ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 5, Issue 6, December 2015

Resistance Estimation for Sensor less Permanent Magnet Synchronous Motor Drives

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Abstract*—Stator resistance estimation is extremely important for various reasons in permanent magnet synchronous motor (PMSM) drives. The thermal loading of the stator can be indicated as the increase of the resistance. In this paper, direct torque control is employed as a speed controller for PMSM drives, also, model reference adaptive system (MRAS) has been developed to estimate the speed and stator resistance simultaneously, stator resistance estimation is necessary particularly when the motor is operated at low speed. The validity of the proposed technique is tested in MATLAB/SIMULINK.

***Index Terms*—PMSM**, **direct torque control (DTC), MRAS Sensor less, Stator Resistance Identification.**

I. INTRODUCTION

PMSM are used more in the variable speed applications due to some advantages like more simplicity, low maintenance, low dependency on the motor parameters, good dynamic torque response, high rate torque/inertia and simplicity of design[1].

Direct torque control (DTC)method have become increasingly popular in the industrial drives since 1980 due to the simplicity in control structure and high dynamic performance of instantaneous electromagnetic torque [2].

The control of PMSM needs a speed sensor to estimate the speed and position, but this may increase the complexity, weight and cost of the system. The research and development work on the sensor less driver is progressing greatly [3].

Many techniques have been proposed in order to estimate the rotor speed and position, such as open-loop estimators using stator voltages and currents, back EMF-based position estimators, MRAS estimators, observe-based position speed and position estimators, high-frequency signal injection and artificial intelligence [4].

In the process of estimation, the stator resistance may cause a mismatch in the calculation of the ohmic drop value, so the variation has a great influence on the speed estimation at the low speed region since the actual current may deviate from their set values. Hence the estimation of stator resistance is necessary in sensorless speed control applications especially at low and very low speed regions [3].

Due to the simpler implementation, less computational effort and good stability, the method of MRAS is widely used in the estimation of parameters or speed for motor drives. the method of MRAS for speed estimation with on-line tuning the stator resistance are proposed for sensorless PMSM [3].

II. THE MATHEMATICAL MODEL OF PMSM

The PMSM equations in rotor reference frame (d-q) are given as :

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \qquad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \omega_e \lambda_f \qquad (2)$$

Where ;

$$\lambda_d = L_d i_d + \lambda_f \qquad (3)$$

$$\lambda_q = L_q i_q \qquad (4)$$

Where; $\lambda_d, \lambda_q, v_d, v_q, i_d, i_q, L_d,$,are the stator flux linkage, stator voltages, stator currents, statorinductancesin rotor reference frame (d-q) respectively; is stator resistance; is rotor magneto motive force .

Since $\omega_e = p\,\omega_r,$, are electrical angular velocity and rotor angular velocity respectively; p is the number of the pole pairs of the motor .

The electromagnetic torque (Te) expressed in terms of motor flux linkage and d-q axis current is :

$$T_e = \frac{3}{2} p\left(\lambda_f i_q - \left(L_d - L_q\right) i_d i_q\right) \qquad (5)$$

The mechanical dynamic equation is given by

$$j \frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \qquad (6)$$

Where: T_e, , electromagnetic and load torques respectively; ,moment of inertia; B ,viscous friction coefficient.

III. SPEED AND RESISTANCE ESTIMATION

From equations (1,2), we could get the reference model :

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L} & p\omega_r \\ -p\omega_r & -\frac{R_s}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L} \\ \frac{v_q}{L} - \frac{p\omega_r \lambda_f}{L} \end{bmatrix} \qquad (7)$$

The equation of the adjustable model can be given as:

ISSN: 2277-3754
ISO 9001:2008 Certified
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$$\frac{d}{dt}\begin{bmatrix}\hat{i}_d\\ \hat{i}_q\end{bmatrix}=\begin{bmatrix}-\frac{\hat{R}_s}{L} & p\hat{\omega}_r\\ -p\hat{\omega}_r & -\frac{\hat{R}_s}{L}\end{bmatrix}\begin{bmatrix}\hat{i}_d\\ \hat{i}_q\end{bmatrix}+\begin{bmatrix}\frac{v_d}{L}\\ \frac{v_q}{L}-\frac{p\hat{\omega}_r\lambda_f}{L}\end{bmatrix} \quad (8)$$

From Eqns. (7) and (8), we could get:

$$\begin{cases}\dot{i}=A\,i+Bv\\ \dot{\hat{i}}=\hat{A}\hat{i}+Bv\end{cases} \quad (9)$$

Where

$$i=\begin{bmatrix}i_d\\ i_q\end{bmatrix},\hat{i}=\begin{bmatrix}\hat{i}_d\\ \hat{i}_q\end{bmatrix}$$

$$A=\begin{bmatrix}-\frac{R_s}{L} & p\omega_r\\ -p\omega_r & -\frac{R_s}{L}\end{bmatrix}, \quad \hat{A}=\begin{bmatrix}-\frac{\hat{R}_s}{L} & p\hat{\omega}_r\\ -p\hat{\omega}_r & -\frac{\hat{R}_s}{L}\end{bmatrix}$$

$$Bv=\begin{bmatrix}\frac{v_d}{L}\\ \frac{v_q}{L}-\frac{p\omega_r\lambda_f}{L}\end{bmatrix}, \hat{B}v=\begin{bmatrix}\frac{v_d}{L}\\ \frac{v_q}{L}-\frac{p\hat{\omega}_r\lambda_f}{L}\end{bmatrix}$$

Proceeding further, let $x=i-\hat{i}$ be the generalized errorvector, Subtracting Eqn.(7) from Eqn.(8), we could get

$$\begin{aligned}\dot{x}&=\dot{i}-\dot{\hat{i}}\\ &=Ax+[A-\hat{A}]\hat{i}+[B-\hat{B}]v\\ &=Ax+\omega_1\end{aligned} \quad (10)$$

Defining $\omega=-\omega_1$ then

$$\omega=-\{[A-\hat{A}]\hat{i}+[B-\hat{B}]v\}$$

$$=\begin{bmatrix}-\frac{\hat{i}_d}{L} & p\hat{i}_q\\ -\frac{\hat{i}_q}{L} & -p\hat{i}_d-\frac{p\lambda_f}{L}\end{bmatrix}\begin{bmatrix}\hat{R}_s-R_s\\ \hat{\omega}_r-\omega_r\end{bmatrix}$$

$$=G(t)[\hat{\theta}(t)-\theta(t)] \quad (11)$$

Where ;$\hat{\theta}(t)=\begin{bmatrix}\hat{R}_s\\ \hat{\omega}_r\end{bmatrix}$, $\theta(t)=\begin{bmatrix}R_s\\ \omega_r\end{bmatrix}$,

$$G(t)=\begin{bmatrix}-\frac{\hat{i}_d}{L} & p\hat{i}_q\\ -\frac{\hat{i}_q}{L} & -p\hat{i}_d-\frac{p\lambda_f}{L}\end{bmatrix}$$

Introducing the output generalized error $e$as :

$$e=cx \quad (12)$$

Then using equations.(10),(11),(12), we could get,

$$\begin{cases}\dot{x}=Ax+I(-\omega)\\ e=Cx+J(-\omega)\\ \omega=G(t)[\hat{\theta}(t)-\theta(t)]\end{cases} \quad (13)$$

Where $I=\begin{bmatrix}1&0\\0&1\end{bmatrix}$, $J=\begin{bmatrix}0&0\\0&0\end{bmatrix}$, $c=\begin{bmatrix}k&0\\0&k\end{bmatrix}$, $k>0$

Based on MRAS with PI as adaptation control law, the speed and resistance estimation can be obtained:

$$\hat{\theta}(t)=\begin{bmatrix}\hat{\theta}_1\\ \hat{\theta}_2\end{bmatrix}$$

$$=\begin{bmatrix}\hat{R}_s\\ \hat{\omega}_r\end{bmatrix}$$

$$=\begin{bmatrix}\left(\frac{k_{i1}}{p}+k_{p1}\right)S_1\\ \left(\frac{k_{i2}}{p}+k_{p2}\right)S_2\end{bmatrix} \quad (14)$$

Defining s_1 and $s_2$as :-

$$\begin{cases}s_1=\frac{\hat{i}_d}{L}(\hat{i}_d-i_d)+\frac{\hat{i}_q}{L}(\hat{i}_q+i_q)\\ s_2=p\left[-\hat{i}_q(\hat{i}_d-i_d)+(\hat{i}_d+\frac{\lambda_f}{L})(\hat{i}_q+i_q)\right]\end{cases} \quad (15)$$

IV. CONVENTIONAL DTC

DTC for induction motor was introduced about more than twenty years by Takahashi and Depenbrock.

The main advantages of DTC are the simple control scheme, a very good torque dynamic response, as well as the fact that it does not need the rotor speed or position to realize the torque and flux control, moreover DTC is not sensitive to parameters variations (except stator resistor)[1] .

However, it still has some disadvantages: high torque ripples and variable switching frequency, which is varying with speed, load torque, selected hysteresis bands and difficulty to control torque and flux at very low speed [1].

The basic principle of DTC is to directly select stator voltage vectors according to the differences between the reference and actual torque and stator flux linkage.[4]

The methods of DTC as shown in Fig 1 consist of directly controlling the turn off or turn on of the inverter switches on calculated values of stator flux and torque from relation .

The aim of the switches control is to give the vector representing the stator flux the direction determined by the reference value [5]

$$\begin{cases}\varphi_{s\alpha}=\int_0^t(v_{s\alpha}-R_s i_{s\alpha})dt\\ \varphi_{s\beta}=\int_0^t(v_{s\beta}-R_s i_{s\beta})dt\end{cases} \quad (16)$$

The DTC is deduced based on the two approximations described by the formulas (17) and (18).

$$\bar{\varphi}_s(k+1)\approx\bar{\varphi}_s(k)+\bar{V}_s T_E\rightarrow\Delta\bar{\varphi}_s\approx\bar{V}_s T_E (17)$$

$$T_e=k(\bar{\varphi}_s\times\bar{\varphi}= \quad k|\bar{\varphi}_s||\bar{\varphi}'_r|\sin(\delta) \quad (1$$

More over:

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 5, Issue 6, December 2015

$$\begin{cases} \hat{\varphi}_s = \sqrt{\hat{\varphi}_{s\alpha}^2 + \hat{\varphi}_{s\beta}^2} \\ \angle\hat{\varphi}_s = arctg\,\dfrac{\hat{\varphi}_{s\alpha}}{\hat{\varphi}_{s\beta}} \end{cases} \qquad (19)$$

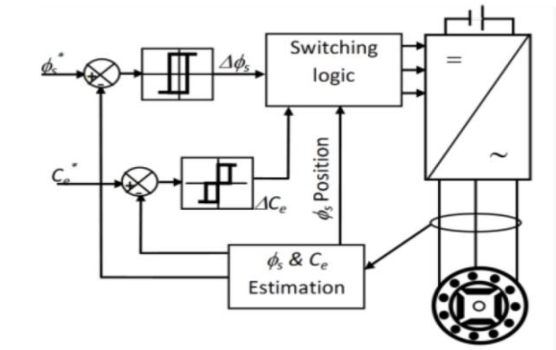

Fig1: Diagram of DTC control applied for PMSM supplied with a three-phase inverter

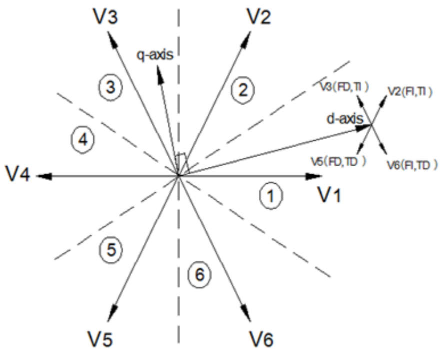

Fig2: Different vectors of stator voltages provided by a two levels inverter

Where;

IF,DF : Increase and Decrease of Flux amplitude.
IT,DT : Increase and Decrease of Torque

Table 1have the sequences corresponding to the position of the stator flux vector in different sectors (see Fig 2)

Table 1.Switching table for Conventional DTC

Sector		S_1	S_2	S_3	S_4	S_5	S_6
$\Delta\text{Ø}_s$	ΔC_e						
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_6	V_1	V_2	V_3	V_4	V_5
-1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

Where ;
The stator voltage-vectors (-)are given as :
$V_0 = (00,\quad V_1 = (10,\quad V_2 = (11,\quad V_3 = (01,$
$V_4 = (01,\quad V_5 = (00,\quad V_6 = (10,\quad V_7 = (00.$

V. SIMULATION MODEL AND RESULTS

A. *Simulation Model :-*

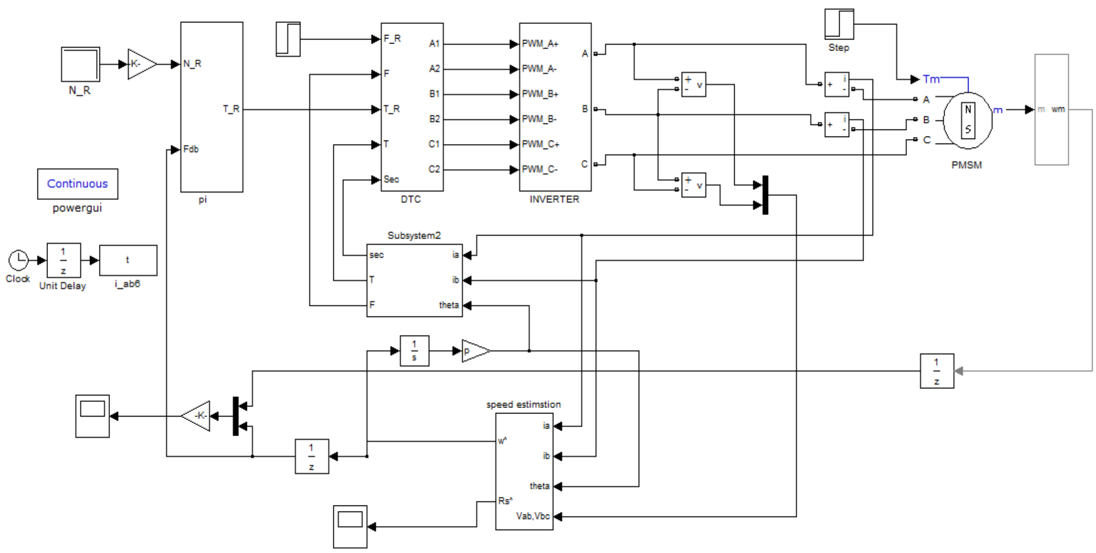

Fig3.Simulink model for sensor less speed control for PMSM control drive system

ISSN: 2277-3754
ISO 9001:2008 Certified
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B. Simulation Results:

Table 2, show the *PMSM* parameters used in this simulation.

Table 2 .PMSM parameters

speed	2000 RPM
Stator resistance	0.9585 Ω
Inductance Ld	0.00525 H
Inductance Lq	0.00525 H
Magnet flux linkage	0.1827 Wb
Number of pole pairs	4
Inertia	0.0006329 Kg.m^2
Friction factor	0.0003035 N.m.s

Figure3 shows the block diagram of speed sensor less control of PMSM.

Figure 4illustrates estimated speed (RPM) issued by MRAS, and actual speed (RPM) simulate with MATLAB software.

The reference speed of simulated the system is 2000 (RPM) , The reference speed changes from zero to 2000(RPM) at the time of 0.0154 s, and at the time of 0.1s speed has changed from 2000(RPM) to -2000(RPM) ,the speed reached to -2000 (RPM) at the time of 0.119 s .

The PMSM is started with no load. but at the time of 0.05(s), the PMSM is tracking load equal to 8 (Nm)As shown in Figure 7 .

Figure 5, show The error between estimated .and Figure 6, illustrates the evolution of stator resistance, actual and estimated.

Figure 8, shows reference and estimated Stator flux, and, Figure 9, and shows Estimated and actual current in q-axis

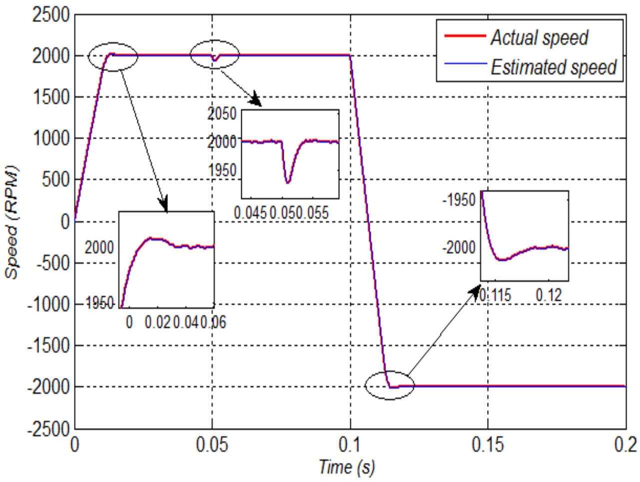

Fig4: Estimated and actual speed

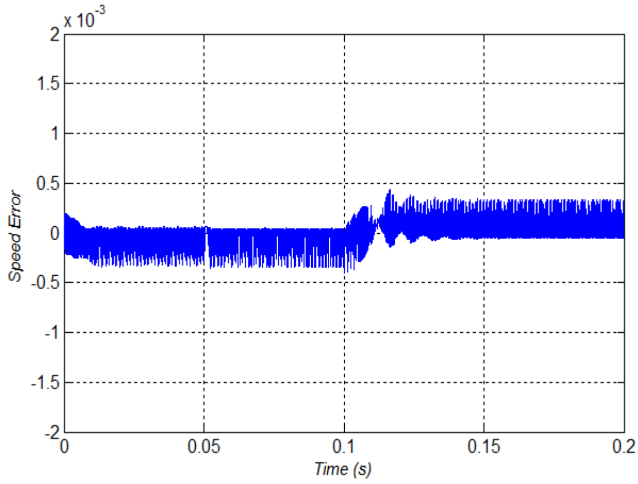

Fig 5 :The error between estimated and actual speed

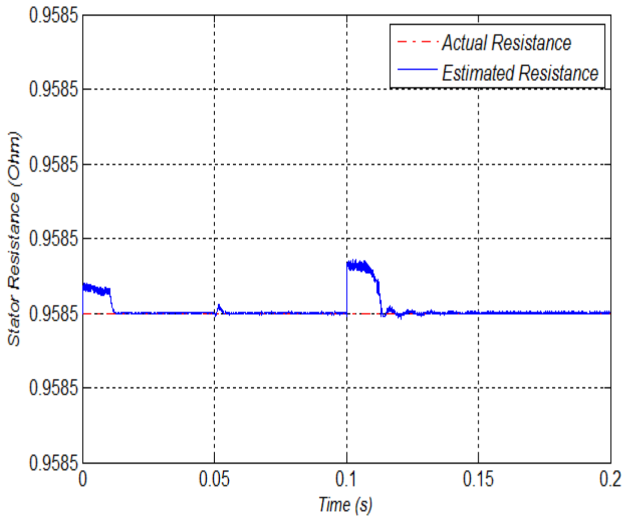

Fig 6: Estimated and actual resistance

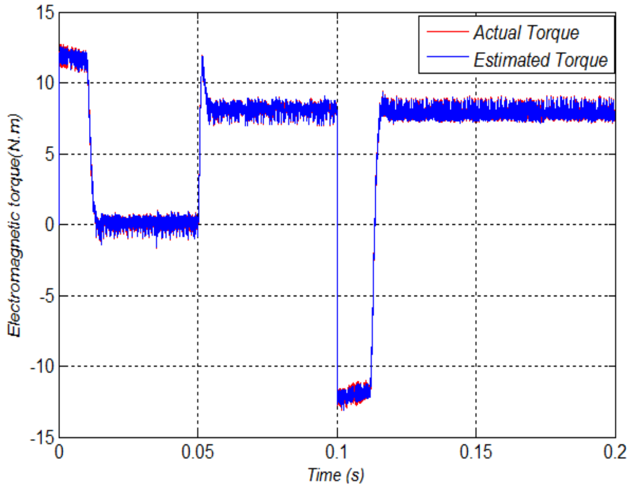

Fig7: Electromagnetic torque

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International Journal of Engineering and Innovative Technology (IJEIT)
Volume 5, Issue 6, December 2015

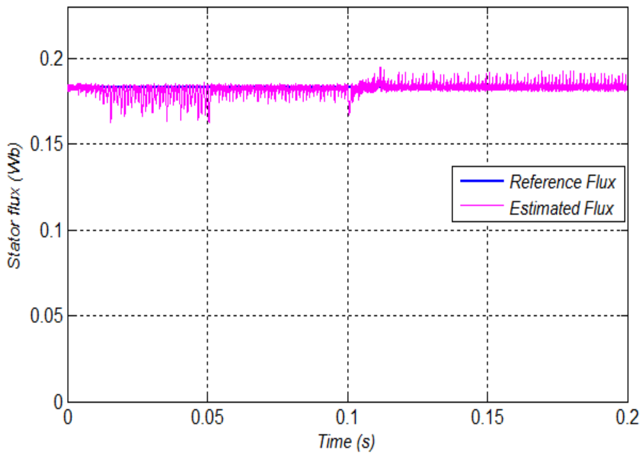

Fig 8 : Stator flux

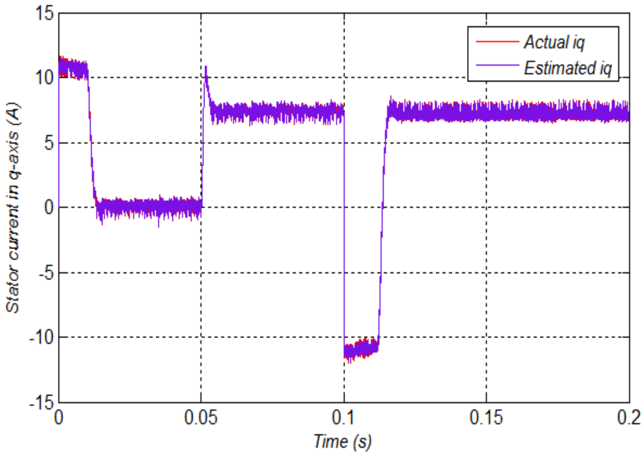

Fig 9: Estimated and actual current in q-axis

VI. CONCLUSION

In our work , a sensor less method of DTC is employed as controller for speed the PMSM drives and. model reference adaptive system has been presented for estimating the stator resistance and speed of a PMSM in order to achieve a robust speed sensorless*DTC*, MRAS technique is simple and it will reduce the mathematical computation time .

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