ROTOR ANGULAR POSITION AND SPEED ESTIMATION WITH USE OF ELECTROMAGNETIC RESOLVERS FOR MOTOR DRIVES

Drazen Dujic
School of Engineering
Liverpool John Moores University, UK
d.dujic@2006.ljmu.ac.uk

Darko Ostojic
Faculty of Technical Sciences
University of Novi Sad
ostojic@uns.ns.ac.yu

Abstract

This paper deals with methods for a rotor position measurement with electromagnetic resolver in motor drives. Angle-tracking observer and trigonometric method of rotor angle estimation with use of an ADMC401 DSP board are considered. Based on the laboratory rig of a vector controlled motor drive with permanent magnet synchronous machine (PMSM), two methods are examined and compared.

Key words

Electromagnetic Resolver, Motor Drives, PMSM, Angle-Tracking Observer, DSP.

1 Introduction

Most of the electromechanical installations end with some form of rotation movement. Demands for fast and accurate rotor position estimation in high performance motor drives are increased. Encoders (incremental, absolute, sine...), electromagnetic resolvers, Hall sensors are common sensor types that are in use. To choose right one for a certain application often depends on variety of factors like: working environment, temperature, moisture, dust, radiation…

Modern high performance motor drive systems are usually based on electric machine such as the ac induction motor or the permanent magnet synchronous motor (PMSM). The principles of vector control are now well established for the control of these ac motors. The achievable closed loop bandwidths are directly related to the rate at which the computationally intensive vector control algorithms and associated vector rotations can be implemented in real time.

Synchronous machines have absolute location of rotor magnetic poles, which is unlike the location of slipping poles in an induction motor. Therefore, in vector controlled drive with PMSM, continuous information of rotor position with high accuracy is mandatory. An electromagnetic resolver offers more robust and better environment contamination-insensitivity characteristics, when compared to encoders. However, for the majority of the environments encountered, an encoder is completely adequate, with its simple system interface. In some cases, when high performances are desired, the use of resolver offers some advantages over an encoder. On the other hand, dynamic performances of a resolver have to be considered in high performance control system design [1]. The analog output signals from resolver can be used directly or they can be processed through a resolver-to-digital converter (RDC) to obtain the digital signal. In general, the RDC can be considered as a close loop position tracking system and nowadays there is a lot of commercially available RDC`s integrated into a single chip. However, when dealing with DSP based motor drives, there is a possibility to implement RDC directly in DSP control software with addition of some electronic circuit for conditioning signals from resolver.

2 Vector Controlled Drive with PMSM

Structure of PMSM vector controlled drive is well known and it is shown on Fig. 1. The desired direct and quadrature axis currents are compared with measured quantities. The both measured current components are obtained by measuring two or the motor line currents with software calculation of third one, applying a three-phase to two-phase transformation followed by a vector rotation [2]. For the vector rotation which is also known as *Forward Park Transformation* (1) it is necessary to have continuous information about rotor angle position.

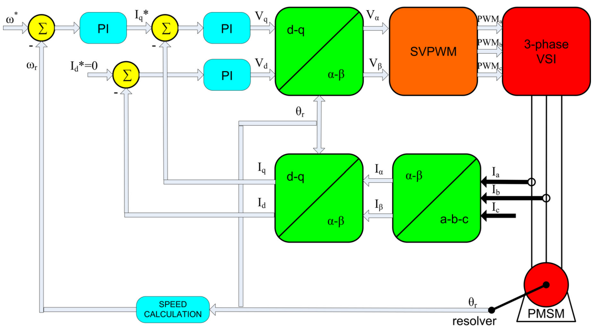

Figure 1: Structure of PMSM vector controlled drive

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (1)$$

Whole system is implemented into ADMC401, DSP optimized for motor control. In each cycle processor must perform the following: motor current sampling and conversion, rotor position measurement and speed estimation, Clark and Park transformation (both, forward and inverse), dual PI regulator routine, voltage decoupling, SVPWM algorithm. For the chosen switching frequency of 10 kHz, processor has 100µs to perform all the necessary computations [3]. The board that is used has: 26 MIPS fixed point DSP core; 38.5ns for single cycle instruction execution; three phase 16-bit PWM generation unit; eight 12-bit analog-to-digital converter and satisfy all this requirements [4].

3 Rotor Angular Position Measurement

3.1 Electromagnetic Resolver

The electromagnetic resolver is basically a two part machine that is excited by a rotor-mounted field winding, which is excited by a carrier wave of several kHz frequency (Fig. 2). The resolver is brushless because the rotor winding is excited by a revolving transformer whose primary is supplied from some sine voltage source (2).

$$u_s(t) = U \cdot \sin(\omega_s t) \qquad (2)$$

After some rearranging and taking into account resolver secondary windings orthogonallity, it yields expressions (3), (4) for the resolver output voltages.

$$u_{\cos} = k \cdot \psi_p \cdot \omega_s \cdot \sin(\omega_s) \cdot \cos\theta \qquad (3)$$

$$u_{\sin} = k \cdot \psi_p \cdot \omega_s \cdot \sin(\omega_s) \cdot \sin\theta \qquad (4)$$

3.2 Trigonometric method

From the last two expressions it can be seen that the information about rotor position is modulated into resolver secondary windings voltages and it can be extracted. For an ideal case, applying arc tan function on the (3) and (4) gives the rotor angle value (5).

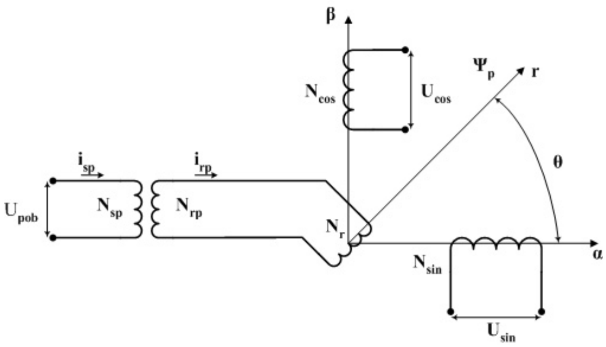

Figure 2: Electric scheme of electromagnetic resolver

$$\theta = arctg\left(\frac{u_{\sin}}{u_{\cos}}\right) \qquad (5)$$

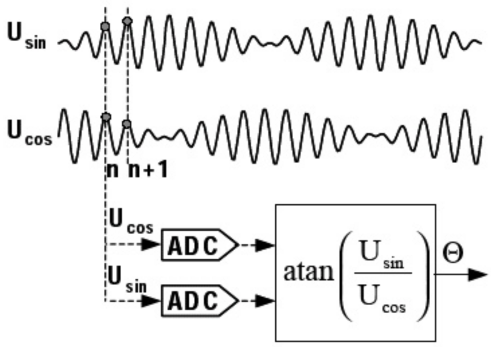

Figure 3: Concept of a trigonometric method

Simple concept of a trigonometric method (Fig. 3) is based on simultaneously sampling of *sine* and *cosine* signal from resolver, A/D conversion and calculating trigonometric function. Calculation of trigonometric function is achieved through approximation of the function by means of a fifth order Taylor series expansion. Main drawback of this method is lack of any information regarding rotor speed, so it is necessary to perform additional calculation in order to obtain speed information. Trigonometric method is also very sensitive on noise that can occur at different stages of signal path. Utilizing structure known as angle-tracking observer, these drawbacks can be eliminated.

3.3 Angle-tracking observer

In realization with an angle-tracking observer (Fig. 4) after sampling, signals are passed through low pass filter and some parasitic effects are reduced. Main advantage of this method, compared to the trigonometric method is smoothing capability achieved by the series connection of a PI regulator and integrator closed by a unit feedback loop. Two factors $K_1 = \omega_0^2, K_2 = 2\xi / \omega_0$ have to be selected according to the dynamic requirement of the speed and position loop of a drive. Parameters are determined so that the overshoot and settling time are satisfactory.

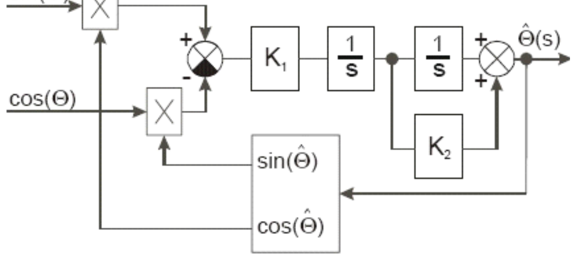

Figure 4: Angle-tracking observer

They can be adapted dynamically to improve the drive behavior under various operating conditions. On the Fig. 5 is shown magnified observer response to an 180^0 step change of actual rotor angle, obtained with the simulation of the observer transfer function. During simulation natural frequency is kept at value ω_0=500 rad/s, while the damping factor has changed through values ξ=0.70, 0.75, 0.80, 0.85 and 0.90. This gives a set of curves with different settling time and overshoot necessary for dynamic analysis of observer behavior. For the purpose of detailed analysis of impact of natural frequency and damping factor on the observer behavior additional simulation have been performed.

On Fig. 6 and Fig. 7 is shown how those two parameters influence on settling time and peak overshoot, respectively. In both cases parameters are varied in range: $300 \leq \omega_0 \leq 1500$ [rad/s] for natural frequency and $0.5 \leq \zeta \leq 2.0$ for damping factor. As it can be seen, the increase of damping factor leads into smaller peek overshoot, while on the other hand settling time becomes longer. Natural frequency has no impact on peak overshoot, but has great influence on the settling time [5],[6]. Choosing right parameters for a certain applications is trade-off problem of achieving fast response with small oveshoot with satisfactory settling time.

3.4 Hardware

Vector controlled drive with PMSM is implemented with the use of equipment developed for laboratory testing. Laboratory rig for those purposes is shown on Fig. 8. For the frequency converter, IGBT transistors are used for 3-phase voltage source inverter with 1000μF capacitance in DC-link and three-phase diode rectifier at the input stage. Hall effect (LEM) sensors are used for current measurement with additional on board filtering for cutting off the switching frequency harmonics. Data for the used PMSM motor are given in table I. Both methods for rotor angle estimation are implemented in software together with other routines necessary for performing vector control.

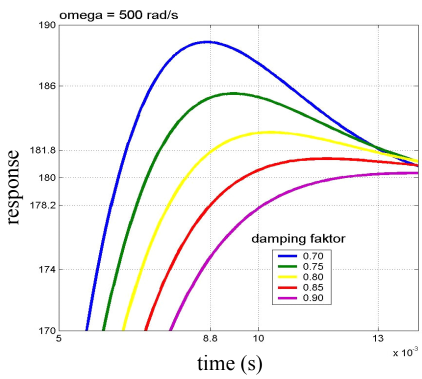

Figure 5: Dynamic response of the rotor angle estimation

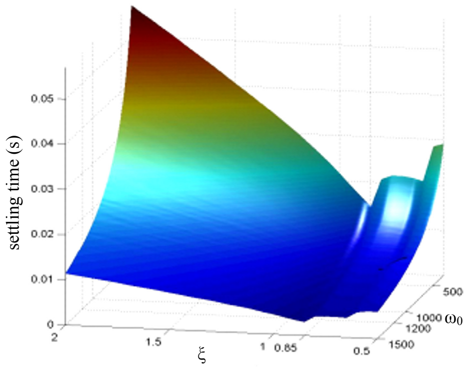

Figure 6: Settling time as a function of ω_0 and ξ

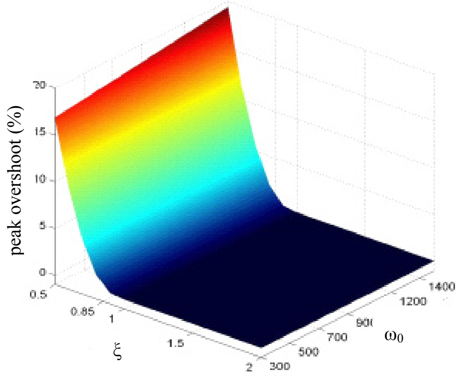

Figure 7: Peak overshoot as a function of ω_0 and ξ

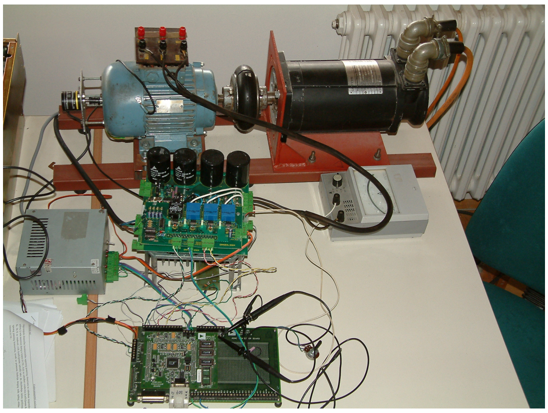
Figure 8: Laboratory rig with PMSM drive

Additional hardware board is developed for the purpose of providing resolver excitation signal (5 kHz sine wave carrier), with adjustable phase shift, and voltage level at the ADC input of DSP. A/D system on a processor permit up to eight dedicated analog inputs all to be converted in less than 2 μs (26MHz) through a single 12 bit pipeline flash ADC. Setting processor ADC unit into simultaneous sampling mode provides that sine and cosine signals from resolver are sampled simultaneously on every occurrence of PWM interrupt. In order to provide valid data from the resolver two basic demands have to be accomplished:

1) Output signals from the resolver have to be sampled in the local maximum of each half period.

2) Total input range of A/D converter has to be covered with output resolver signals amplitudes.

Output signals (5 kHz) from the resolver are sampled with 10 kHz sample rate. Fig. 9 shows a correct timing (adjusted delay) between the signal from resolver and DSP. Since the samples represent envelope of the sine and cosine signals, this is necessary for accurate and correct rotor position estimation. Sampling signals at any other instance different from peak value will have as a result greater angle error during estimation. Because of a signed fixed-point representation of sampled data, full A/D range has to be covered in order to keep good dynamic during mathematical calculations.

Since there are two sample events per one period of resolver sine and cosine signals, some precautions are considered in software regarding a sign of a sample data. Sampled data are used in both software routines for calculation of a rotor angle position.

3.5 Software Implementation

Software codes for both methods are written as independent routines that can be used as modules for further drive control programs. There are some differences in implementation of methods that will be mentioned here. Trigonometric methods require less memory space for implementation because of simplicity. But, as it is mentioned before, suffer from lack of immunity to noise which is very likely to occur in noisy environment in drive application. Finite word length of a processor combined with quantization error of the 12-bit resolution of A/D converter is also one of possible causes of errors. It can be found that position error caused by the A/D quantization and by numeric signal processing principle, normalized to 360 degree per revolution results in value of ±0.014 deg [6]. Angle tracking observer software code requires more memory space because of mathematical calculation, but gives some advantages over trigonometric method.

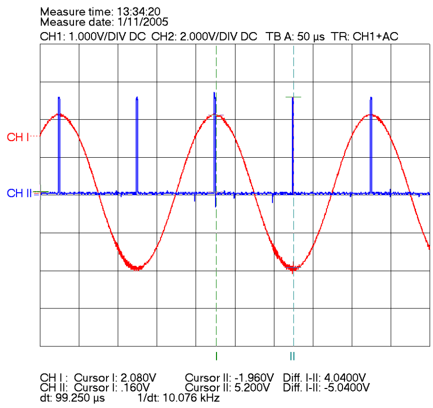

Figure 9: (CH I) sine signals from resolver, (CH II) sampling moments

Selecting desired natural frequency ω_0 and damping factor ξ, in accordance with previous analysis, factors K_1 and K_2 can be calculated. Those two factors can be easily changed, for achieving better dynamic performances. Regarding time consumption and load of processor during one switching period (100µs) for the execution of a trigonometric method it takes 109 clock cycles while angle tracking observer routine takes 147 clock cycles. Total time necessary for execution of PMSM vector control in one switching period is about 840 clock cycles (32µs). Compared with that, angle estimation procedure load processor with 14% approximately. This gives a lot of unused resources for implementing different kinds of protection and communications functions in software that are not included in implemented laboratory drive.

4. Measurement Results

In order to test and compare routines, laboratory rig with PMSM is used. AC induction motor coupled with PMSM is used to drive PMSM during preliminary tests of angle estimation routines. After testing and setting software factors AC induction motor is later used as a load. Rotor angle is measured at various speed of rotation. At the Fig. 10 is given estimated angle position at speed of 1500 rpm with angle tracking observer. Trace represent rotor angle range in between ($-\pi$: π) and it is used for necessary trigonometric transformation in software.

Angle position estimation results obtained with trigonometric method are similar to the results given by angle tracking observer. However, measurement of rotor speed with those two methods shows some differences. Since information about rotor speed cannot be directly obtained from trigonometric method, additional calculations are performed in accordance with (6). Since the sample rate is fixed at 100µs it is possible to calculate speed knowing change of rotor angle position over sample time.

$$\omega = \frac{d\theta}{dt} = \frac{\theta_{n+1} - \theta_n}{\Delta T} \tag{6}$$

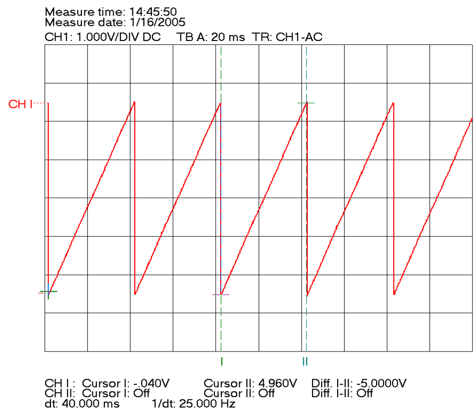

Figure 10: Measured position with use of angle-tracking observer (1500 rpm)

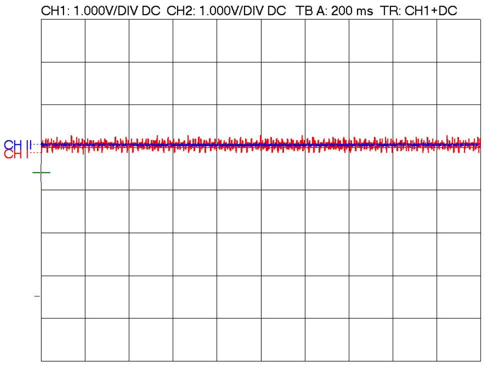

Figure 11: Measured speed, (CH I) encoder, trigonometric method (CH II)

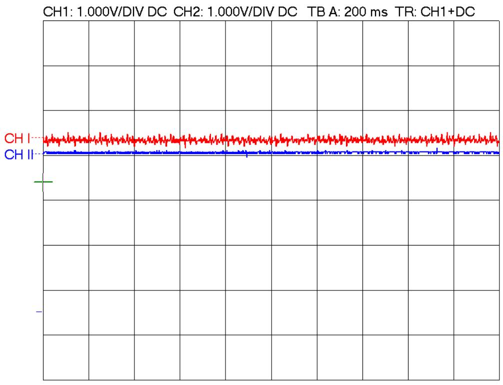

Figure 12: Measured speed, (CH I) angle-tracking observer, (CH II) encoder

For the purpose of comparison, speed information obtained with incremental encoder has been used. ADMC401 incorporates powerful encoder interface unit that can easily process quadrature signals from the encoder. In software is implemented N/T method that gives good results in whole range of speed. On Fig.11 are given speed traces from trigonometric and encoder estimation. Same results obtained with observer are given on the Fig. 12. It is noticeable presence of noise on both speed signal obtained from resolver (Fig. 11 and Fig. 12) which have as a result less accuracy of speed estimation. Angle tracking observer gives better results compared with trigonometric method. The presence of the noise in estimated speed signal has an impact on the work of speed PI regulator which generates quadrature current reference for the current regulator.

5 Conclusion

Fast and precise rotor angle estimation plays very important role during implementation of high performance motor drives. The use of a resolver for measuring rotor angle position offers robust mechanical characteristic compared with encoders. Results presented in this paper are obtained from experiments with PMSM drive, developed for laboratory testing purposes. With the addition of simple electronic board for resolver signals conditioning and DSP software code, rotor angle position can be easily measured. Some problems are noticed during speed estimation. Results obtained with resolver were not as good as those produced with encoder. The presence of noise in estimated speed signal can have negative impact on the final performance of PMSM drive. For further improvement there is a need to implement more complex and sophisticated algorithm based on observers as proposed in [10].

TABLE I

GETTYS	AEG
Permanent Magnet Servo Motor	
Catalog No. M321-SMRA-1001	Serial No. 0068-03 90
Back EMF Ke 51.2 V/Krpm	Tach V/Krpm
Torque Constant Kt 7.5 lb-in/Amp	Sealing IP55
Rated Current Stall 9.5 Amp	
Conn. Dia. 497-302-0037	Outline Drwg. 497-208-9999
Brake: Hz Volts 24	Torque 90 lb-in
Gettys Corporation Racine Wisconsin, U.S.A.	MT46418-5

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