A New Sensorless Vector Control Method for Permanent Magnet Synchronous Motor without Velocity Estimator

Hamid D. Taghirad*, N. Abedi and E. Noohi

Department of Electrical Engineering
K.N. Toosi University. of Technology
P.O. Box 16315-1355, Tehran, Iran
*taghirad@novindana.com

Abstract: *In this paper a novel vector control method for permanent magnet synchronous motors is presented. In this method the velocity estimation is completely vanished and the vector control is accomplished in a new coordinate system. In the conventional vector control methods, the control effort is calculated in the rotating coordinate with the synchronous speed of* ω_r. *However, in the proposed method the control effort is calculated in the rotating coordinate with the reference speed* ω^*. *This change of coordinate, decreases the calculation effort, significantly. In order to verify the applicability of the proposed control law, a Lyapunov based stability condition is derived and then, the performance of the controller is verified through simulations and experiments. The obtained results illustrate the effectiveness of the proposed method despite the simplicity of its implementation.*

1 Introduction

Permanent magnet motors are widely used ***in*** industrial applications, because of their superior advantages. High performance, low inertia, high torque to current ratio, high power factor, and almost no need for maintenance are among the important advantages of these type of motors causing their extensive use in different applications. However, the need of position or velocity sensor in order to apply effective vector-control algorithms, is one of their main constraints. Therefore, vector-control methods in the absence of any position or speed sensor, have been investigated by many researchers [1,2,3]. In most of the methods the main proposed alternative is the estimation of the motor position or velocity. In some methods (indirect methods) [4], first the estimation of velocity is performed and then the trigonometric values, which are required for the vector control, are calculated. In some other methods [5], the required trigonometric values are directly estimated from motor state equations. Estimation theory and especially Extended Kalman Filter method is extensively used in indirect methods [6]. However, Flux equations are the base of trigonometric value determination in direct methods [7]. In both methods the state equations are derived in the rotor coordinate system. Hence, because of the use of synchronous coordinate in the estimation procedure, usually the estimation error propagation is observed in practice. This problem is magnified in the presence of noise, or inaccurate knowledge of the motor parameters [6,7].

In this paper a novel method is proposed, in which the modeling and control of the motor is derived in a new coordinate system. Due to the characteristics of the derived model, there is no need to estimate the position or velocity. The speed of rotation of this frame is ω^* (reference Speed) instead of ω_r; therefore, all the required trigonometric equation can be derived and implemented in a completely determined frame. The significance of this change of coordinate is elaborated in next sections. One of the main important advantages of this method is its capability to control the motor at very low velocities.

The method can be categorized as a Lyapunov-based control method, in which the closed loop system is designed such that its asymptotic stability, in the sense of Lyapunov, is guaranteed. In other words the controller is designed to regulate the system about its equilibrium state. Hence, the variation of the Equilibrium State of the system is constrained to remain close to the desired trajectory. Satisfying this condition guarantees the tracking performance of the system [8]. Similar Lyapunov-based control methods for vector control of a synchronous motor, are examined by few researchers [9,10].

2 Experimental Setup

In order to verify the performance of the proposed controller in practice, an experimental test bed is integrated. The experimental setup consists of three main components: A 200 watts permanent magnet synchronous motor, the required power inverter, and a DSP board. The setup is integrated by TechnoSoft Co., in which a software interface is build into the system. The software enables the user to initialize different hardware connections, as well as to emulate, debug and test the program. The compiled program is downloaded into the DSP via the serial port of the computer. The DSP used in the emulator board is from 2407 series of Texas Instrument manufactured DSP's. This board accommodates connection to the inverter through a cable. The measured current and command signals are conveyed through it. The inverter produces the required three-phase voltage needed for the synchronous motor by its DC voltage command input within 0 to 36 volts. The speed of the board is 50 kHz, which limits the frequency of producible PWM signal. There exists a current sensor, which converts the current from ±6.33 Amps to the range of [0-3.3] Volts. Finally the Synchronous motor used in the setup is from 3441 series produced by Pittman Co. whose technical specifications are given in Table 1. Fig 1 illustrates the experimental setup.

Table 1, Permanent Magnet Motor Specs

R	5.25 Ω
L	0.46 mH
λ	50 mNm/A
J	9*10-7 Kgm2
P	2 pole pair

3 Control Algorithm

As introduced before, the main idea of the proposed control algorithm is the use of reference speed in the dynamic equation of the system. The dynamic equation of the motor in the synchronous frame is as following:

$$\begin{cases} L_q \dot{I}_q = V_q - RI_q - L_d \omega_r P I_d - \lambda \omega_r P \\ L_d \dot{I}_d = V_d - RI_d + L_q \omega_r P I_q \\ J\dot{\omega}_r = \frac{3}{2} P \lambda I_q + \frac{3}{2} P (L_d - L_q) I_d I_q - F\omega_r - T_m \end{cases} \quad (1)$$

According to Fig 2, the reference speed ω^* is used in the Park transformations. It leads us to define a new frame, rotating with the reference speed ω^* which can be called as "*Reference Frame*". The controller equations are described in this frame.

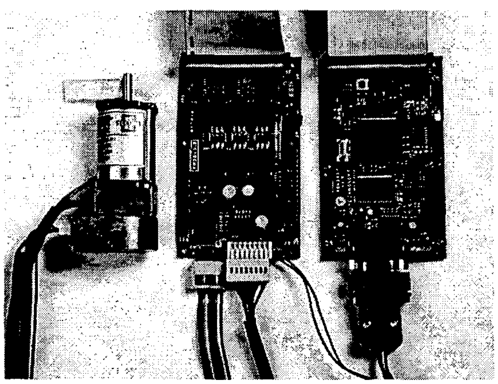

Fig 1, Experimental Setup

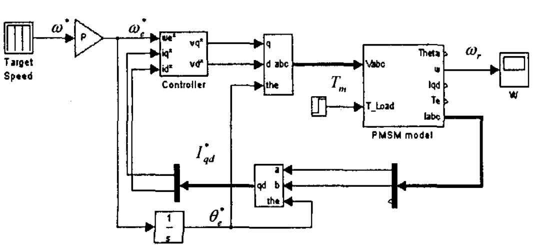

Fig 2, Block Diagram of Control Algorithm

Hence, the similarity transformations between two frames can be evaluated from the following equation:

$$\begin{cases} V_{qd} = TV_{qd}^* \\ I_{qd} = TI_{qd}^* \end{cases} \quad T = \begin{bmatrix} \cos(\theta_e - \theta_e^*) & -\sin(\theta_e - \theta_e^*) \\ \sin(\theta_e - \theta_e^*) & \cos(\theta_e - \theta_e^*) \end{bmatrix} \quad (2)$$

In which θ_e^* is the reference electrical position, and the superscript * denotes that the variable is evaluated in the reference frame. The following nonlinear control is applied on the system:

$$\begin{cases} V_q^* = L^* \omega^* P I_d^* + K \lambda \omega^* P \\ V_d^* = -L^* \omega^* P I_q^* \end{cases} \quad (3)$$

Due to the independence of the instantaneous rotor speed, there is no need for speed estimation in this method. On the other hand, only six multiplications and one addition are required for digital implementation.

4 Stability Analysis

In order to validate the effectiveness of the proposed control law, it is necessary to analyze the stability of the closed loop system. In order to apply the control law into the dynamic equation of the motor their coordinates must be the same. Using similarity transformation given in equation 2, the control law can be rewritten in the synchronous frame. The closed loop system dynamics result in:

$$\begin{cases} L_q \dot{I}_q = -RI_q - L_d \omega_r P I_d - \lambda \omega_r P + L^* \omega^* P I_d + \\ \qquad K \lambda \omega^* P \cos(\theta_e - \theta_e^*) \\ L_d \dot{I}_d = -RI_d + L_q \omega_r P I_q - L^* \omega^* P I_q + \\ \qquad K \lambda \omega^* P \sin(\theta_e - \theta_e^*) \\ J\dot{\omega}_r = \frac{3}{2} P \lambda I_q + \frac{3}{2} P (L_d - L_q) I_d I_q - F\omega_r - T_m \end{cases} \quad (4)$$

Fortunately, stability of the closed loop system about reference speed ω^* is guaranteed by mild condition on K, L^*. Therefore, by setting $\omega^* = \omega_{ref}$ tracking performance is expected to be satisfied.
To analyze the stability, let us examine the linearized equation of motion about ω^*. For simplicity of calculation, assume $L_d = L_q = L$. In this case by choosing $L^* = L$ results in a simple controller, by which the closed loop symmetric system equation is as following:

$$\begin{cases} L_q \dot{I}_q = -RI_q - L(\omega_r - \omega^*) P I_d - \lambda \omega_r P + \\ \qquad K \lambda \omega^* P \cos(\theta_e - \theta_e^*) \\ L_d \dot{I}_d = -RI_d + L(\omega_r - \omega^*) P I_q + K \lambda \omega^* P \sin(\theta_e - \theta_e^*) \\ J\dot{\omega}_r = \frac{3}{2} P \lambda I_q - F\omega_r - T_m \\ \dot{\theta}_r = \omega_r \end{cases} \quad (5)$$

It can be shown that this system has an equilibrium point at:

$$X_0 = \begin{bmatrix} I_{q0} \\ I_{d0} \\ \omega_{r0} \\ \theta_{r0} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}\left(\frac{F\omega^* + T_m}{P\lambda}\right) \\ \frac{P}{R} K \lambda \omega^* \sin(\Delta) \\ \omega^* \\ \theta^* + \frac{\Delta}{P} \end{bmatrix} \quad (6)$$

In which

$$\cos(\Delta)=\frac{1}{K}\left(1+\tfrac{2}{3}R\frac{F\omega^{*}+T_m}{P^2\lambda^2\omega^{*}}\right) \tag{7}$$

The incremental dynamics of the system about the equilibrium point has the form of:

$$\Delta\dot{x}=F\cdot\Delta x \tag{8}$$

In which F is the Jacobian of the nonlinear equation and can be evaluated from:

$$F=\frac{\partial f}{\partial X}\Big|_{X=X_0}=\begin{bmatrix}-\frac{R}{L} & 0 & -PI_{d0}-\frac{P\lambda}{L} & -K\frac{P}{L}\lambda\omega^{*}\cos(\Delta)\\ 0 & -\frac{R}{L} & PI_{q0} & K\frac{P}{L}\lambda\omega^{*}\sin(\Delta)\\ \frac{3}{2}\frac{P\lambda}{J} & 0 & -\frac{F}{J} & 0\\ 0 & 0 & 1 & 0\end{bmatrix} \tag{9}$$

In order to analyze the stability of the system with the first method of Lyapunov, the characteristic equation of the linearized system (Eq. (8)) is evaluated symbolically as following:

$$P(X)=\frac{(LS+R)}{2L^2J}\{2RLJS^3+2(LF+RJ)S^2+ (2RF+3P^2\lambda^2+3P^2L\lambda I_{d0})S+3P^2\lambda^2K\omega^{*}\cos(\Delta)\} \tag{10}$$

To have a stable system, all of the above coefficients must be positive and $-1<cos(\Delta)<1$. From these conditions the stability conditions result in:

$$\begin{aligned} &0<T_m<\tfrac{3}{2}(K-1)\frac{P^2\lambda^2\omega^{*}}{R}-F\omega^{*} && \omega^{*}>0\\ &0<T_m<-\tfrac{3}{2}(K+1)\frac{P^2\lambda^2\omega^{*}}{R}-F\omega^{*} && \omega^{*}<0\\ &K\omega^{*}\cos(\Delta)>0 && K\omega^{*}\sin(\Delta)>0\end{aligned} \tag{11}$$

From the first method of Lyapunov stability theorem, The system is asymptotically stable in a local neighborhood about x_o. If Δx is small enough, this approximation is valid for the nonlinear system, and the motor speed ω_r converges to ω^{*}, asymptotically. This condition is certainly satisfied if the rate of variation of ω^{*} is much slower than the smallest pole of the closed loop stable system. Similar to this analysis, stability conditions can be determined for $L_d \neq L_q$. However, it is verified through simulations and experiments, that $L^{*}=\max(L_d,L_q)$ is an appropriate choice in practice.

5 Simulation and Experimental Results

First, the proposed control law with $K=1.3$ is implemented in the computer simulations introduced in Section 2, and the results are given in Fig 3. As it is illustrated in Fig 3-c, in this simulation a disturbance load torque of amplitude 0.01 is applied at time 0.4 seconds. As it is seen in Fig 3-a the tracking response in presence of the torque disturbance is very fast and well behaved. Moreover, the speed variation at initial time is well rejected. In Fig 3-b and 3-d the motor currents I_d^{*}, I_q^{*} and $\cos(\varphi)$ is plotted, respectively. As it is illustrated both motor currents converge to non-zero constant values. This is contrary to what is seen for the conventional control algorithms, and that's the main reason for the insensitivity of the proposed method to noise at low velocities. This is one of main important characteristics of the method, which is obtained through the cost of having nonzero currents even at no load low velocities.

The Speed diagram of Fig 3-a is in rad/sec, and all of the other signals in Fig 3 are in Metric system.

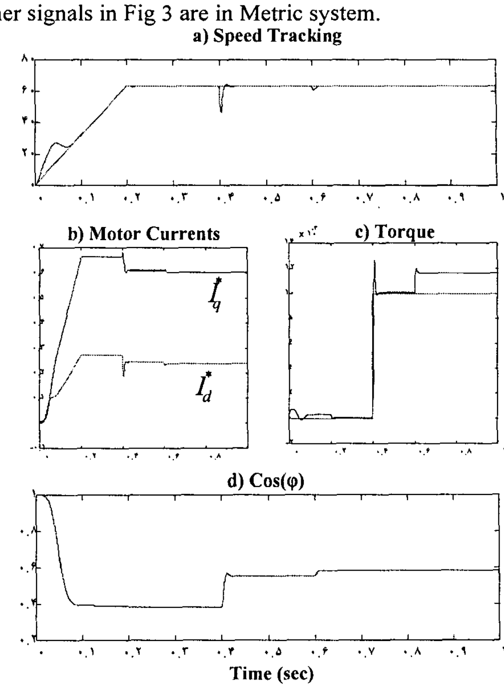

Fig 3, Simulation Results

After promising results obtained by the simulations, the proposed algorithm has been applied on the experimental test bed. Fig 4 illustrates the tracking performance of the motor speed, for a varying signal with rather sharp edges. The performance of the closed loop system is very good as expected. In order to see the speed variation in detail, the reference and measured speed is zoomed out in Fig 5. The illustrated noise on the tracked speed is due to the numerical truncation errors of the fixed-point calculations at the DSP, in order to generate the command PWM signal, and the encoder resolutions. The relatively large motor currents depicted in Fig 6 are the main reason of insensitivity to noise at low velocities, as explained before. Next, the experimental results for the motor tracking performance under load are illustrated in Fig 7. As it is clear in the motor current curves the load is exerted on the system in about four seconds and is released at fourteen seconds. At this time almost no effect is observed in the speed tracking performance. In this experiments $K=1.8$ is implemented. All diagrams in Fig 4 - Fig 7 are per unit due to the nature of fixed calculation in DSP. Speed diagrams must scale with 100 rad/sec and current diagrams must scale with 6.33 Amps.

The spectacular tracking performance obtained in these experiments clearly shows the effectiveness of the proposed control algorithm, despite its simplicity of implementation.

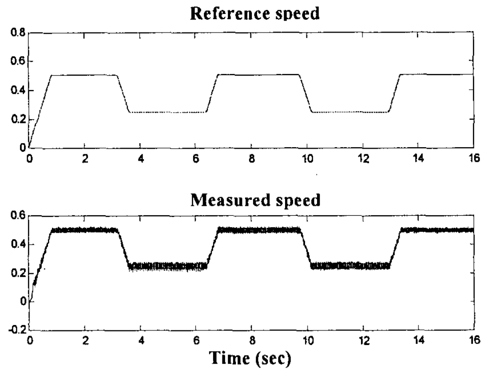

Fig 4, Experimental results- speed tracking

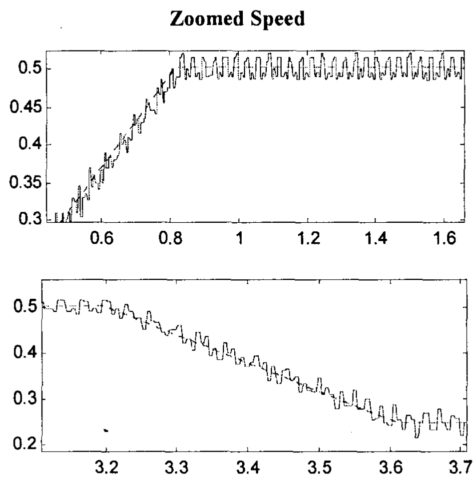

Fig 5, Experimental results- zoomed speed

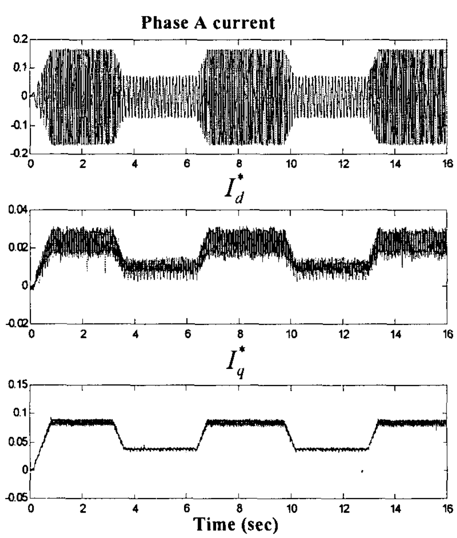

Fig 6, Experimental results- motor currents

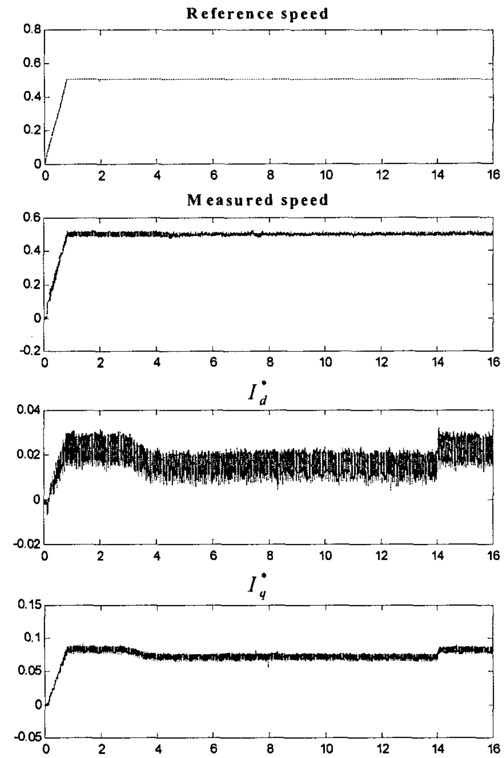

Fig 7, Experimental results- motor under load

6 Conclusions

In this paper a new and simply-implementable method for sensorless vector control of permanent magnet synchronous motor is presented. In this method the velocity estimation is completely vanished and the vector control is implemented in a new coordinate system. The stability and tracking condition for the proposed controller is derived and the performance of the controller is verified through simulations and experiments. It is illustrated in the experimental results, that because of the existence of nonzero motor currents at low speed, the control scheme is insensitive to the external noises at low velocities. This characteristic is superior compared to the results obtained from conventional methods. Finally, the closed-loop performance characteristics are presented, which illustrate the effectiveness of the proposed method despite its simplicity of implementation.

References

[1] A. Consoli,G. Scarcella,and A. Testa, "Industry Application of Zero-Speed Sensorless Control Techniques for PM Synchronous Motors", IEEE Trans. Ind. App., vol. 37, No. 2, pp 513-519 March/April 2001

[2] S Bolognani, M Zigliotto, and M Zordan "Extended-Range PMSM Sensorless Speed Drive Based on Stochastic Filtering", IEEE Trans. Power

Elec, Vol. 16, No. 1, January 2001

[3] M. Leksell, L. Harnefors and M. Jansson, "Direct Sensorless Speed Control of PM-Motors - a Simple and Effective Sensorless Method", Published in the Proc. of Power Elec. Specialist Conference (PESC '01), Vancouver, Canada, June 2001

[4] Y. Bas, G. Tadmor and M. Stankovich, "Passivity Based Sensorless Control of a Smooth Rotor Permanent Magnet Synchronous Motor", Proc. Of 36th Conf. On Decision and Control, San Diego, USA, Dec. 1997

[5] K.S. Low, Y.Z. Deng, X.L. Guo, "Tow-degree-of-freedom Control of PMSM Drive without Mechanical Sensor", IEEE 1998

[6] S. Bolognani, R. Oboe and M. Zigliotto, "Sensorless Full-Digital PMSM Drive With EKF Estimation of Speed and Rotor Position", IEEE Trans. Ind. Elec, vol. 46, No. 1, pp 184-191, February 1999

[7] T. Senjyu, T. Shimabukuro, K. Uezato, "Vector Control of Permanent Magnet Synchronous Motors without Position and Speed Sensors", IEEE 1995

[8] Hassan K Khalil, Michigan State University, "NONLINEAR SYSTEMS", Second Edition Chapter 13, Prentice Hall, Upper Saddle River, NJ07458

[9] F. Parasiliti, R. Petrella, M. Tursini: "Sensorless Speed Control of a PM Synchronous Motor by Sliding Mode Observer". IEEE International Symposium on Industrial Electronics (ISIE '97), Portugal, July 7-11 1997

[10] V. Nardocci, F. Parasiliti, M. Tursini: "Speed Sensorless Field-oriented Control of Induction Motors by Sliding Mode observer", 32Th. Universities Power Engineering Conference (UPEC'97), (UK), 10-12 September 1997