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Sensorless Scalar Control of Induction Motor with Model Reference Adaptive System Technique

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Abstract: This paper describes a closed loop v/f control of induction motor (IM) drive with Model Reference Adaptive System (MRAS) based sensorless rotor speed estimation technique. Generally to get the speed information of induction motor, tachometers are used. Speed sensor need additional space for mounting and care and hence increases the cost and the size of the drive system. To make the drive mechanically more vigorous, we need to avoid the speed sensor. Researches introduced different sensorless methodologies to get the estimated rotor speed of IM drives. Such methods are divided into two types, one is signal inoculation method and another is model based method. In the Model-Based technique, MRAS is the simplest approach which is more effectively applied for estimation of rotor speed. Theoretical basis of scalar control and MRAS is described in detail and it is instigated in MATLAB/SIMULINK.

1. INTRODUCTION

For variable speed applications, AC machines are most commonly used in industry. Among the AC machines, Induction Motors are maintenance free; cost effective which is more suitable for adjustable speed applications in terms of weight, speed of rotation, size, weight, controllability, efficiency and reliability [1].The variable speed drives are used in all industries to control the speed of IM driving loads reaching from pumps and fans to complex drives [2]. IMs do not have innately the ability of adaptable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. Due to the recent advances in speed control methods of the IM which will make use in almost all electrical drives [3]. Different techniques of speed control of an IM such as variable stator voltage, frequency variation, constant V/f control, variable rotor resistance, pole changing, slip retrieval method. Closed loop constant V/f speed control method is used mostly. In this method to maintain flux constant we need to keep the V/f ratio constant so that unaffected maximum torque is attained [4].

Constant volts-per-hertz (V/f) control is more robust and simple control structure at the cost of reduced dynamic performance, which is acceptable for applications like pump and fan drive, and tolerable for other application if cost is an issue. These cost-saving features are definitely essential for small power applications. At higher power, the power components themselves dominate the system cost, authorizing the execution of more refined control methods which serve to overcome the disadvantages of v/f control i: e reduced dynamic performance. The cost advantage makes scalar control very striking for small power applications, while their vigour helps its use at high power, when fast response is not required. Such systems give a substantial portion in the market with speed sensorless drives. On-going study has concentrating on the removal of the tachometer at the shaft of the machine without failing the performance of the drives. By using sensorless methodology the difficulty of hardware is reduced and inferior cost, reduced size of the drive, sensor cable is eliminated, better noise exception, reliability of the drive increased and less maintenance requirements. Mostly in hostile environment operation motor without speed sensor is more suitable rather than sensor approach.

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2. SCALAR CONTROL TECHNIQUE

In scalar control technique, speed is controlling by linearly changing the voltage and the frequency in order to sustain the air-gap flux constant [5-7]. In constant V/f speed control, a variable voltage and variable frequency is applied to the induction motor. Both the VSI and CSI (voltage source and current source inverter) are used in variable speed ac drives. Block diagram of Conventional closed loop V/f control of IM with tachometer is shown in below Figure 1.

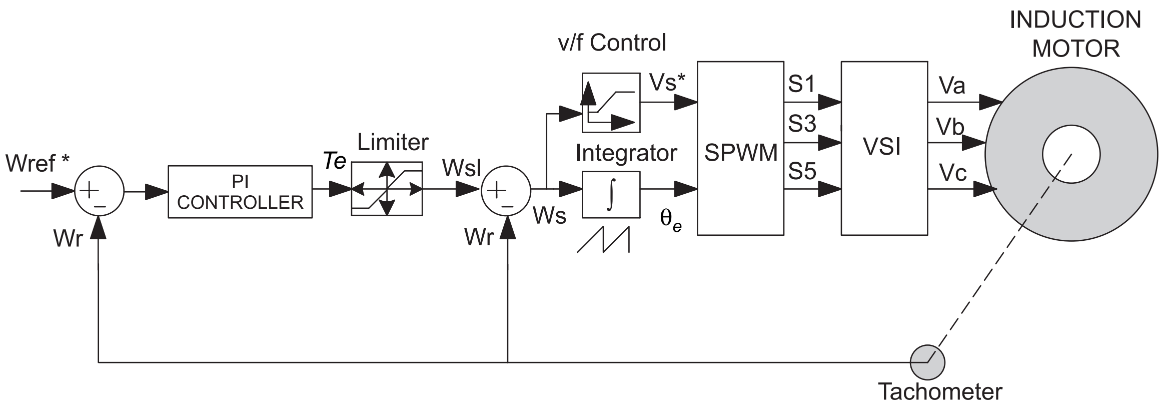

Figure 1: Conventional Closed Loop V/f control of IM with Tachometer

A Tachometer or a speed encoder is used to get the information of the actual speed (W_r) of the IM and then it is compared with the reference speed (W_{ref}). The difference between the two speeds will generates an error speed and obtained speed error is send to proportional controller (PI). The output of the PI Controller is the torque command which is directly proportional to the slip speed command (ω_{sl}). The slip speed command is limited by using limiter. Synchronous speed (ω_s) is achieved by summing the actual rotor speed command (ω_r) and the slip speed command (ω_{sl}) i.e. ($\omega_r = \omega_s + \omega_{sl}$). To determines the inverter frequency command (f_s).

The voltage command (V_s^*) is generated from frequency

$$\phi \propto \frac{V_s^*}{\omega_s} \tag{1}$$

$$\theta_e = \int \omega_s \, dt \tag{2}$$

In this method to maintain air gap flux ( ) constant we need to keep the (V/f) ratio constant then unaffected maximum torque is obtained. Voltage (V_s^*) and Angle (θ_e) is used to produce the 3 sinusoidal reference voltages (V_a^*, V_b^*, V_c^*) as in Equation (3)

$$\begin{aligned} V_a^* &= \sqrt{2}\, V_s^* \sin \theta_e \\ V_b^* &= \sqrt{2}\, V_s^* \sin\left(\theta_e - \frac{2\pi}{3}\right) \\ V_c^* &= \sqrt{2}\, V_s^* \sin\left(\theta_e + \frac{2\pi}{3}\right) \end{aligned} \tag{3}$$

In SPWM technique, reference wave is compared with carrier wave. When reference is greater than carrier the required pulse is generated. The pulses are given as the input (gate signals) to switches of the voltage source inverter (VSI). The voltage source inverter which converts dc-ac supply and ac supply is given as the input to the induction motor.

3. MRAS SPEED ESTIMATION TECHNIQUE

To make the drive mechanically more vigorous, we need to avoid the speed sensor. Researches introduced different sensorless methodologies to get the estimated rotor speed of IM drives [8]-[11]. Such methods are divided into two types: one is signal inoculation method and another is model based method. In the Model-Based technique, MRAS is the simplest approach which is effectively applied for speed estimation. In this paper, Rotor Flux based sensorless approach is used to form MRAS for rotor speed estimation was studied. MRAS structure which is more effective and difficulty is reduced. MRAS approach consists of two models. Reference model (voltage model) which does not involve the quantity to be estimated (ω_r). Adaptive model (current model) which does involves the quantity to be estimated (ω_r). The voltage model output is related with the output of an adjustable model till the error difference between the voltage model and adjustable model disappear to zero and with the correct value of rotor speed (ω_r), the rotor fluxes determined from the two models (voltage model and adjustable model) should match. An adaptation system with PI control is used to adjust the rotor speed (ω_r) value until the two flux values equal. In Figure 2(a) and Figure 2(c),Basic diagram and block diagram of MRAS is shown. In Figure 2(b) and Figure 2(d), Transformations (3 phase to 2 phase) and Rotor Flux Linkage of MRAS is shown.

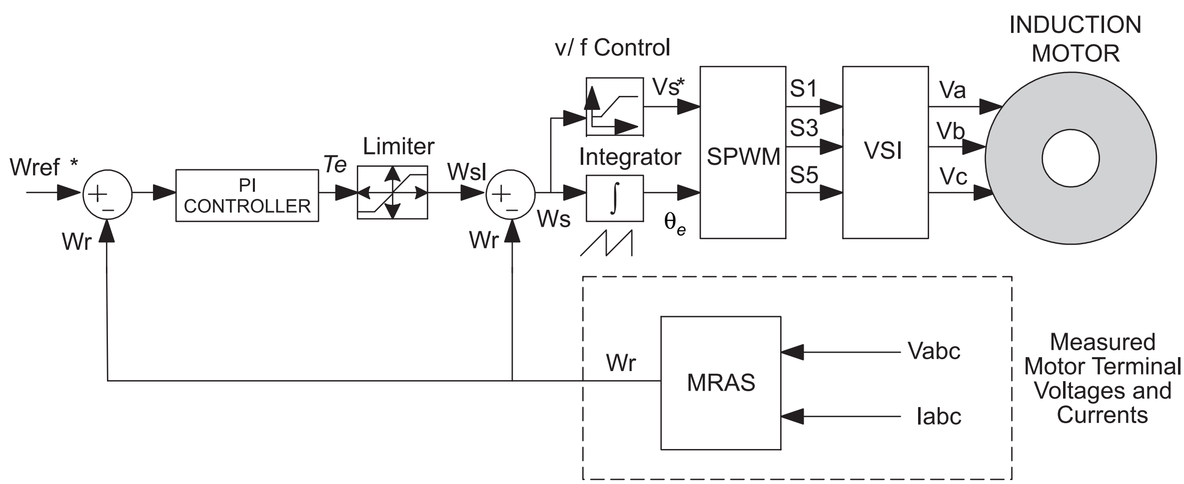

Figure 2: (a) MRAS Speed Estimation Technique

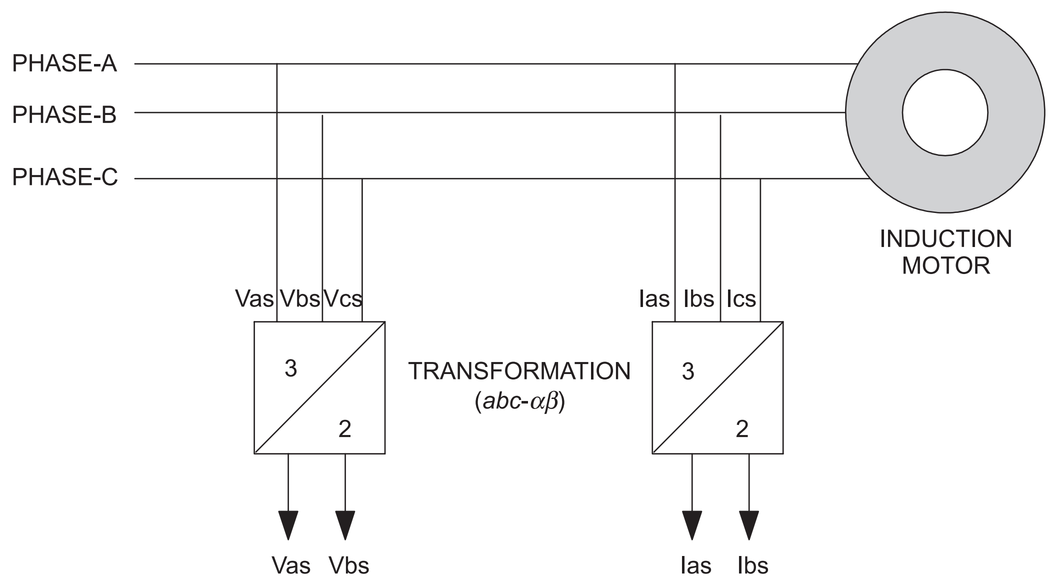

Figure 2: (b) Transformation (*abc* to αβ) of Voltages and Currents

Transformation of Voltages (*abc* to αβ):

$$\begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & -\sqrt{\left(\frac{3}{2}\right)} & \sqrt{\left(\frac{3}{2}\right)} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

Transformation of Currents (*abc* to αβ):

$$\begin{bmatrix} I_{\alpha s} \\ I_{\beta s} \\ I_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & -\sqrt{\left(\frac{3}{2}\right)} & \sqrt{\left(\frac{3}{2}\right)} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$

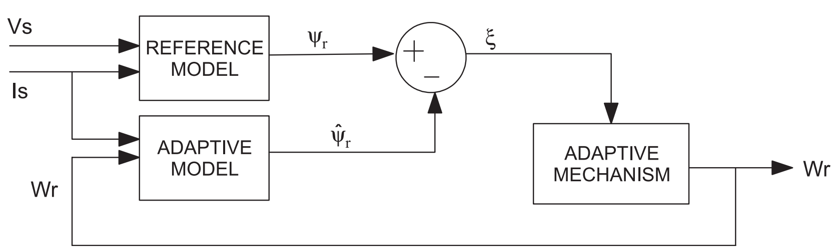

Figure 2: (c) Basic Structure of MRAS

Adaptive Model Equations:

$$\hat{\psi}_{dr} = \int\left(\frac{L_m}{T_r} i_{ds} - \omega_r \hat{\psi}_{qr} - \frac{1}{T_r}\hat{\psi}_{dr}\right) \tag{6}$$

$$\hat{\psi}_{qr} = \int\left(\frac{L_m}{T_r} i_{qs} - \omega_r \hat{\psi}_{dr} - \frac{1}{T_r}\hat{\psi}_{qr}\right) \tag{7}$$

Reference Model Equations:

$$\dot{\psi}_{dr} = \frac{L_r}{L_m}\left[V_{ds} - \left(R_s + \sigma L_s \frac{d}{dt}\right) i_{ds}\right] \tag{4}$$

$$\dot{\psi}_{qr} = \frac{L_r}{L_m}\left[V_{qs} - \left(R_s + \sigma L_s \frac{d}{dt}\right) i_{qs}\right] \tag{5}$$

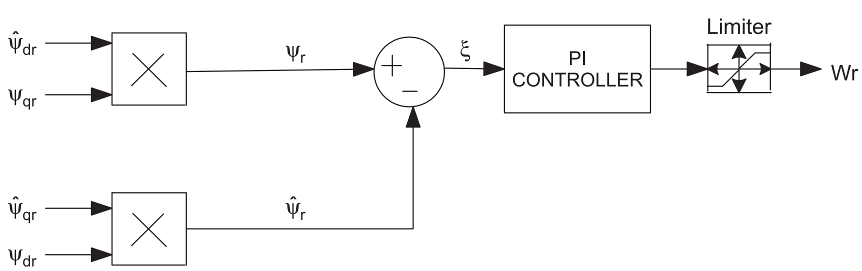

Figure 2: (d) Rotor Flux Linkage of MRAS

Adaptive mechanism for Rotor Speed:

$$\omega_r = \xi\left(K_p + K_i \frac{1}{S}\right) \tag{8}$$

$$\xi = \hat{\psi}_{dr}\psi_{qr} - \hat{\psi}_{qr}\psi_{dr} \tag{9}$$

Where V_{ds}, V_{qs} is the Stator Voltages (*d*-axis, *q*-axis)

I_{ds}, I_{qs} is the Stator Currents (*d*-axis, *q*-axis)

L_s, L_r, L_m is the Stator, Rotor and Mutual Inductances

ψ_{ds}, ψ_{qs} is the Rotar Flux Linkage (*d*-axis, *q*-axis)

$T_r = \frac{L_r}{R_r}$ is the Rotar Time Constant

$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the Motor leakage Coefficient

4. SIMULATION RESULTS

Simulation of sensorless scalar control of induction motor with rotor flux based MRAS technique is done in MATLAB/SIMULINK as shown in below Figure 3(a), Figure 3(b), Figure 3(c), Figure 3(d) by using the induction motor parameters which is shown in Table 1.

Table 1
Induction Motor Parameters

Machine Parameters	
Parameters	*Values*
No of Poles Pairs (P)	2
Frequency (f_s)	60 Hz
Hp	3
Voltage (V)	220 V
Stator Resistance (R_s)	0.435 Ω
Rotor Resistance (R_r)	0.82 Ω
Stator Leakage Reactance (X_{sl})	0.755 Ω
Rotor Leakage Reactance (X_{rl})	0.755 Ω
Mutual Reactance (X_m)	26.13 Ω
Rotor Inertia (J)	$0.089\,\text{Kg}-\text{m}^2$

The result for three cases are specified below

Case 1: No Load

Case 2: Under Loaded Condition

Case 3: Due to Step Change in reference speed Command at $t = 1$ sec.

Simulation Models:

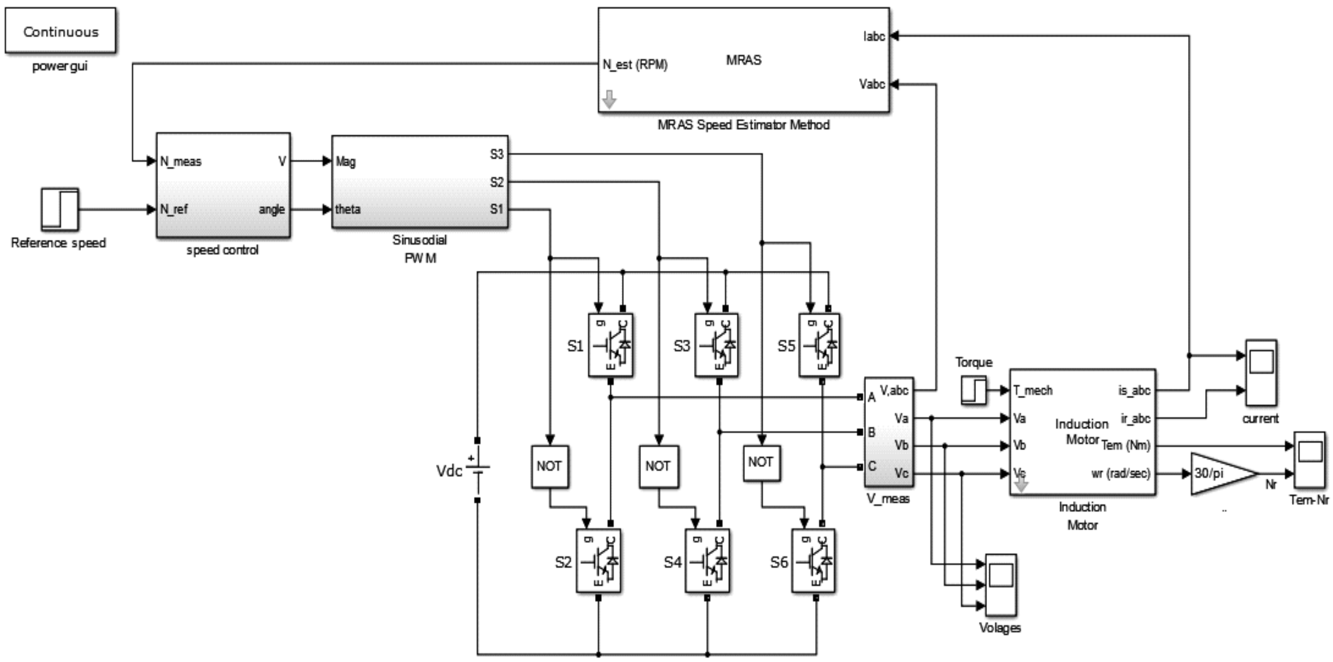

Figure 3: (a) Scalar Control of IM with MRAS Speed Estimation Technique

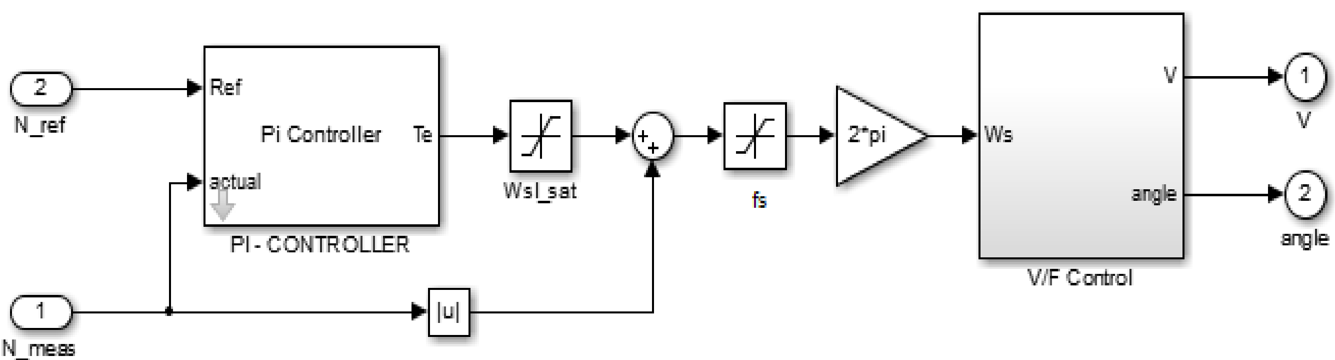

Figure 3: (b) V/f Control

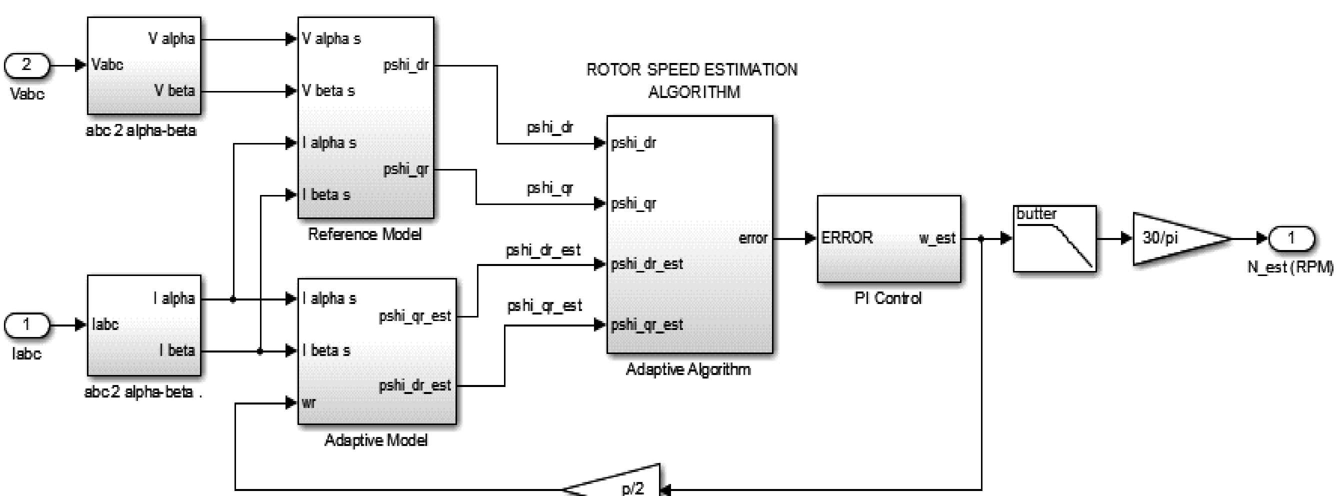

Figure 3: (c) Rotor-Flux Based MRAS Speed Estimation Technique

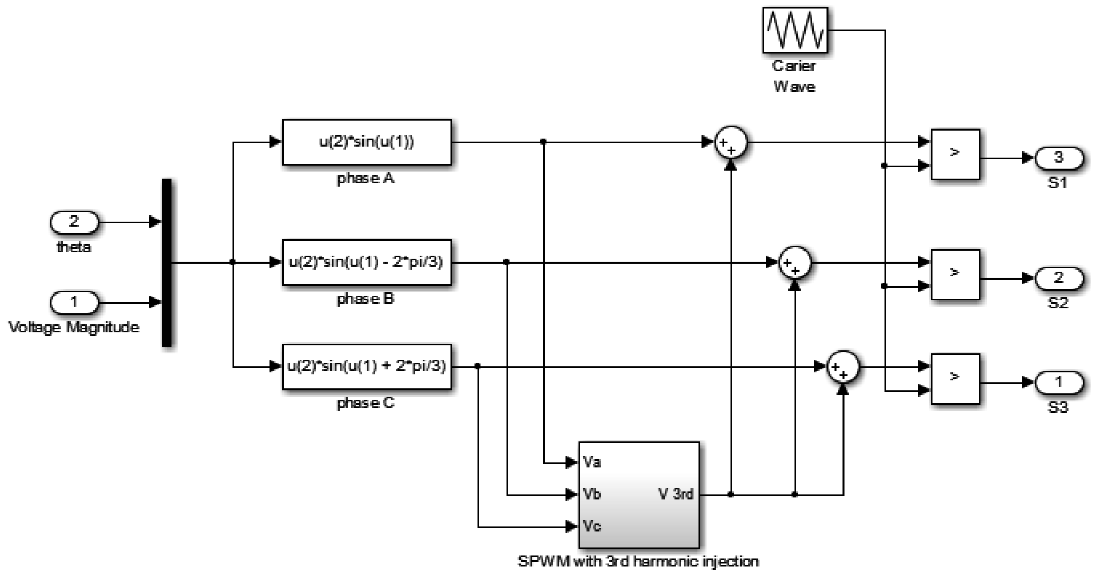

Figure 3: (d) SPWM with 3rd Harmonic Injection Method

Case 1: No Load Condition

Under no load condition (TL = 0) the torque and speed response is shown in Figure 4(a) & Figure 4(b). In Figure 4(a), the reference torque is (TL = 9 N-M) but the actual torque will take time ($t = 0.5$) to settle at reference torque. In Figure 4(b), the actual motor speed will settle at $t = 0.5$ but the estimated rotor speed by using MRAS have some oscillations during starting with delay compared to the actual motor speed. Stator Currents (I_{abc}) and Stator Voltages (I_{abc}) under no load as shown in below Figure 4(c) and Figure 4(d).

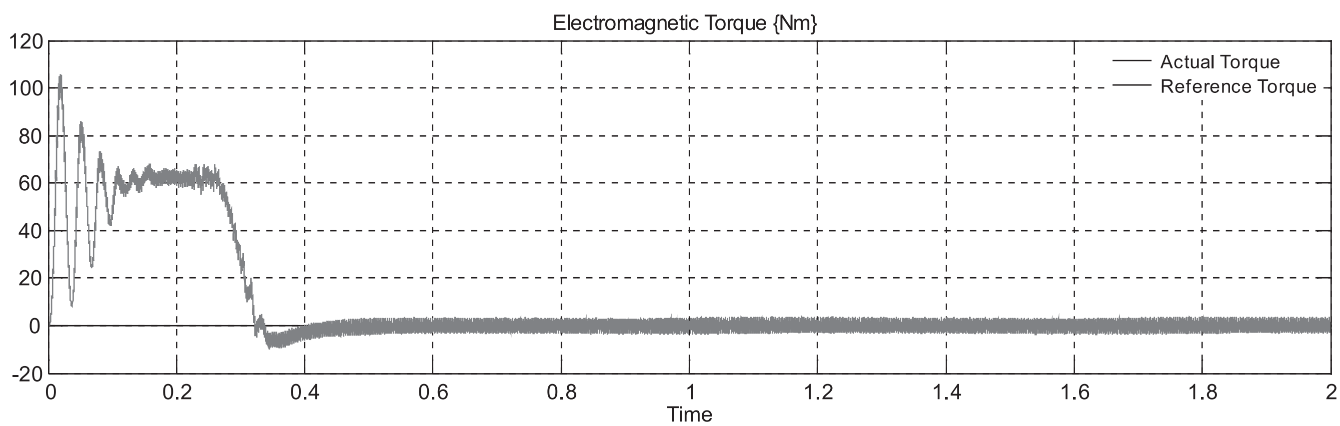

Figure 4: (a) Torque Response under no load condition

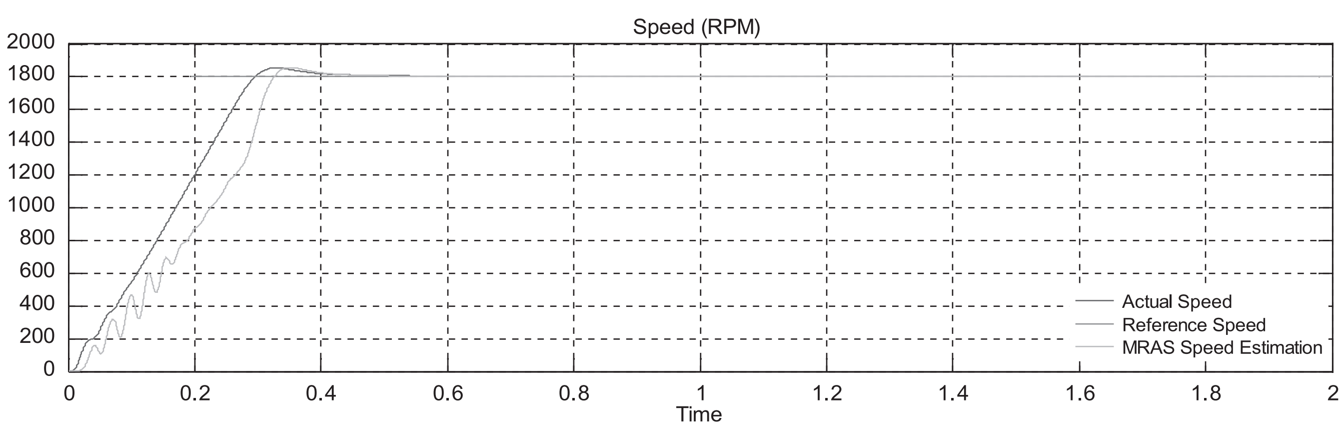

Figure 4: (b) Speed Response under no load condition

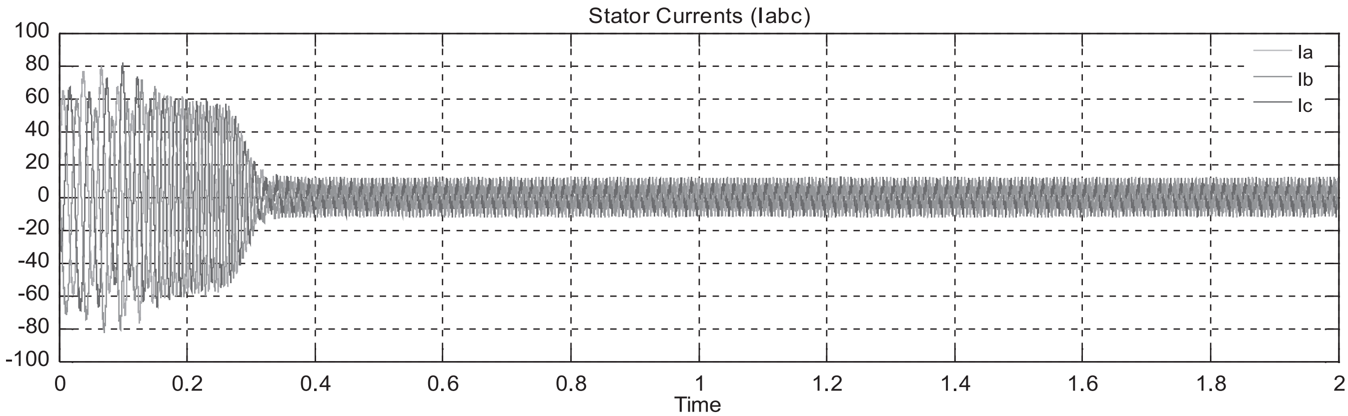

Figure 4: (c) Stator Currents under no load condition

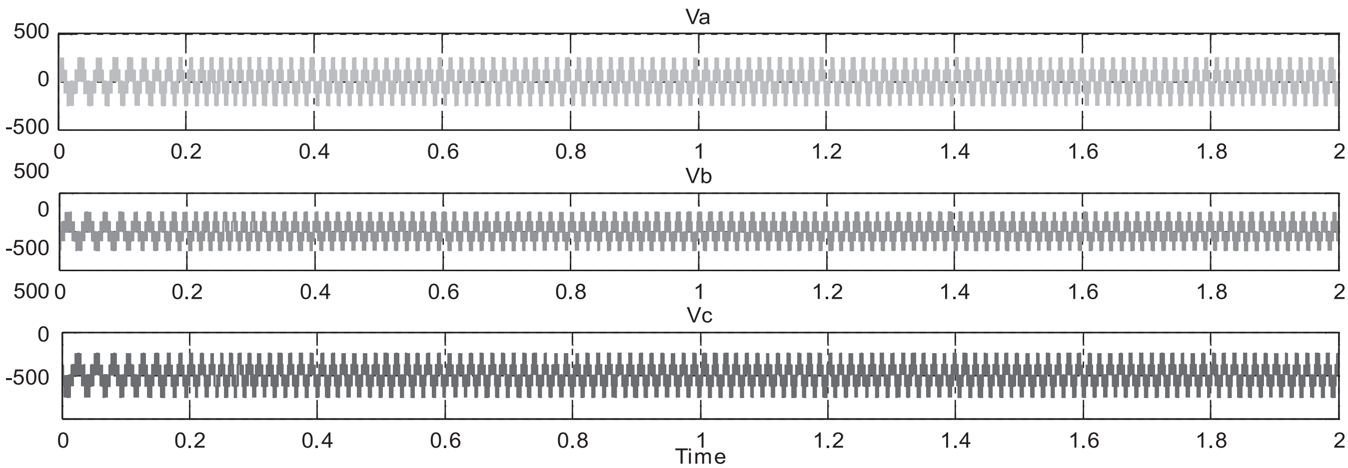

Figure 4: (d) Stator Voltages (V_{abc}) to the IM

Case 2: Under Load Condition at $t = 1$ sec

Under loaded condition, Load (TL = 9 N-M) is applied as a step input at $t = 1$ sec, the torque and speed response as shown in Figure 5(a) & Figure 5(b). In Figure 5(a), the reference torque is TL = 9 N-M but the actual torque is settle at time ($t = 0.5$) and maintain constant upto $t = 1$ sec. At $t = 1$ sec step input is applied then actual torque is raised and settle at reference torque. In Figure 5(b), the actual motor speed will settle at $t = 0.5$ but the estimated rotor speed by using MRAS have some oscillations during starting with some delay compared to the actual motor speed. At time $t = 1$ sec, due to step input load varies. Due to load variation, the speed is reduced and settle after some time. Stator Currents (I_{abc}) under loaded condition is shown in Figure 5(c).

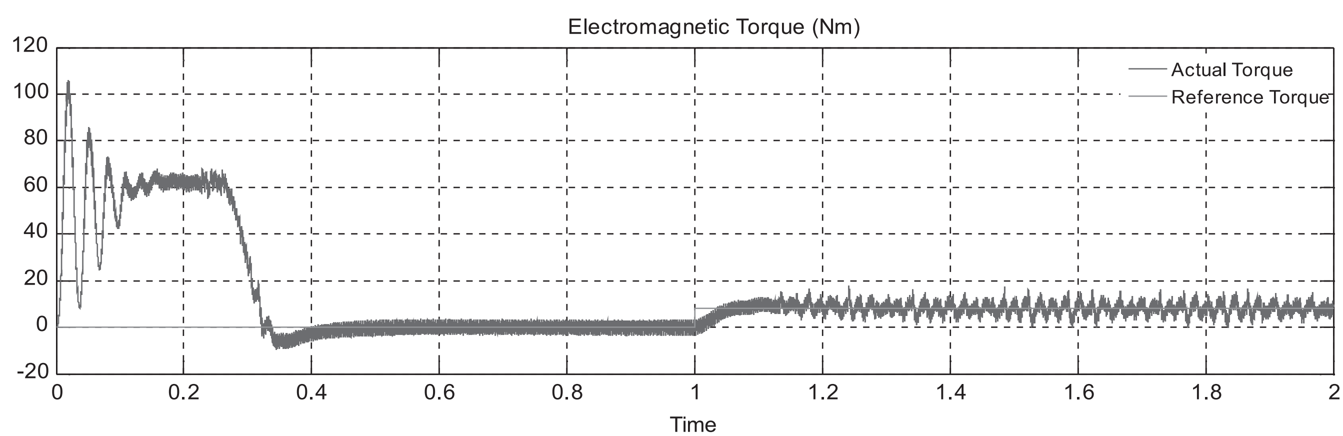

Figure 5: (a) Torque Response at TL = 9 N-M

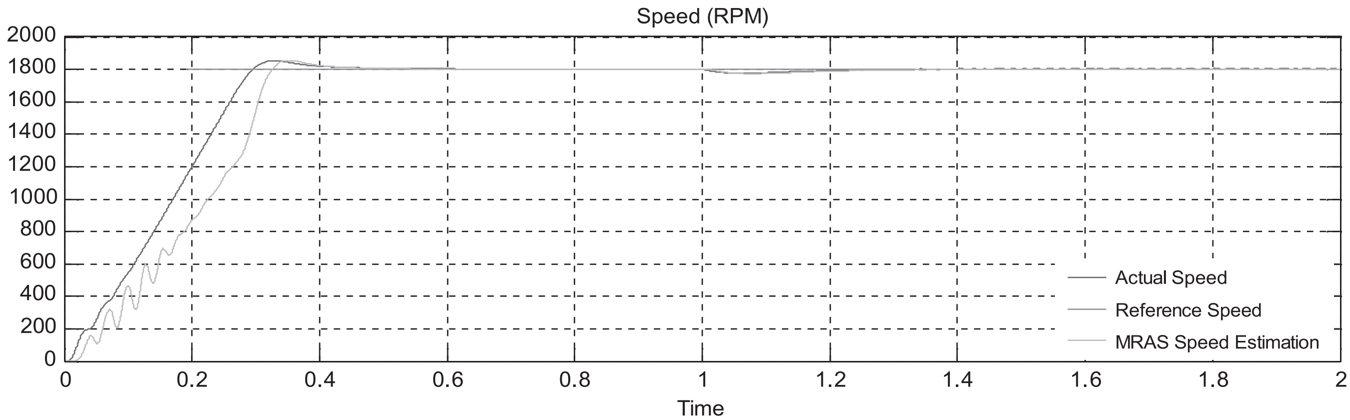

Figure 5: (b) Speed Response at TL = 9 N-M

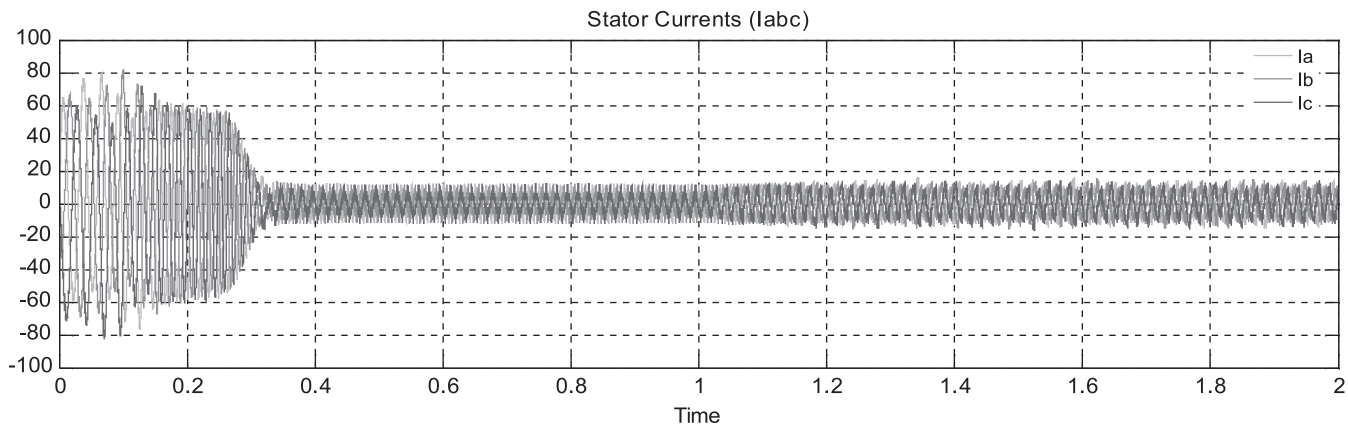

Figure 5: (c) Stator Currents at TL = 9 N-M

Case 3: Due to Step Change in Reference Speed Command at *t* = 1 sec

Reference Speed is at 1800 rpm and now applied a step input as 1500 rpm at t = 1 sec then the torque and speed response is shown in Figure 6(a) and Figure 6(b). In Figure 6(a), the reference torque is TL = 0 but the torque is settle at time ($t = 0.5$) and maintain constant upto $t = 1$ sec. At $t = 1$ sec, step input is applied then actual torque is reduced and settle at reference torque. In figure 5(b), the actual motor speed will settle at $t = 0.5$ but the estimated rotor speed by using MRAS have some oscillations during starting with some delay compared to the actual motor speed. At time $t = 1$ sec, due to step input the speed is reduced and settle afters time ($t = 1.4$ sec). Stator Currents (I_{abc}) under step change of reference speed condition at $t = 1$ sec is shown in Figure 6(c).

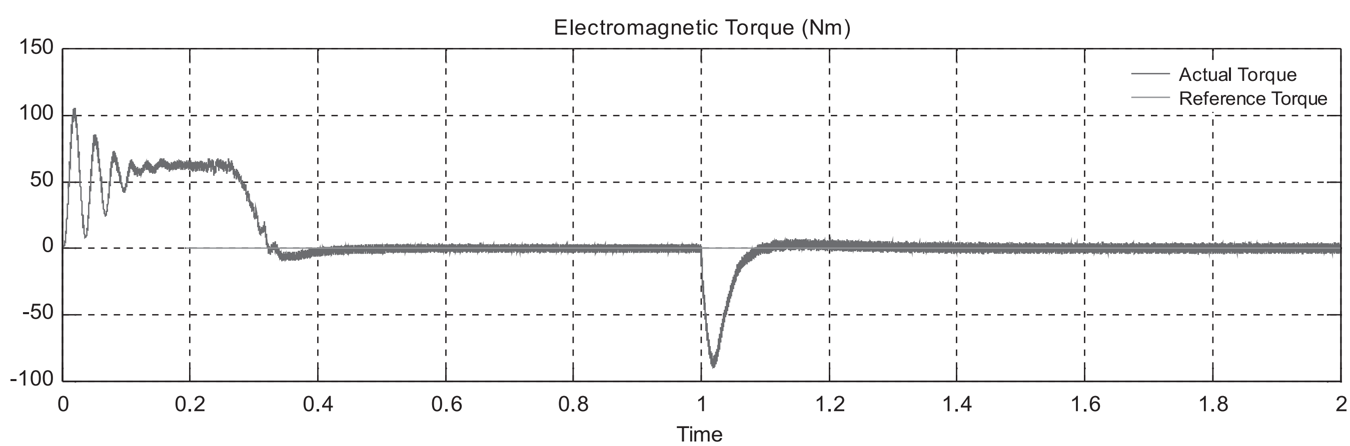

Figure 6: (a) Torque Response due to step change of reference speed command at *t* = 1 sec

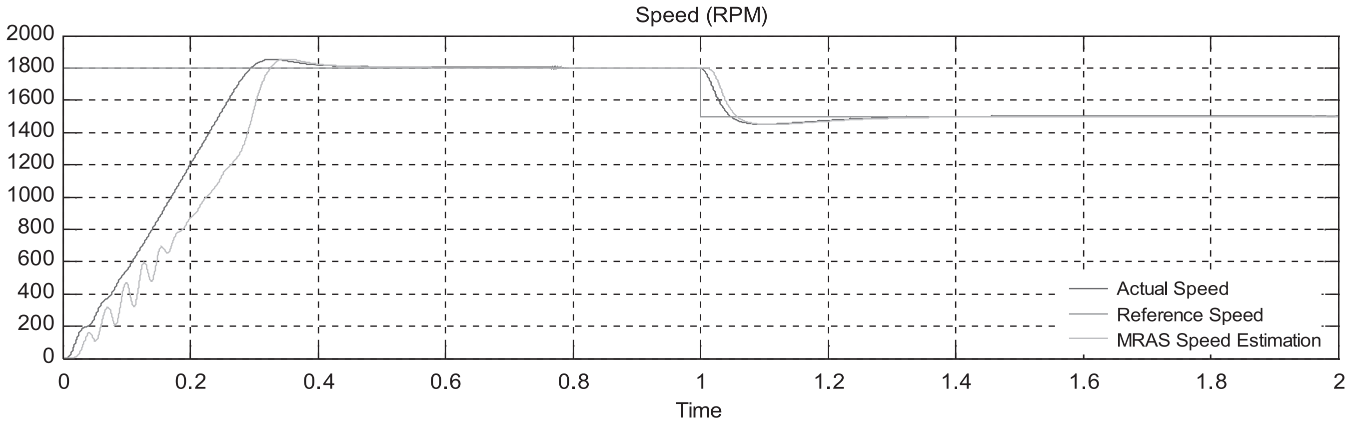

Figure 6: (b) Speed Response due to step change of reference speed command at *t* = 1 sec

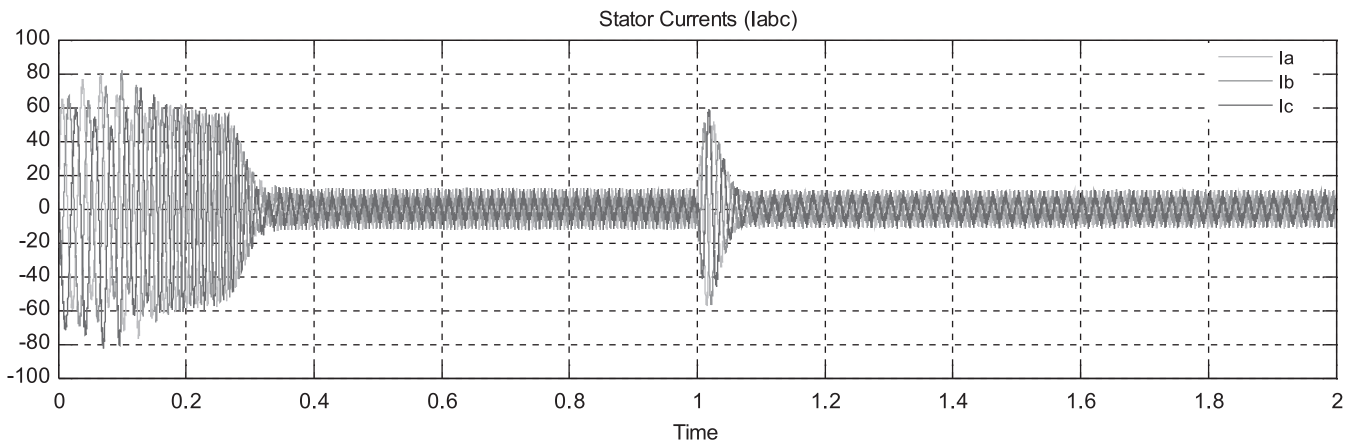

Figure 6: (c) Stator Currents (I_{abc}) due to step change of reference speed command at *t* = 1 sec

Comparison of speed and torque response at steady state for different cases which is shown in below Table 2.

Table 2
Comparison of Speed and Torque Response at steady state for different cases

Conditions	*Speed (rpm)*	*Torque (Nm)*
Under No-Load Condition	0.5	0.5
Under Loaded Condition at *t* = 1 sec	1.2	1.2
Step Change of Reference Speed Command at *t* = 1 sec	1.4	1.4

5. CONCLUSION

This paper presents a scalar control (v/f) of IM using sensorless rotor flux based MRAS technique. In simulation, MRAS speed estimation is done for different cases and obtained results is shown above. Rotor flux based MRAS technique which will reduce hardware complexity and cheaper cost, reduce size of the drive machine, elimination of the sensor cable, better sound protection, and improve consistency and less maintenance requirement.

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