# One-line Detection of Rotor Position for Vector Controlled IPMSM

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***Abstract-*** **Interior Permanent Magnet Synchronous Motors (IPMSMs) are receiving increased attention for drive applications such as; robotics, rolling mills, traction and spindle drive, because of their high torque to inertia ratio, superior power density, high efficiency, low noise and robustness. In order to control IPMSM, position and speed sensors are indispensable because both current and voltage should be controlled depending on the rotor position. On the other hand, the vector control drive provides a wide range of speeds, high torque capability and high efficiency. However, conventional vector control of IPMSM 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. The zero reference position is usually taken such that the d-axis (North Pole), where the magnetic flux exists coincides with phase-A. Therefore, any error in determining the actual rotor position will affect the overall drive system performance. In such case, the speed is measured using the shaft encoder which is fixed manually on the rotor such that the positive the edge of the home signal per one revolution Z of the shaft encoder coincides with the zero edge of phase-A. However, in fact, 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. This paper shows 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 quadrature-axis component of current. However, in this paper a novel technique has been theoretically proposed and experimentally applied to determine on-line the value of the error angle $\theta_{error}$ between the positive edge of the home signal Z of the shaft encoder and the zero position (North Pole) of phase-A, where it is shown to achieve better dynamic performance of a vector controlled IPMSM. The proposed method can be implemented on-line and does not require any additional or special circuitry or hardware.**

***Index terms-I*****nterior permanent magnet of 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 (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]. Also, with the advent of high performance (PM) with high coactivity and high residual flux, it has been possible for the IPMSMs to be superior to general-purpose induction motors in power density, torque-to-inertia ratio, and efficiency. Therefore, the IPMSMs are of more interest in many industrial applications as substitutes for induction motors. 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.

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 over DC motors. Moreover, the vector control drive provides a wide range of speeds, high torque capability and high efficiency. Also, the vector control of IPMSMs is much simpler than of induction motors because there is no-need to consider the slip frequency as in induction motor drive [3]. 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]. But, the techniques used for vector control can be placed into two major categories; those require shaft encoder [5], [6], [7] and those that are based on a sensorless approach, for example that use back electromagnetic force (EMF) zero crossing [7]. An advantage of the first approach is its relatively simple implementation and reliable operation with variable mechanical loads, even at very low speeds (where sensorless control may not always be effective).

In such case, the speed is measured using the shaft encoder which is fixed manually on the rotor such that the positive the edge of the home signal per one revolution Z of the shaft encoder coincides with the zero edge of phase-A. In other word, 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 [8]. 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 [9]. 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, with some phase(s) conducting for longer and other phase(s) conducting for shorter time intervals. The resulting unbalance among the phases leads to a number of adverse phenomena, such as an increase in torque pulsation, vibrations, and acoustic noise, as well as reduced overall electromechanical performance [9]. 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 as will be explained in section (III).

Although there exists a large number of publications on IPMSM drives, after conducting extensive literature search, it was found that only few address the misplacement of the shaft encoder. A misalignment of Hall sensors was documented in [10], where the authors 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. The authors of [11] demonstrate their carefully made prototype and relate the 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 [12], 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 [13] 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 $\theta_{error}$ 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 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. Our 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
$\phi_f$ : Constant 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.
$T_L$, $T_e$ : load and electromechanical torque, Nm
$\omega_r$, $\omega_r{}^*$ : actual and command control signal 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 over DC motors. 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 that is why vector control is often employed in IPM drives [14]. In such case, the generated torque is the product of two components; the magnetizing and the torque producing current components. By keeping the magnetizing current component at constant value, the motor torque is linearly proportional to the torque producing component, which is similar to the control of a separately excited DC motor. It is to be noted that the stator can be adjusted by controlling the d-q axis current components. 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 [15].

Since $\Phi_f$ is constant, the electromagnetic torque is then directly proportional to $i_q$. The torque equation is similar to that of separately exited DC motor. It is evident from eq. (6) that the speed control can be achieved by controlling the q-axis component $i_q$ of the supply current as long as the d-axis current $i_d$ is maintained at zero. After decoupling the d, q-axis components $i_d$ and $i_q$ the field oriented PMSM drive scheme is shown in Fig. 1.

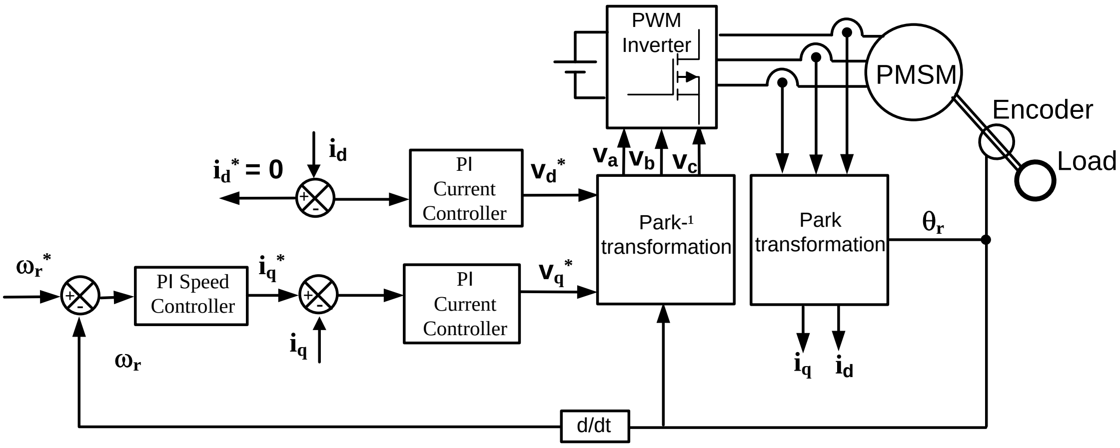


Fig. 1. Decoupled vector control scheme of the PMSM drive.

The IPMSM can be modeled where, the stator voltage equations in the rotor reference frame are expressed as follows [16]:

$$v_d = R_a\, i_d - \omega_r\, L_q i_q + L_d p i_d \tag{1}$$

$$v_q = R_a\, i_q + \omega_r\, L_d\, i_d + L_q p i_q + \omega_r \Phi_f \tag{2}$$

The electromechanical equation is given by:

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

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 [17]:

$$v_d = -\omega_r L_q i_q \tag{4}$$

$$v_q = R_a i_q + \omega_r \phi_f \tag{5}$$

And the electromechanical torque will be:

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

Hence, the electric torque depends only on the quadrature axis current $i_q$ an the reluctance torque is zero [18]. This control drive maintains maximum efficiency in a wide range of speeds and takes into consideration torque changes with transient response.

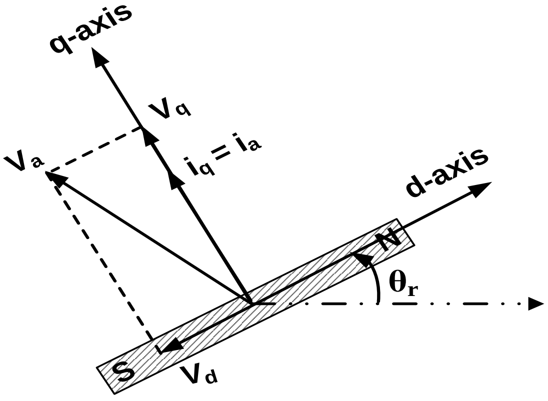


Fig. 2.d-q frame coincides with North Pole of the rotor in case of decoupled vector control.

## III. EFFECT OF ROTOR POSITION ERROR IN DECOUPLED VECTOR CONTROL

In fact, 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 zero position of phase-A. This error angle can be around 1to4degree [19] 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.

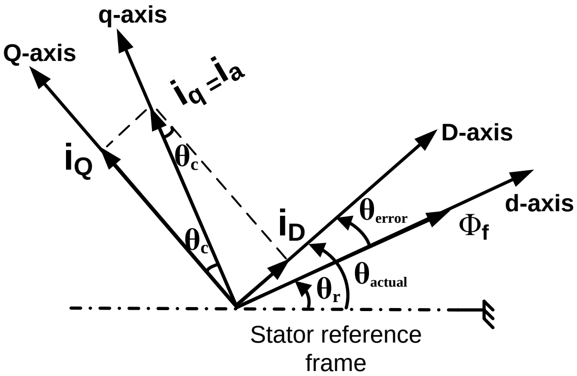


Fig. 3.Phasor diagram showing the relation between the current measured d-q frame and the actual D-Q frame.

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, $[A] = \begin{bmatrix} \cos\theta_c & -\sin\theta_c \\ \sin\theta_c & \cos\theta_c \end{bmatrix}$ and $\theta_c$ is the compensated angle which the angle between the current measured d-q frame (rotor frame) and the actual D-Q frame.(It will be adjusted to be equal to $\theta_{error}$)

Substituting (8) into (3), yields to:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\Phi_f\, i_q \cos\theta_c + \left(L_d - L_q\right)\sin\theta_c \cos\theta_c\, i_q^2\right] \tag{9}$$

Assume a rotor position error ($\theta_{error}$) around 10° electrical due to inaccurate placement of the shaft encoder during fixing, in such case, 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 eq.(9)) compared to the torque obtained from conventional vector control without rotor position error (see eq.(6)).

## IV. STRATEGY OF THE PROPOSED METHOD

In order to solve the problem discussed above, a method has been proposed in this paper to accurately detect the zero rotor position on-line. If the current measured d-q frame (rotor frame) is suppressed into another D-Q frame (actual frame) as shown in Fig. 3, due to the existence of an error in the rotor position ($\theta_{error}$), 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 $\theta_c$, substitute the decoupled vector control condition ($i_d = 0$) into equation (7), a relation between D-Q stator currents is obtained as follows:

$$\frac{i_D}{i_Q} = \frac{\sin\ \theta_c}{\cos\ \theta_c} \tag{10}$$

$$\text{Therefore,} \theta_c = \tan^{-1}\frac{i_D}{i_Q} \tag{11}$$

To identify the initial rotor position, assume that there is an error in the rotor position called ($\theta_{error}$), between the rotor position ($\theta_r$) and the actual position ($\theta_{actual}$) as shown in Fig. 3, such that [19]:

$$\theta_{actual} = \theta_r \pm \theta_{error} \tag{12}$$

Therefore, the D-axis stator current $i_D$ has to be adjusted on-line until it satisfies the following condition (obtained from substituting $i_d = 0$ into equation (2)):

$$v_q - R_a i_q - \omega_r \Phi_f = \omega_r L_d i_d = f(i_D^*) = 0 \tag{13}$$

This condition is satisfied if and only if the compensated angle will be equal to the error angle i.e.

$$\theta_c = \theta_{error} \tag{14}$$

Knowing the value of the currents $i_D$ and $i_Q$ which satisfy equation (13), the compensated angle $\theta_c$ can be calculated from eq. (11). Then, this compensated angle $\theta_c$ (which is equal to the error angle $\theta_{error}$), will be subtracted from the rotor angle $\theta_r$ coming from the shaft in order to make the angle inside the controller equal the actual rotor angle $\theta_{actual}$ (according to equation(12)).

The proposed method does not require any additional or special circuitry or hardware. However, the only disadvantage of this method is that it depends on the motor parameters but usually these motor parameters can be measured accurately from the beginning.

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

The model depicted in Fig. 4 has been simulated to determine the value of the error angle $\theta_{error}$ that exists already in the actual rotor angle $\theta_{actual}$.

First, assume on purpose the presence of an error angle $\theta_{error}$ of any value let say (10°). Thus, the compensated angle $\theta_c$ can be estimated according to the strategy explained above (from equation (11)). Then, a slider gain is used to adjust the value of $i_D$ such that the function $f(i_D^*) = v_q - R_a\, i_q - \omega_r \Phi_f$ is equal to zero. At this condition, the compensated angle $\theta_c$ will be equal to the error angle $\theta_{error}$.

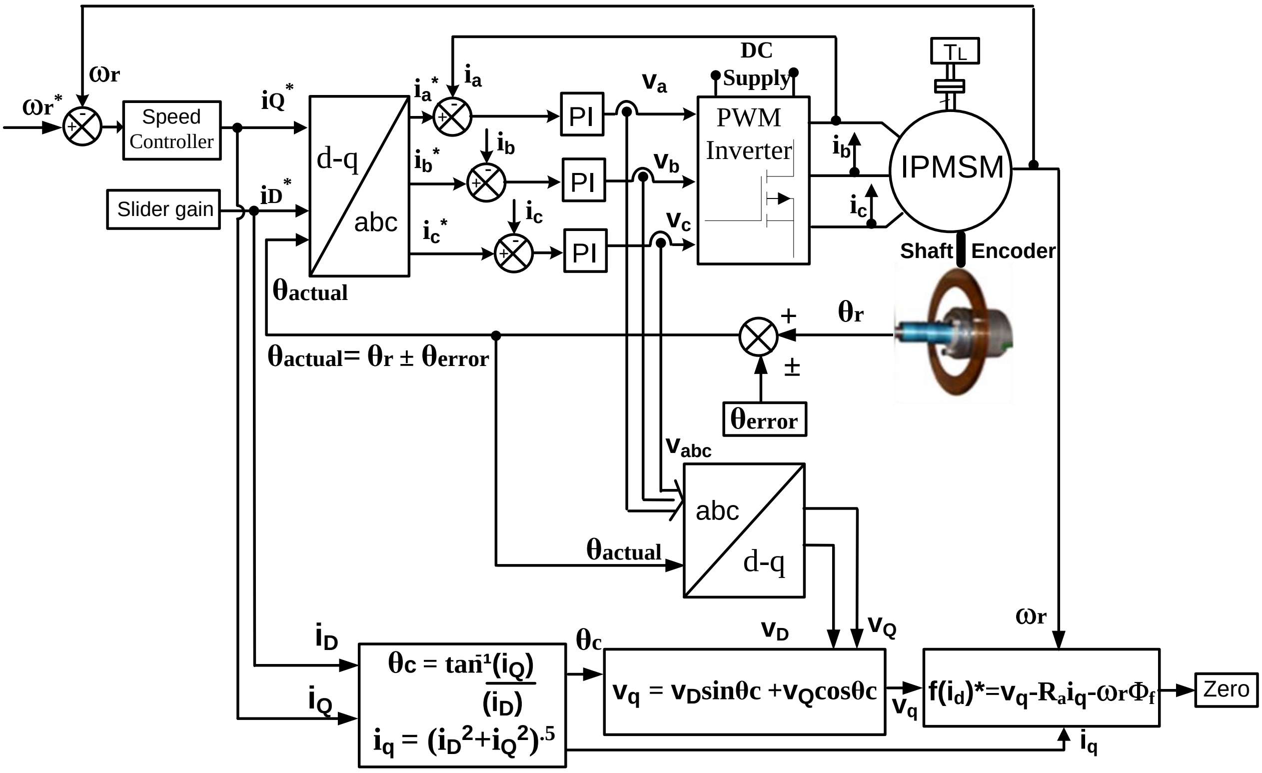
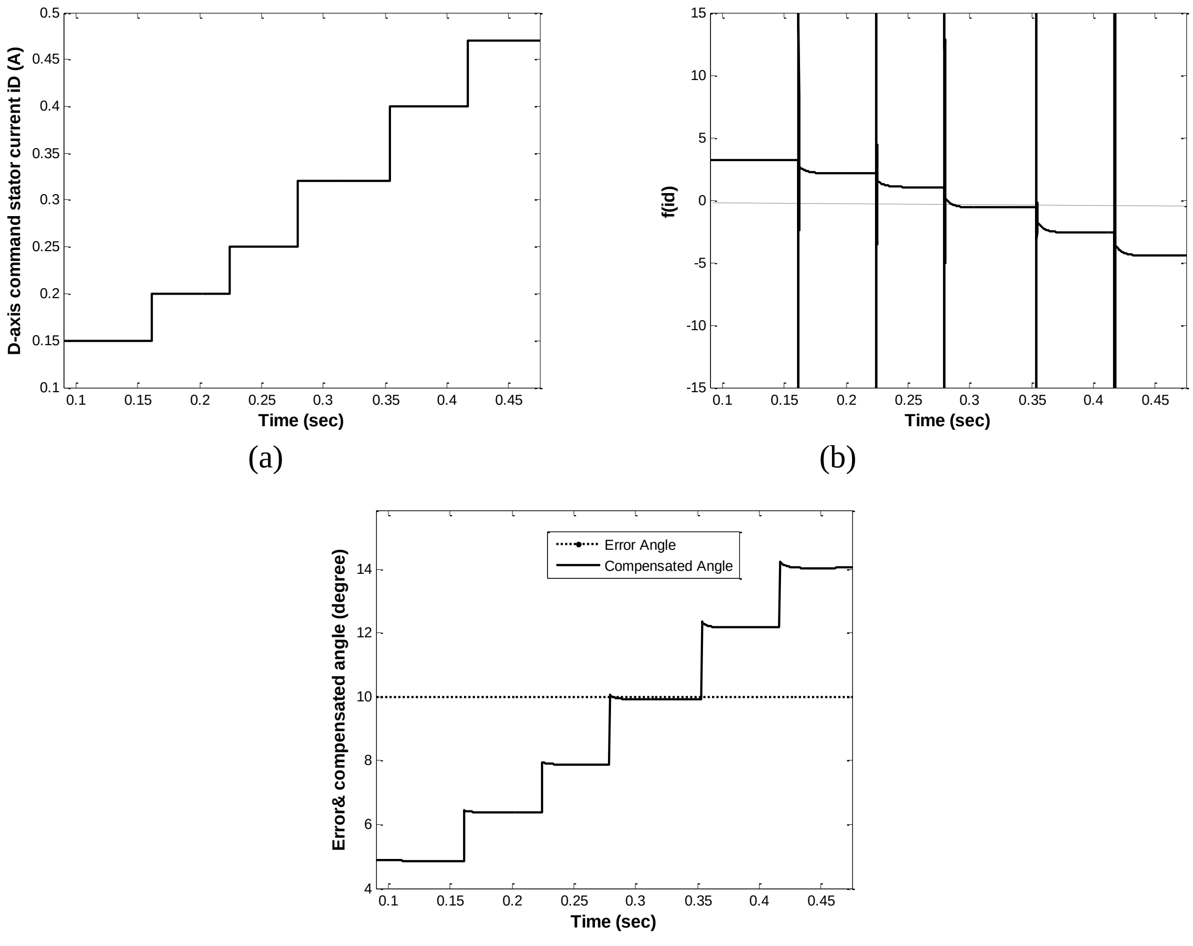


Fig. 4.Block diagram of the novel method to determine the actual rotor position.



(a) (b)

(c)

Fig. 5.Relationship between time and: (a) D-axis stator command current, (b) The function $f(i_D^*)$, (c) $\theta_{error}$ with $\theta_c$

From Fig. 5, it is clear that $\theta_c = \theta_{error}$ at the instant (from t = 0.275s to t = 0.365s), where the function $f(i_D^*) = 0$. Thus, the value of $i_D^*$ that satisfies this condition is detected, and found to be equal to 0.325A. Fig. 5 shows that the proposed novel technique is able to achieve good dynamic transient performance of a vector controlled IPMSM, approaching that of a motor with ideally placed shaft encoder. The exact value of the error in the rotor position is determined, which can be used experimentally as shown in Fig. 6.

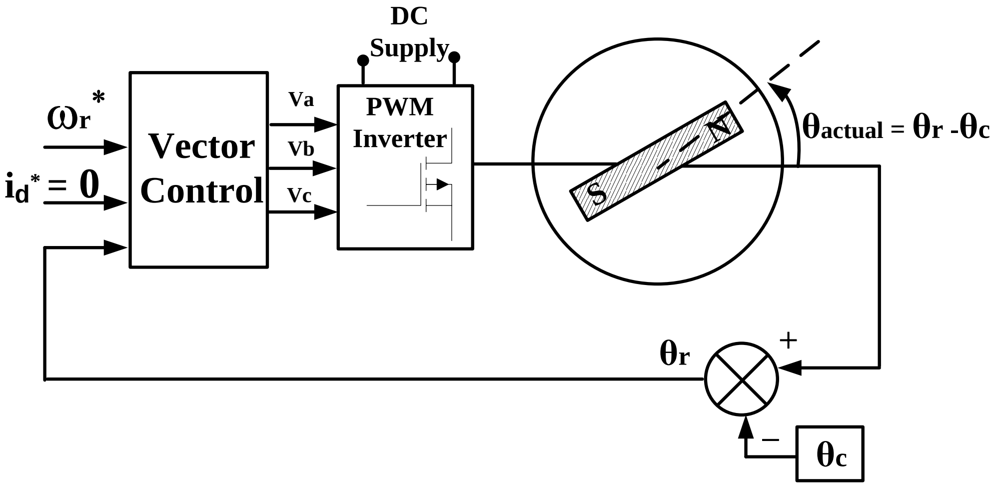


Fig. 6.Experimental diagram of the rotor position detection

# 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) two voltage transducers, vi) digital signal processor DSP and vii) its interface (isolation and drivers) card.

Fig. 7.Experimental set up for IPMSM

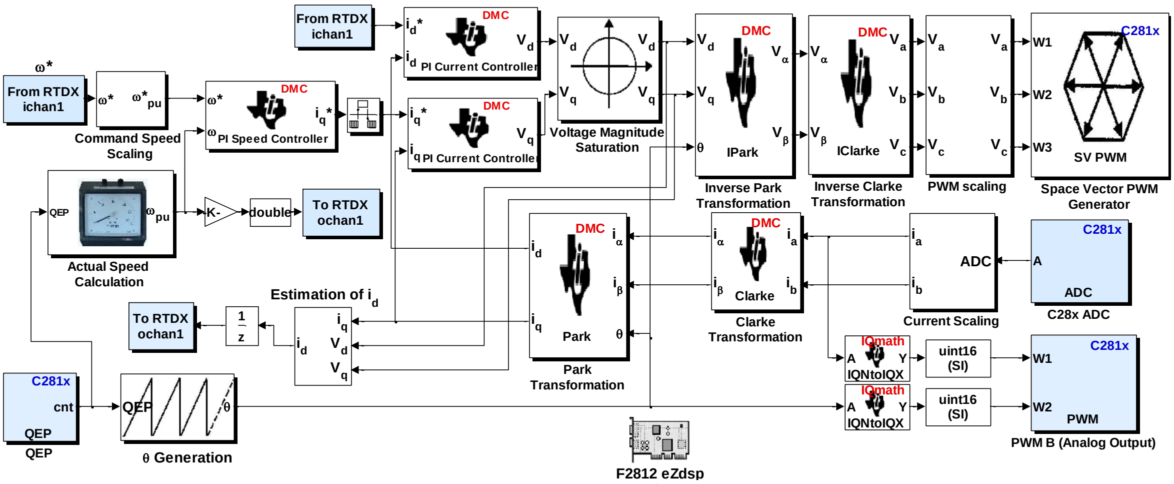


Fig. 8.Experimental set up for IPMSM

The role of the DSP in FOC 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 symmetric, an asymmetric space vector PWM, whereby the pulse pattern is computed on-line by the DSP. Therefore, PMSM FOC can be integrated in one single DSP controller thus avoiding the need to wire separate CPU and external silicon performing features, such as PWM, ADC and position determination. 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. A block named "**From RTDX**" which inputs data from RTDX channel to DSP software, and a block named "**To RTDX**" 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 $f(i_D^*) = v_q - R_a i_q - \omega_r \Phi_f$ is equal to zero. At this condition, the compensated angle $\theta_c$ will be equal to the error angle $\theta_{error}$.

## 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. In fact, 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 system 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 quadrature-axis component of current. However, in this paper a simple but very effective and practical novel technique has been theoretically proposed and experimentally applied to determine on-line the value of the error angle $\theta_{error}$ 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 1.
3-ϕ Sinusoidal back-EMF IPMSM
Rating and Parameters

| | |
|---|---|
| $R_a$ | 12. 5Ω |
| $L_q$ | (- 0.18578 iq + 0.46612) H |
| $L_d$ | 0.1339H |
| $\Phi_f$ | 0.36 V/rad/s |
| $n_{rating}$ | 15000 r.p.m |
| $T_{rating}$ | 2 Nm |
| J | $0.68*10^{-3}$Kg-$m^2$ |
| f | 0.008707Nm/rad/s |
| Power | 311W |
| $V_{rated}$ | 200 V |
| frequency | 50 Hz |