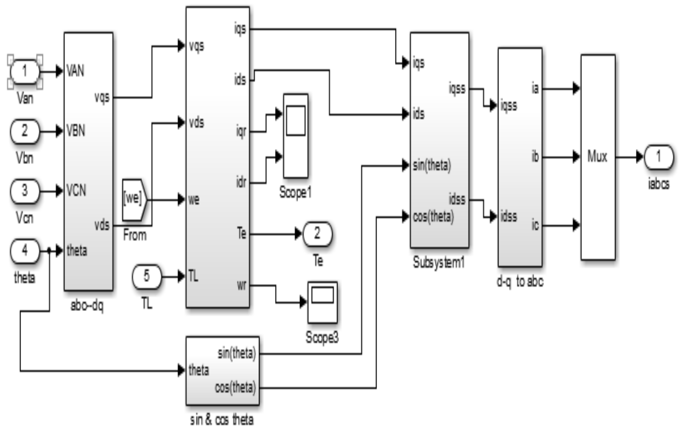

Fig. 7 Simulink Model of Induction Motor

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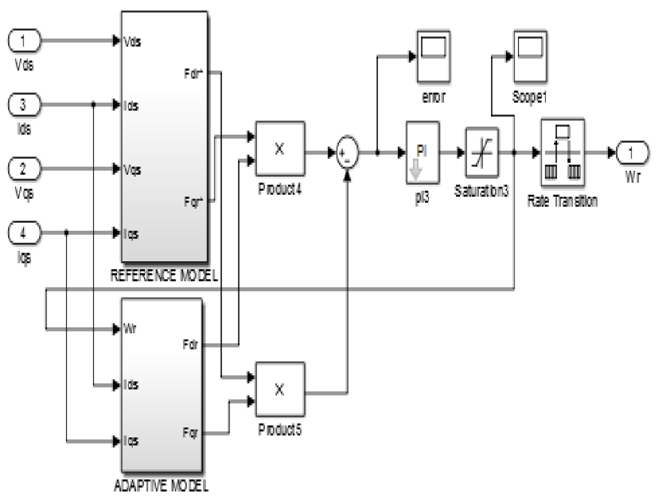

Fig. 8 Simulink Model of Rotor Flux Based MRAS Speed Observer

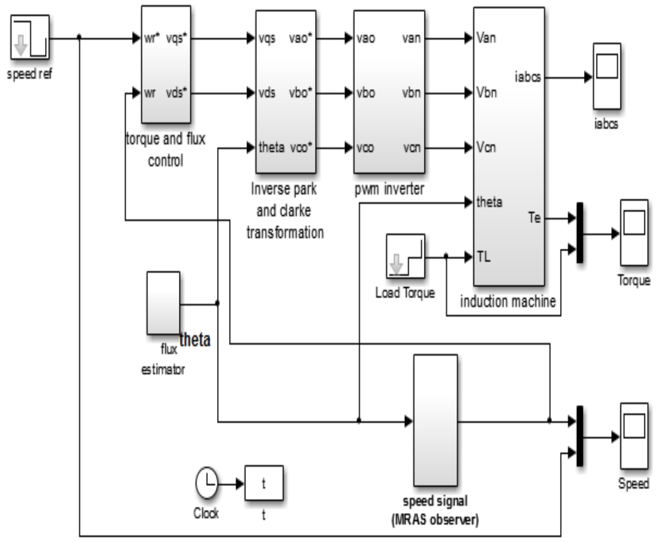

Fig. 9 Simulink Model of Indirect Field Oriented Control of IM Drive with MRAS Speed Observer

Sensorless vector control simulation of the induction motor is presented below. The response of the induction motor is shown in two different cases

1. with step changes in speed reference and load torque
2. with speed reversal (Four quadrant operation)

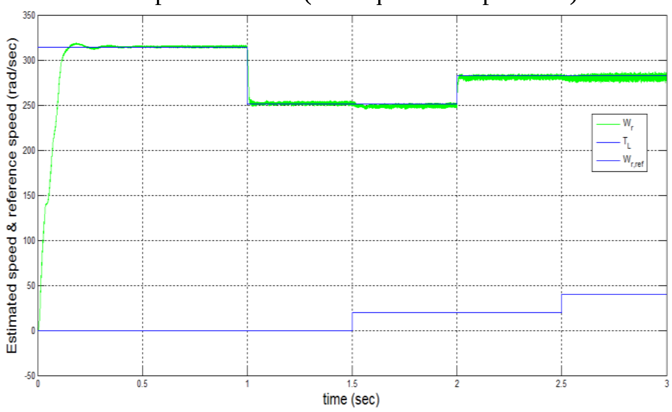

Fig. 10 Estimated and reference speed of the motor with step changes in load torque

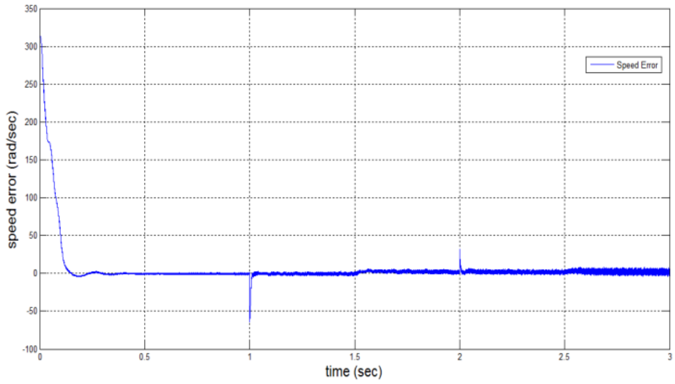

Fig. 11 speed error of the motor for changes in speed and load torque

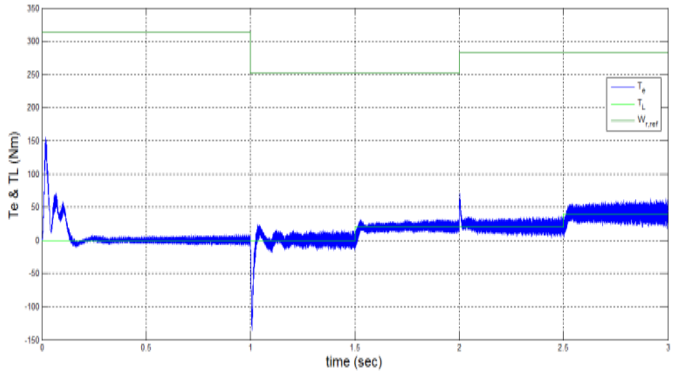

Fig. 12 Generated torque of the motor with step changes in load torque

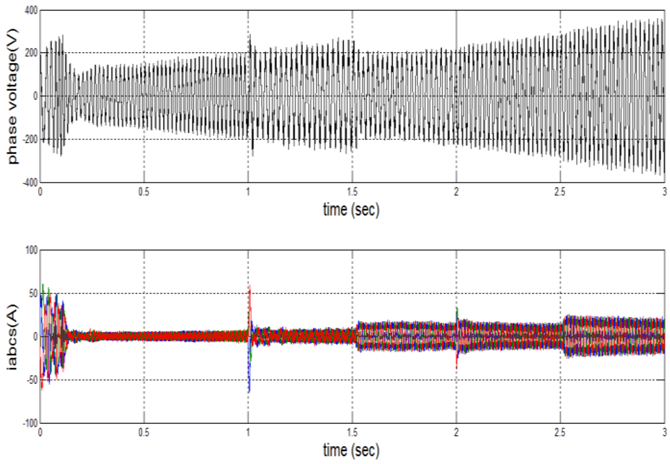

Fig. 13 Phase voltage vao and 3-ph currents of the motor with step changes in load torque

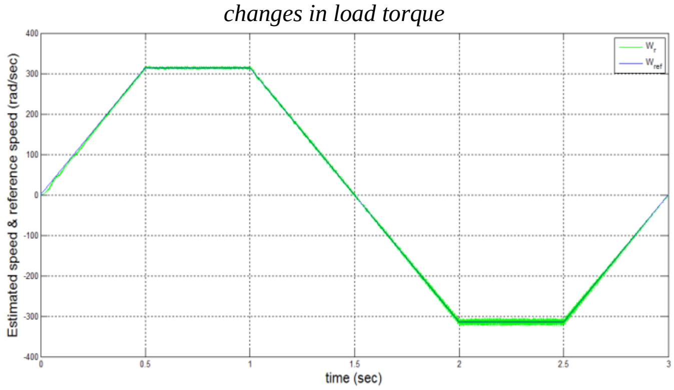

Fig. 14 *Four quadrant Estimated speed and reference speed*

From the above results we can conclude that

- With the application of the load only torque component i_{qs} changes but not flux producing component i_{ds}.

- Actual speed of the motor traces the Reference speed irrespective of the load torque within permissible limits. There can be a slight dip in speed at the instant of application of load torque but it should settle to the reference speed after some time.
- Generated torque (Te) and load torque (T_L) waveforms follow the same trace.

VI. CONCLUSIONS

In this paper, Indirect Field Oriented Control and sensorless vector control with MRAS observer technique for the control of induction machine are presented. First, generalized dynamic mathematical model of the induction motor is studied. Next, mathematical model of induction motor developed in synchronous reference frame is simulated and investigated. By using this motor dynamic model an indirect field orientation control is simulated. An adaptive state observer, MRAS is tested to observe rotor speed. The high performance of this scheme is shown in simulation results. Using this observer, Sensorless vector control is simulated and dq-axis rotor-stator fluxes, rotor speed were estimated and found. In Sensorless vector control also proper field orientation is achieved because the value of q axis flux is zero and there is no change in d axis current due to the application of load torque. The MRAS provides the estimation of only one state or one parameter instantaneously. Therefore this criterion depends on the requirements of FOC algorithms. One may use MRAS not as a state observer but an online parameter tuning tool that tunes different state observers.

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