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SIMULATION OF SENSORLESS PERMANENT MAGNET SYNCHRONOUS MACHINE USING MODEL REFERENCE ADAPTIVE CONTROL

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Abstract**—**Permanent-magnet-synchronous-machine (PMSM) drives have been increasingly applied in a variety of industrial applications which require fast dynamic response and accurate control over wide speed ranges. At the basis of analysis of the mathematical model of the permanent-magnet synchronous motor (PMSM) and the principle of field-orientated vector control, a novel method for modeling and simulink of PMSM system based on SVPWM is proposed. This paper presents the parameters of permanent magnet synchronous motor i.e. speed (Wr), stator resistance (RS), q-axis inductance (Lq), and torque (Ts) is to be estimated by using Model Reference adaptive System (MRAS).

Keywords-- Model reference adaptive system, Reactive power, Vector control, Permanent magnet synchronous motor

1. INTRODUCTION

Electrical ac machines have been playing an important role in industry progress during the last few decades. All kinds of electrical ac drives have been developed and applied, which serve to drive manufacturing facilities such as conveyor belts, robot arms, cranes, steel process lines, paper mills, waste water treatment and so on. With the advances in power semiconductor devices, converter topologies, microprocessors, application specific ICs (ASIC) and computer-aided design techniques since 1980s, ac drives are currently making tremendous impact in the area of variable speed motor control systems. Among the ac drives, permanent magnet synchronous machine (PMSM) drives have been increasingly applied in a wide variety of industrial applications. The reason comes from the advantages of PMSM: high power density and efficiency, high torque to inertia ratio, and high reliability. Recently, the continuous cost reduction of magnetic materials with high energy density and coercivity (e.g., samarium cobalt and neodymium-boron2iron) makes the ac drives based on PMSM more attractive and competitive. In the high performance applications, the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor and wide operating speed range. This has opened up new possibilities for large-scale application of PMSM. Consequently, a continuous increase in the use of PMSM drives will surely be witnessed in the near future. In general, PM synchronous machines with approximately sinusoidal back electromotive force (i.e., back-EMF) can be broadly categorized into two types: 1)interior (or buried) permanent magnet motors (IPM) and 2) surface-mounted permanent magnet motors (SPM). In the first category, magnets are buried inside the rotor. Due to this interior-permanent structure, the equivalent air gap is not uniform and it makes saliency effect obvious, although the IPM motor physically looks like a smooth-air-gap machine. As a result, the quadrature-axis synchronous inductance of IPM is larger than its direct-axis inductance, i.e., Lq > Ld , which significantly changes the torque production mechanism. Therefore, both magnetic and reluctance torque can be produced by IPM motor. In the second category, the magnets are mounted on the surface of the rotor. Because the incremental permeability of the magnets is 1.02-1.20 relative to external fields, the magnets have high reluctance and accordingly the SPM motor can be considered to have a large and uniform effective air gap. This property makes the saliency effect negligible.

2. PERMANENT MAGNET SYNCHRONOUS MOTOR

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications.

A. PERMANENT MAGNET MATERIALS

The properties of the permanent magnet material will affect directly the performance of the motor and proper knowledge is required for the selection of the materials and for understanding PM motors. In recent years other magnet materials such as Aluminum Nickel and Cobalt alloys (ALNICO), Strontium Ferrite or Barium Ferrite (Ferrite), Samarium Cobalt (First generation rare earth magnet) (SmCo) and Neodymium Iron-Boron (Second generation rare earth magnet) (NdFeB) have been developed and used for making permanent magnets. The rare earth magnets are categorized into two classes: Samarium Cobalt (SmCo) magnets and Neodymium Iron Boride (NdFeB) magnets. SmCo magnets have higher flux density levels but they are very expensive. NdFeB magnets are the most common rare earth magnets used in motors these days. A flux density versus magnetizing field for these magnets show in the Figure 1.

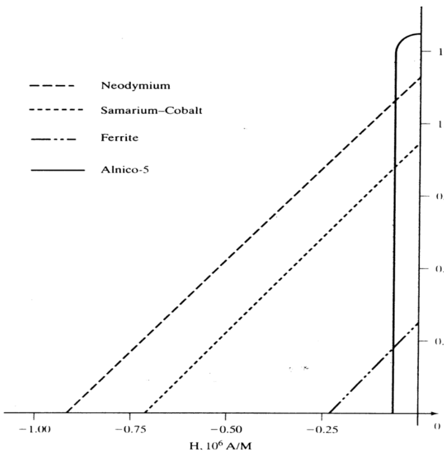

Figure 1 shows Flux Density versus Magnetizing Field of Permanent Magnetic Materials

3. MATHEMATICAL MODEL OF PM SYNCHRONOUS MACHINES IN THE STATIONARY REFERENCE FRAME

For the purpose of understanding and designing control schemes for PMSM drives, it is necessary to know the dynamic model of PMSM subjected to control. The machine models may vary when using them to design control and observation algorithms of PMSM. Mathematic models valid for instantaneous variation of voltage and current and adequately describing the performance of PMSM in both steady state and transient are commonly obtained by the utilization of space-phasor theory. Figure 2 shows the cross-section view of a simplified symmetrical three-phase, two-pole PMSM with wyes connected concentrated identical stator windings. These, however, represent distributed windings which at every instant produce sinusoidal MMF waves centered on the magnetic axes of the respective phases. The phase windings are displaced by 120electrical degrees from each other. In Figure 2, θr is the rotor position angle, which is between the magnetic axes of stator winding sA and rotor magnet flux (i.e., d-axis). The positive direction of the magnetic axes of the stator windings coincides with the direction of fas, fbs and fcs. The angular velocity of rotor is calculated by ωr=dθr/dt, and its positive direction is also shown. It is assumed that the permeability of iron parts of PMSM under consideration is infinite and flux density is radial in the air-gap. The effects of iron losses, saturation and end-effects are neglected. The analysis given here is valid for linear magnetic circuits.

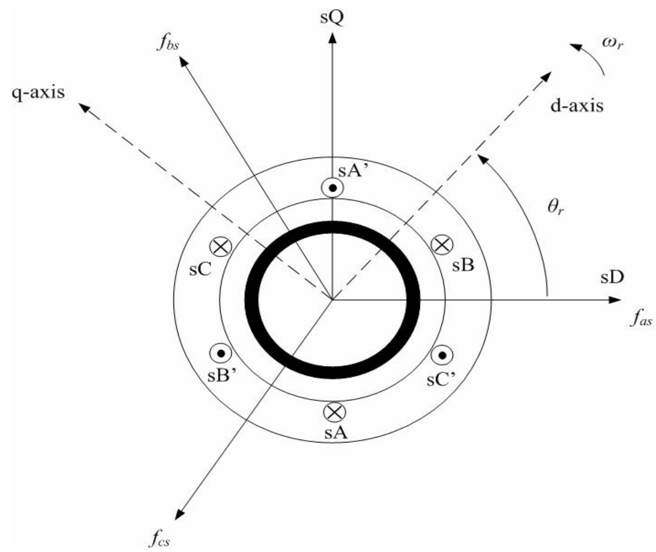

Figure 2 shows Cross-section view of a simplified symmetrical three-phase,two-pole PMSM.

A. General model of PMSM with saliency

By polarity convention for phase currents and voltages of a PMSM [3, 12] its voltage equations can be expressed in terms of instantaneous currents and flux linkages by

$$v_{abcs} = r_{abcs} . i_{abcs} + p . \lambda_{abcs} \quad (3.1)$$

Where

$$V_{abcs} = [Vas \quad Vbs \quad Vcs]^T$$

$$i_{abcs} = [i_{as} \quad i_{bs} \quad i_{cs}]^T$$

$$\lambda_{abcs} = [\lambda_{as} \quad \lambda_{bs} \quad \lambda_{cs}]^T$$

$$r_{abcs} = diag \; [R_s \quad R_s \quad R_s]$$

In the above, the s subscript denotes variables and parameters associated with the stator circuits, and r subscript denotes those with the rotor circuits. The operator p represents the differentiating operation d/dt. For a magnetically linear system, the flux linkages can be calculated as follows:

$$\lambda_{abcs} = L_{abcs} \cdot i_{abcs} + \lambda_{abcm} \quad (3.3)$$

Where

$$L_{abcs} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cd} & L_{cc} \end{bmatrix} \quad (3.4)$$

$$\vec{\lambda}_{abcm} = \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos(\theta_r - 2\pi/3) \\ \cos(\theta_r + 2\pi/3) \end{bmatrix} \quad (3.5)$$

And the winding inductances are respectively

$$L_{aa} = L_{ls} + L_{os} + L_{2s} \cos 2\theta_r \quad (3.6)$$

$$L_{bb} = L_{ls} + L_{os} + L_{2s} \cos 2\left(\theta_r - \frac{2\pi}{3}\right) \quad (3.7)$$

$$L_{cc} = L_{ls} + L_{os} + L_{2s} \cos 2\left(\theta_r + \frac{2\pi}{3}\right) \quad (3.8)$$

$$L_{ab} = L_{ba} = -\frac{1}{2} L_{os} + L_{2s} \cos 2\left(\theta_r - \frac{\pi}{3}\right) \quad (3.9)$$

$$L_{ac} = L_{ca} = -\frac{1}{2} L_{os} + L_{2s} \cos 2\left(\theta_r + \frac{\pi}{3}\right) \quad (3.10)$$

$$L_{bc} = L_{cb} = -\frac{1}{2} L_{os} + L_{2s} \cos 2(\theta_r + \pi) \quad (3.11)$$

In the above, Lls is the leakage inductance and L0s and L2s the magnetizing inductance components of the stator windings; λm is the flux linkage established by the rotor magnets. It should be noted that the magnetizing inductance components are functions of the rotor position; and the coefficient L2s is negative while L0s positive in the case of interior PM motors due to their unique rotor structure. Therefore, the quadrature-axis magnetizing inductance Lmq is larger than the direct-axis magnetizing inductance Lmd of interior PM motor, which is opposite to general salient-pole synchronous machines. The flux linkage equation can be extended to the form of

$$\begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{ab} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos(\theta_r - 2\pi/3) \\ \cos(\theta_r + 2\pi/3) \end{bmatrix} \quad (3.12)$$

By two-axis theory, an equivalent quadrature-phase machine is used to represent the three-phase machine, in which the direct-axis and quadrature-axis currents, fictitious components, are flowing in virtual windings and are related to the actual three-phase stator currents as follows:

$$\vec{i}_{\alpha\beta os} = T_{abc \to \alpha\beta 0} \cdot \vec{i}_{abcs} \quad (3.13)$$

Where

$$T_{abc \to \alpha\beta 0} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (3.14)$$

The above transformation of variables is also known as Clark Transformation. Then the new stationary reference frame referring to the quadrature-phase machine is called (α-β) frame. Whereas, the previous stationary frame is to be called (a-b-c) frame. Similarly, voltage and flux linkage variables can be transformed from (a-b-c) frame to (α-β) frame and consequently the voltage equations expressed in the (α-β) frame as

$$\vec{v}_{\alpha\beta 0s} = r_{\alpha\beta 0s} \cdot \vec{i} + p \cdot \vec{\lambda}_{\alpha\beta 0s} \quad (3.15)$$

Where

$$\vec{v}_{\alpha\beta 0s} \left[v_{as} \quad V_{\beta s} \quad V_{0s}\right]^T$$
$$\vec{i}_{\alpha\beta 0s} = \left[i_{as} \quad i_{\beta s} \quad i_{0s}\right]^T$$
$$\vec{\lambda}_{\alpha\beta 0s} = \left[\lambda_{as} \quad \lambda_{\beta s} \quad \lambda_{0s}\right]^T \quad (3.16)$$

The flux linkages in (3.3) change to

$$\vec{\lambda}_{\alpha\beta 0s} = L_{\alpha\beta 0s} + .\vec{i}_{\alpha\beta 0s} + \lambda_{\alpha\beta 0m} \quad (3.17)$$

Where

$$L_{\alpha\beta 0s} = \begin{bmatrix} L_{ls} + \frac{3}{2}(L_{0s} + L_{2s}\cos 2\theta_r) & \frac{3}{2}L_{2s\sin 2\theta_r} & 0 \\ \frac{3}{2}L_{2s\sin 2\theta_r} & L_{ls} + \frac{3}{2}(L_{0s} + L_{2s}\cos 2\theta_r) & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} \quad (3.18)$$

$$\vec{\lambda}_{\alpha\beta 0m} = \lambda_m \begin{bmatrix} \cos\theta_r \\ \sin\theta_r \\ 0 \end{bmatrix} \quad (3.19)$$

Provided that the stator windings are in wye-connected arrangement with floating neutral point and supplied with three-phase currents, which vary arbitrarily in time, the sum of the three phase currents are always equal to zero regardless of three-phase balanced condition. As a result, the 0-axis component of current variable in the (α-β) frame, i.e., i0s, is zero and so are the 0-axis components of voltage and flux linkage variables. Therefore, the equations (3.15 – 3.19) can be reduced to

$$\vec{v}_{\alpha\beta s} = r_{\alpha\beta s} .\vec{i} + p.\vec{\lambda}_{\alpha\beta s} \quad (3.20)$$

$$\vec{v}_{\alpha\beta s} = [v_{\alpha s} \; v_{\beta s}]^T$$
$$\vec{i}_{\alpha\beta s} = [i_{\alpha s} \; i_{\phi s}]^T$$
$$\vec{\lambda}_{\alpha\beta s} = [\lambda_{\alpha s} \; \lambda_{\beta s}]^T \quad (3.21)$$

$$\vec{\lambda}_{\alpha\beta s} = L_{\alpha\beta s} .\vec{i}_{\alpha\beta s} + \vec{\lambda}_{\alpha\beta n} \quad (3.22)$$

Where

$$L_{\alpha\beta s} = \begin{bmatrix} L_{ls} + \frac{3}{2}(L_{0s} + L_{2s}\cos 2\theta_r) & \frac{3}{2}L_{2s}\sin 2\theta_r \\ \frac{3}{2}L_{2s}\sin 2\theta_r & L_{ls} + \frac{3}{2}(L_{0s} - L_{2s}\cos 2\theta_r) \end{bmatrix} \quad (3.23)$$

$$\vec{\lambda}_{\alpha\beta m} = \lambda_m \begin{bmatrix} \cos\theta_r \\ \sin\theta_r \end{bmatrix} \quad (3.24)$$

4. GENERAL MODEL OF PMSM WITHOUT SALIENCY

For a magnetically symmetrical PMSM, e.g., surface-mounted PM motor, the effective air gap is considered to be uniform, which makes the effects of saliency negligible. Thus the direct-axis magnetizing inductance Lmd is equal to the quadrature axis magnetizing inductance Lmq, i.e., Lmd = Lmq= Lms (namely stator magnetizing inductance). And the inductance matrix expressed in (3.4) and (3.23) changes respectively to

$$L_{abcs} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}ms & L_{ls} + L_{ms} & L_{bc} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix} \quad (3.25)$$

$$L_{\alpha\beta 0s} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_0 \end{bmatrix} \quad (3.26)$$

Where

$$L_s = L_{ls} + \frac{3}{2}L_{ms}$$

It is interesting to note that the transformed inductance matrix by Clark Transformation and Park Transformation (discussed in the next section) may reduce to a diagonal matrix, which, in effect, magnetically decouples the substitute or transformed variables in every reference frame other than the (a-b-c) frame. For a wye-connected PMSM without saliency, the reduced voltage equation in the (α-β) frame is often of the form

$$\vec{v}_{\alpha\beta s} = r_{\alpha\beta s} .\vec{i}_{\alpha\beta s} + L_{\alpha\beta s} .\vec{i}_{\alpha\beta s} + \vec{e}_{\alpha\beta s} \quad (3.27)$$

Where

$$r_{\alpha\beta s} = \begin{bmatrix} R_s & 0 \\ - & R_s \end{bmatrix} \quad (3.28)$$

$$L_{\alpha\beta s} = \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix} \quad (3.29)$$

$$\vec{e}_{\alpha\beta s} = \begin{bmatrix} e_{\alpha s} \\ e_{\beta s} \end{bmatrix} = \omega_r \lambda_m . \begin{bmatrix} -\sin(\theta_r) \\ \cos(\theta_r) \end{bmatrix} \quad (3.30)$$

In the above, the last item on the right, i.e., eαβs , represents the induced back EMF in the windings of the fictitious quadrature-phase machine. By selecting the stator currents as independent variables, we rewrite the voltage equation given in (3.27) and get the state or differential equation of PMSM in the (α-β) frame as

$$\vec{i}_{\alpha\beta s} = -L_{\alpha\beta s}{}^{-1} r_{\alpha\beta s} \cdot \vec{i}_{\alpha\beta s} + L_{\alpha\beta s}{}^{-1}(\vec{v}_{\alpha\beta s} - \vec{e}_{\alpha\beta s}) \quad (3.31)$$

More commonly, a matrix form is used like:

$$\begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} = \begin{bmatrix} -R_s/L_s & 0 \\ 0 & -R_s/L_s \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} + \begin{bmatrix} 1/L_s & 0 \\ 0 & 1/L_s \end{bmatrix} \left(\begin{bmatrix} v_{\alpha s} \\ v_{\beta s} \end{bmatrix} - \begin{bmatrix} e_{\alpha s} \\ e_{\beta s} \end{bmatrix} \right) \quad (3.32)$$

5. SIMULATION IN SIMULINK

The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device.

The PMSM drive simulation was built in several steps like dqo variables transformation to abc phase, calculation torque and speed, control circuit, inverter and PMSM. The dqo variables transformation to abc phase is built using the reverse Parks transformation. For simulation purpose the voltages are the inputs and the current are output.

The system built in Simulink for a PMSM drive system has been tested with the space vector modulation method at the constant torque region of operation.

The motor parameters used for simulation are given in Table 1

NO	NAME	SYMBOL	VALUE
1.	Stator phase resistance		2.8750
2.	d-axis Inductance		0.0085 H
3.	q-axis Inductance		0.0085 H
4.	Flux linkage established by magnet	V.s	0.175
5.	Voltage constant	V	126.966
6.	Torque constant	T	1.05
7.	Inertia	J	1e-3
8.	Friction factor	F	0
9.	Pole pair	P	4
10.	Initial condition		0
11.	Rated speed	N	1500

Table 1: Motor parameters used for simulation

The simulation model of SVPWM is in the figure 3.

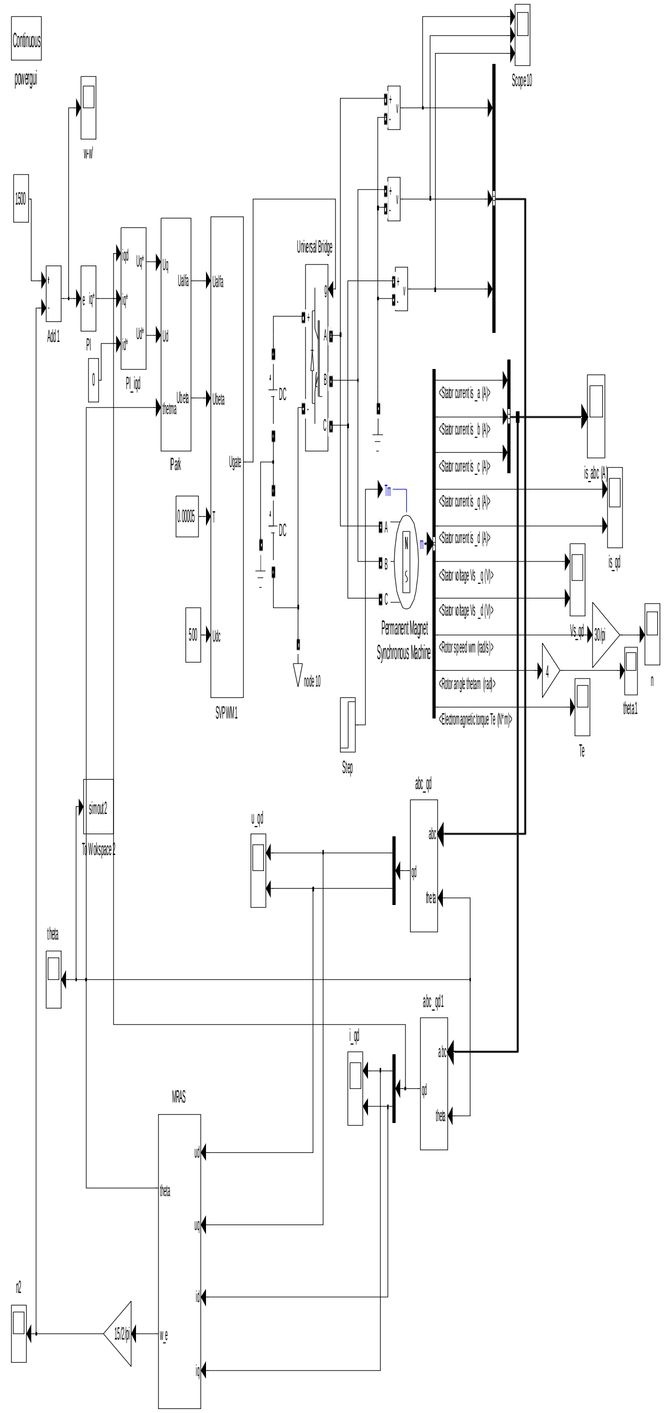

Figure 3 shows The simulation model of SVPWM

6. RESULTS

Figure 4 shows the real three phase currents drawn by the motor as a result of the 3SVPWM control for a speed step of 1500rpm and load of 3.66 Nm. It is clear that the current is non sinusoidal at the starting and becomes sinusoidal when the motor reaches the controller command speed at steady state.

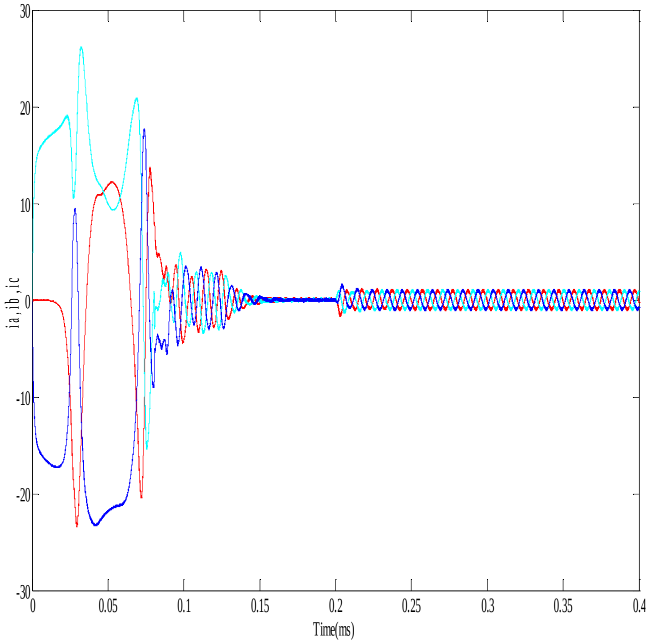

Figure 4 shows Three phase currents drawn by the motor (ia,ib,ic**)**

The given speed is set at 1500rpm, and the motor is in no load startup. When the speed is stable, an abrupt load of 2N·mis applied at 0.2s. Simulation waveforms are shown as follows. Figure 5 shows the actual speed, and Figure 6 shows the estimated speed. The comparison of the estimated and actual angle is shown in Figure 7.

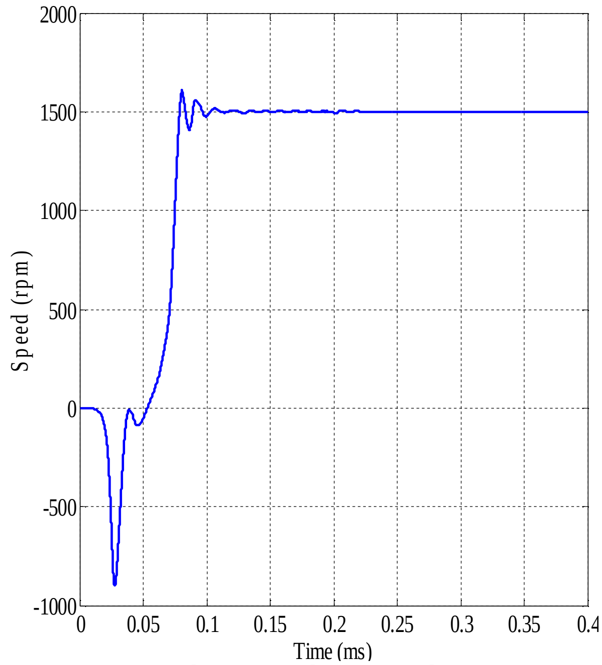

Figure 5 shows Actual rotor speed (MRAS)

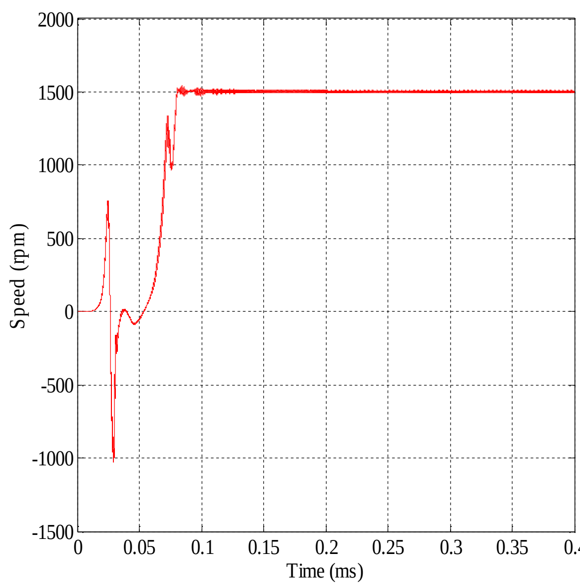

Figure 6 shows Estimated rotor speed (MRAS)

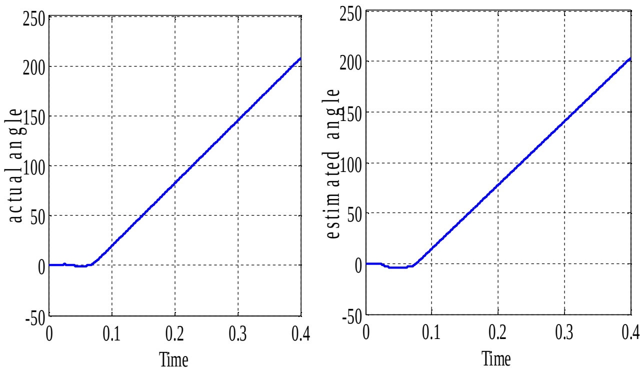

Figure 7 shows Comparison of the estimated and actual angle (MRAS)

From the waveforms, it can conclude that MRAS method has a good stable state precision with a steady-state error of less than 10 rpm, that is, about 0.6%. It takes a long time of more than 0.15s from motor starting to stable. The response is slow, as 0.05s is needed for returning to the stable after the abrupt load is added. As is shown in Figure 7 there is some deviation between the estimated angle and actual angel.

7. CONCLUSION

Based on the rotor field oriented control of permanent magnet synchronous motor, the model of PMSM was developed and applied to SIMULINK AND MATLAB. The simulation results show that the system can run smoothly and still has perfect dynamic and static characteristics under 1500rpm. It has provides a train of thought for the actual PMSM system's design and debugging. By simulation and results analysis, the MRAS method are proved to be available in the sensor less vector control for PMSM, and either has its own superiority. This method has good stable state precision, as parameter identifications are based on the design of stability, and ensure the convergence of parameter estimation. The MRAS method is simple to achieve, but the dynamic property is general, because the prerequisite for MRAS identification is that the rotor angular speed remains constant or changes slowly compared to the convergence rate at least. Hysteresis of PI adaptive controller also influences the property in dynamic process.

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