One-line Detection of Rotor Position for Vector Controlled IPMSM

Topic number: T2

Abstract—**Conventional vector control of IPMSM requires a motor position sensor to correctly orient the current vector orthogonally to the flux. Thus, a high degree of torque control over a wide speed range can be achieved. Rotor speed position is measured using shaft encoder which is fixed manually on the rotor such that positive edge of the home signal per one revolution Z of the shaft encoder coincides with the zero reference position of phase-A. However, shaft encoder placement may be significantly inaccurate due to human mechanical error during fixing. This paper shows that misplaced the shaft encoder not only leads to unbalance operation of the inverter and motor phases, which increases the low frequency harmonics in torque ripple and degrades the overall drive performance but also, reduces the overall torque obtained from the vector controlled drive system due to the reduction of the quadrature-axis component of current. However, a novel technique is theoretically proposed and experimentally applied to determine on-line the value of error angle between positive edge of home signal Z of the shaft encoder and zero position of phase-A, to achieve a better dynamic performance. The proposed method can be implemented on-line and does not require any additional hardware.**

Keywords **—Interior permanent magnet synchronous motor, vector control, rotor position detection.**

I. INTRODUCTION

Recent developments in power semiconductor technology, digital electronics, and control theory have enabled modern AC motor drives to face challenging high efficiency and high performance requirements in industry. In addition, improvement of permanent magnet (PM) materials has widened the application of IPMSMs such that they have became popular in high performance applications compared to other types of AC motors due to their advantageous features including high torque to current ratio as well as high power to weight ratio, high efficiency, low noise and robustness [1]. Precise control of high performance (IPMSM) over wide speed range is an engineering aspect. Motor's fast and accurate response and quick recovery of speed from any disturbances and insensitivity of parameter variations are some of the important characteristic of high performance drive system used in robotics, rolling mills, traction and spindle drive [2]. In order to control the IPMSM, position and speed sensors are indispensable because both current and voltage should be controlled depending on the rotor position. The decoupled vector control technique can be used so that the IPMSM can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC over DC motors. Moreover, the vector control drive provides a wide range of speeds, high torque capability and high efficiency. However, conventional vector control of IPMSM drives requires a motor position sensor to correctly orient the current vector orthogonally to the flux because the rotor flux is obtained from permanent magnets. In such a way, it is possible to directly control the torque by acting simply on the amplitude of the stator current. Thus, a high degree of torque control over a wide speed range including the standstill can be achieved [4].

The speed is measured using the shaft encoder which is fixed manually on the rotor such that the positive edge of the home signal per one revolution Z of the shaft encoder coincides with the zero of phase-A, where, the zero reference position is usually taken such that the d-axis (North Pole), where the magnetic flux exists coincides with phase-A. However, in fact, the shaft encoder placement may be significantly inaccurate due to human mechanical error during fixing. Therefore, this method is not very accurate since there will be a degree of uncertainty in the determination of the rotor position [5]. Therefore, any error in determining the actual rotor position will affect the overall drive system performances completely. The absolute error of sensor placement may reach several mechanical degrees, which translates into an even greater error in electrical degrees for machines with a high number of magnetic poles [6]. Moreover, the effect of the shaft encoder misplacement leads to several consequences; In general, insufficiently precise positioning of the shaft encoder causes unbalanced operation of the motor inverter resulting in increase in torque pulsation, vibrations, and acoustic noise, as well as reduced overall electromechanical performance [6]. In addition, any error in determining the actual rotor position will affect the dynamic performance capabilities of the decoupled vector control technique, since this error will lead to the reduction of the quadrature-axis component of current which in turns will reduce the overall torque obtained from the vector controlled drive system**.** Although there exists a large number of publications on IPMSM drives, but only few address the misplacement of the shaft encoder. A misalignment of Hall sensors was documented in [7], which investigated a relatively sophisticated BLDC motor drive with an advanced observer-based torque ripple mitigation control. For small-scale machines, the accuracy of Hall-sensor positioning may also be a problem. In [8], it is demonstrated a carefully made prototype with the relation of unsymmetrical phase currents to the Hall-sensor inaccuracy. Although the rotor position error appears to be a known problem, yet there are not many solutions. An approach of manually realigning the sensors requires opening the machine (or its back side) and adjusting the sensors until the required accuracy is achieved, which is not very practical especially for large quantity of motors. Introducing additional hardware circuitry is also not desirable because it leads to increased complexity and cost of the drive. The operation of a low-precision BLDC motor with misaligned Hall-sensors was described in [9], where a simple averaging of the time intervals was proposed to improve the steady-state operation. A filtering methodology that can be applied to the shaft encoder was presented in [10] to mitigate the effect of misplacement during transient operation.

However, in this paper a novel technique has been theoretically proposed and experimentally applied to determine on-line the value of the error angle θ_e between the positive edge of the home signal Z of the shaft encoder and the zero position of phase-A. It is shown to achieve better dynamic performance of a vector controlled IPMSM, during both transient and steady-state operations. The present manuscript makes the following overall contributions:

1) The paper describes the phenomena of nonideal placement of shaft encoder based on a hardware prototype vector controlled IPMSM drive and its effect on the overall dynamic performance.
2) A simple but very effective and practical technique is proposed to improve the overall performance of vector controlled IPMSM with significant error in rotor position.
3) The proposed method does not require any additional or special circuitry or hardware. This solution can be implemented on-line, and therefore, may be useful for many applications.

The symbols used in this paper are as follows:

R_a : Stator armature resistance, Ω
ϕ_f : Flux linkage due to rotor permanent magnet, weber
i_d, i_q : d-and q-axis components of stator currents, A.
L_d, L_q :d-and q-axis inductances, H.
p : Differential operator.
P : Number of pole pairs.
v_d, v_q : d-and q-axis components of stator voltages, V.
T_e : Electromechanical torque, Nm
ω_r : Electrical rotor speed, rad/sec

II. DECOUPLED VECTOR CONTROL

Usually high performance motor drive systems used in these domains require fast and accurate speed response, quick recovery of speed from any disturbance and uncertainties. This makes the control of IPMSM difficult at different dynamic operating conditions. Consequently, the decoupled vector control technique can be used so that the IPMSM can achieve the dynamic performance capabilities of the separately excited DC machine, while retaining the general advantages of AC. The basic principle of decoupled vector control is to eliminate the coupling between the direct (d) and quadature (q) axes (i.e. between air-gap flux and torque). This prevents the demagnetization of the PM [11]. In such case, the generated torque is the product of two components; the magnetizing and the torque producing current components. Since the magnetizing is constant, the motor torque is linearly proportional to the torque producing component, which is similar to the control of a separately excited DC motor. In order to achieve maximum torque per ampere with linear characteristics, i_d is forced to zero resulting in the orientation of all the linkage flux in the d-axis [12], as shown in Fig. 1.

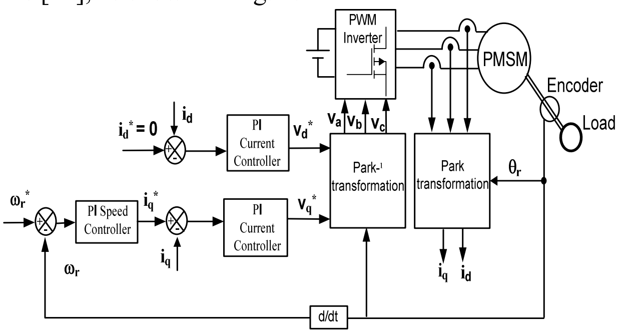


Fig. 1. Decoupled vector control scheme of the PMSM drive.

The IPMSM can be modeled where, the stator voltage equations in the rotor reference frame are expressed as follows [13]:

$$v_d = R_a\, i_d - \omega_r\, L_q i_q + L_d p i_d \quad (1)$$

$$v_q = R_a\, i_q + \omega_r\, L_d\, i_d + L_q p i_q + \omega_r \Phi_f \quad (2)$$

The electromechanical torque equation is given by:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\Phi_f\, i_q + \left(L_d - L_q\right) i_q i_d\right] \quad (3)$$

Substituting $i_d = 0$ (decoupled vector control condition) and p = 0 (steady state condition), the general IPMSM dynamic voltage equations "(1)" to "(3)" will tend to [14]–[15]:

$$v_d = -\omega_r L_q i_q \quad (4)$$

$$v_q = R_a i_q + \omega_r \phi_f \quad (5)$$

And the electromechanical torque will be:

$$T_e = \left({}^{3}/_{2}\right)\left({}^{P}/_{2}\right)\phi_f i_q \quad (6)$$

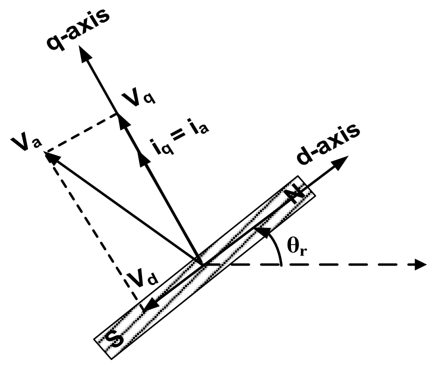


Fig. 2. d-q frame coincides with North Pole of the rotor in case of decoupled vector control.

III. EFFECT OF ROTOR POSITION ERROR IN DECOUPLED VECTOR CONTROL

The shaft encoder placement may be significantly inaccurate due to human mechanical error during fixing. Therefore, there will be an error angle between the positive edge of the home signal Z of the shaft encoder and the actual zero reference position at which phase-A coincides with North Pole. This error angle can be around 1 to 4 degree [16] and will lead to a certain degree of uncertainty in the determination of the rotor position. Any error in determining the actual rotor position will affect the overall drive system performances completely and will lead to the reduction of the quadrature-axis component of current which in turns will reduce the overall torque and hence the efficiency obtained from the vector controlled drive system.

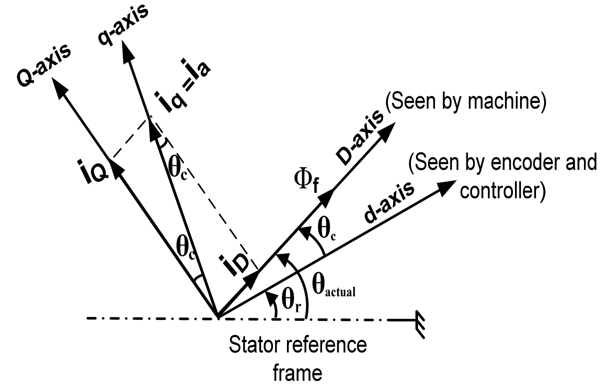


Fig. 3. Phasor diagram showing the relation between current measured d-q frame and actual D-Q frame.

Fig. 3 shows two synchronous reference frame, the dq frame which is measured by the encoder and consequently seen by the controller at which $i_d = 0$ and the DQ frame which is seen by the machine at which the North Pole coincides. The angle θ_c between them is the compensated angle.

From Fig. 3, the relation between the current measured d-q frame (rotor frame) and the actual D-Q frame will be given as follows:

$$[i_{dq}] = [A][i_{DQ}] \tag{7}$$

$$[i_{DQ}] = [A^{-1}][i_{dq}] \tag{8}$$

where, $[A] = \begin{bmatrix} \cos\theta_c & -\sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{bmatrix}$

The torque equation in DQ frame is given by:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\Phi_f\, i_Q + (L_d - L_q) i_Q i_D\right] \tag{9}$$

Substituting “(8)” into “(9)” yields to:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\Phi_f\, i_q \cos\theta_c + (L_d - L_q)\sin\theta_c \cos\theta_c\, i_q^2\right] \tag{10}$$

For a rotor position error (θ_c) around 10° electrical for instance due to inaccurate placement of the shaft encoder during fixing, the q-axis stator current will decrease by about 2.2% ($i_Q = i_q \cos 10 = 0.985\, i_q$), the d-axis stator current will not be equal zero ($i_D = i_q \sin 10 = 0.174\, i_q$ and consequently the electromechanical torque will be reduced by about 10% (see “(10)”) compared to the torque obtained from conventional vector control without rotor position error (see “(6)”).

IV. STRATEGY OF THE PROPOSED METHOD

In order to solve the problem discussed above, a novel method has been proposed to accurately detect the zero rotor position on-line. If the d-q frame (encoder frame) is suppressed into another D-Q frame (actual machine frame) as shown in Fig. 3, due to the existence of an error in the rotor position (θ_c), the D-axis stator current i_D will not be zero as in conventional vector control (see Fig. 2).

In order to calculate the value of the compensated angle θ_c, substitute the decoupled vector control condition ($i_d = 0$) into “(7)”, a relation between D-Q stator currents is obtained as follows:

$$\frac{i_D}{i_Q} = \frac{\sin\theta_c}{\cos\theta_c} \tag{11}$$

$$\text{Therefore,}\ \theta_c = \tan^{-1}\frac{i_D}{i_Q} \tag{12}$$

To identify the initial rotor position, assume that there is an error in the rotor position called (θ_c), between the rotor position (θ_r) and the actual position (θ_{actual}) [16] as shown in Fig. 3, such that:

$$\theta_{actual} = \theta_r \pm \theta_c \tag{13}$$

Then, this angle θ_c will be added to the rotor angle θ_r measured by the shaft encoder in order to compensate the actual rotor angle θ_{actual}.

The proposed method does not require any additional or special circuitry or hardware. However, it depends on the motor parameters Φ_f and R_a but usually these motor parameters are measured with high accuracy.

V. DETECTION ERROR BETWEEN CURRENT MEASURED d-q AND ACTUAL D-Q FRAME

The model depicted in Fig. 4 has been simulated to determine the value of the error angle θ_c that exists already in the measured rotor angle θ_r.

As shown in Fig. 4, the whole drive has two parts: 1) The conventional vector control drive where the two command currents; the current i_Q^* (which is the output from the speed controller) and the current i_D^* are converted using the measured position by the shaft encoder θ_r to three phase command currents i_{abc}^*, which are compared with the actual currents i_{abc} so as to produce the motor voltages v_{abc}. 2) The detection of error position angle θ_e whose idea is to vary the command current i_D^* and each time the DQ voltages and currents are transformed to another arbitrary frame dq, where the q-axis voltage equation which is concluded from “(2)”, is given as follows:

$$\omega_r\, L_d\, i_d = f(i_d) = v_q - R_a\, i_q - \omega_r \Phi_f \tag{14}$$

Equation (14) is continuously monitored until this dq frame coincides with the actual machine frame if and only if the condition $i_d = 0$ is satisfied. This implies that $f(i_d) = 0$ at which θ_c will be the angle between measured position by the encoder and actual position seen by the machine.

It is recommended to do the proposed idea at partial full load corresponding to low value of i_q for two reasons; the first is to avoid saturation value of L_q which may have higher percentage error and the second is to have trivial effect of the term $R_a i_q$ in “(14)”.

First, assume on purpose the presence of an error angle θ_e of any value let say (10°). Thus, the compensated angle θ_c can be estimated according to the strategy explained above (from “(12)”).

Then, a slider gain is used to vary the value of i_D until the function $f(i_D^*)$ calculated from “(14)’ is equal to zero. At this condition, the compensated angle θ_c will be equal to the error angle θ_e.

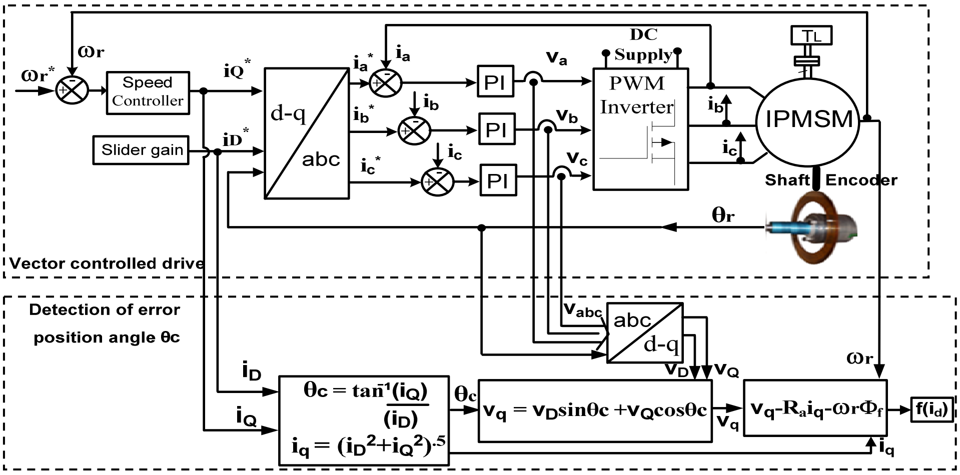
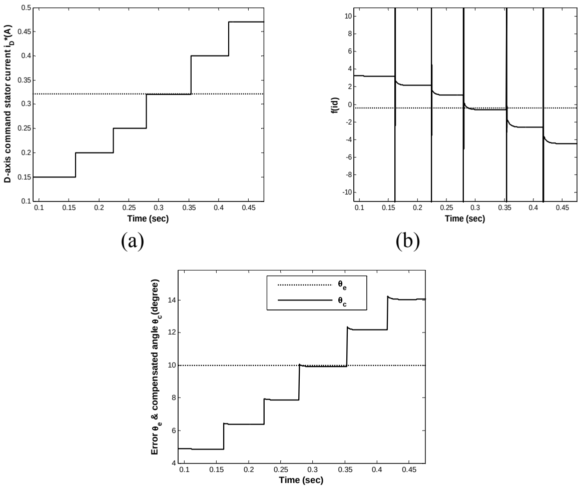


Fig. 4. Block diagram of the novel method to determine the actual rotor position.



(a) (b) (c)

Fig. 5. Relationship between time and: (a) i_D^*, (b $f(i_D^*)$, (c) θ_r and θ_c

From Fig. 5, it is clear that $\theta_c = \theta_e$ at the instant when the function $f(i_D^*) = 0$. That means that an angle of 10° is needed to be subtracted from the angle θ_r measured by the encoder in order to compensate the error in the shaft encoder misalignment as shown in Fig. 6.

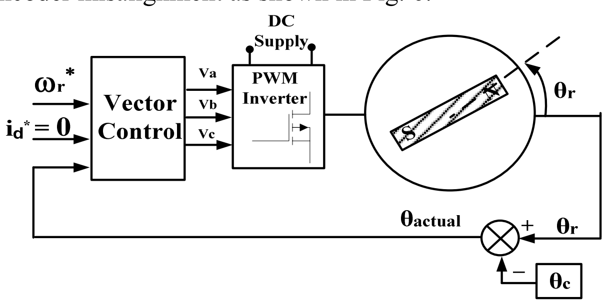


Fig. 6. Experimental diagram of the rotor position detection

VI. EXPERIMENTAL RIG

The schematic of the experimental setup of the drive system is shown in Fig. 7. The drive system consists of: i) IPMSM, ii) shaft encoder, iii) a three phase inverter module, DC link supply evaluation module, iv) two current transducers, v) digital signal processor DSP TMS 320C2812 and vi) its interface (isolation and drivers) card.

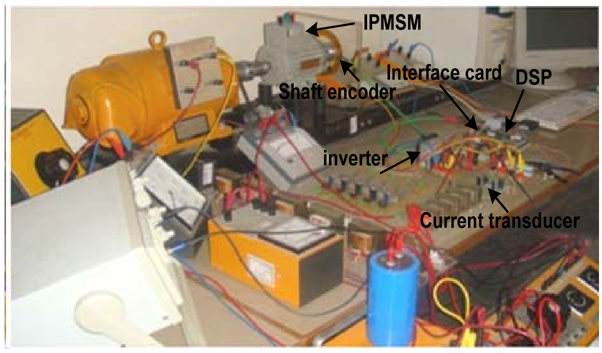


Fig. 7. Experimental set up for IPMSM

The role of the DSP in vector control is to perform the control circuit shown in Fig. 1 and to translate the stator variables (currents and angle) into the rotor coordinates as well as to compare the actual values with the reference values and update the PI controllers. The output voltage is impressed to the machine with a space vector PWM, whereby the pulse pattern is computed on-line by the DSP. Therefore, PMSM field oriented control FOC can be integrated in one single DSP controller. This integration leads to a cost-optimized board that includes both the single chip controller and the power stage.

One of the advantages offered by the Simulink libraries (under MATLAB) is the ease of the real-time communication between the DSP kit and the PC via the Real Time Data eXchange (RTDX) module. The Simulink toolbox offers two blocks for Input/Output data exchange. The "**From RTDX**" block which inputs data from RTDX channel to DSP software, and the "**To RTDX**" block which outputs data calculated from software to RTDX channel as shown in Fig. 8. When the Simulink model in real-time workshop is generated, code generation inserts the C language commands to create RTDX input and output channels on the DSP target. Input channels transfer data from the host (PC) to the target (DSP). Output channels transfer data from the target to the host. The machine starts to run, then using the RTDX input channel, the D-axis command current i_D is changed to a suitable value such that the function $f(i_D^*)$ is equal to zero. At this condition, the compensated angle θ_c equals to the error angle θ_e.

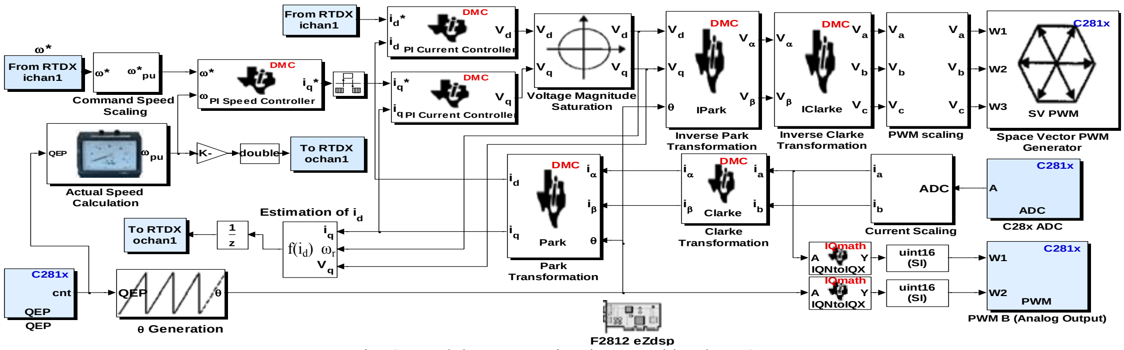


Fig. 8. Matlab program implemented by the DSP

VII. CONCLUSION

This paper describes the phenomena of nonideal placement of the shaft encoder based on a hardware prototype vector controlled IPMSM drive and its effect on the overall dynamic performance. Shaft encoder placement may be significantly inaccurate due to human mechanical error during fixing. Therefore, there will be a degree of uncertainty in the determination of the rotor position. A detailed model of a decoupled vector controlled IPMSM drive has been developed and used to determine the effect of shaft encoder misplacement on the resulting phase currents and developed electromagnetic torque. It was shown that misplaced the shaft encoder not only lead to unbalance operation of the inverter and motor phases, which increases the low frequency harmonics in torque ripple and degrades the overall drive performance but also, reduces the overall torque obtained from the vector controlled drive system due to the reduction of the q-axis component of current. However, in this paper a simple but effective and practical novel technique has been theoretically proposed and experimentally applied to determine on-line the value of the error angle θ_e between the positive edge of the home signal Z of the shaft encoder and the zero position (North Pole) of phase-A. It is shown to achieve good dynamic performance of a vector controlled IPMSM, during transient operation. Therefore, in order to improve the overall performance of vector controlled IPMSM with significant error in rotor position, the proposed method, which does not require any additional or special circuitry or hardware can be implemented on-line and found to be useful for many applications.

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APPENDIX

TABLE I.
3-ϕ IPMSM RATING

R_a	12. 5Ω
L_q, L_d	0.2387 H, 0.1339 H
Φ_f	0.36 V/rad/s
Rated speed	1500 r.p.m
Rated torque T_{rating}	2 Nm
Moment of inertia J	$0.68*10^{-3}$Kg-m^2
Viscous f	0.008707Nm/rad/s
Rated Power	311W
Nominal voltage	200 V
frequency	50 Hz