BLDC MOTOR SENSORED CONTROL BY DIGITAL POSITION OBSERVER

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REZUMAT. Lucrarea prezintă o metodă de estimare a poziției rotorului pentru motorul de current continuu fără perii (BLDC) utilizând traductoare cu rezoluție redusă cu senzori cu efect Hall. În controlul direct al cuplului (DTC), ca şi în controlul cu orientare după câmp, rezoluția ridicată a poziției este esențială pentru creşterea performanței acționării. Informația cu rezoluție redusă furnizată de senzorii de poziție cu efect Hall este trasformată într-un vector de rotație cuantificat spațial, iar un observer cu vector de urmărire (VTO) este utilizat pentru creşterea rezoluției informației de poziție. Cea mai importantă caracteristică a algoritmului de control o reprezintă proiectarea controlerului. Încercările experimentale sunt utilizate pentru a ilustra performanța şi limitele observerului PLL într-o schemă DTC utilizată în acționările electrice cu BLDC.

Cuvinte cheie: pozitie, rezolver, convertor rezolver-digital.

ABSTRACT. This paper presents a rotor position estimation method for Brushless Direct Current (BLDC) motor drives using low-resolution transducer with Hall-effect sensors. In Direct Torque Control (DTC), as well as in Field Oriented Control, the high rotor position resolution is essential for increasing the drive performance. The low-resolution information provided by the Hall-effect position sensors is transformed into a spatially quantized rotating vector and a Vector-Tracking Observer (VTO) is used to increase the rotor position resolution. The control algorithm's most innovative feature is its controller design. Experimental testing is used to illustrate the performance and the limits of the PLL observer topology in a DTC scheme used in BLDC electrical drive.

Keywords: brushless motors, closed loop systems, observers, state estimation, torque control.

1. INTRODUCTION

The interest for the BLDC motors has increased in the last years, because of their high efficiency, high power density and low cost. Position sensors are required in BLDC drives in order to provide the correct current waveform supply. In the conventional control schemes, the BLDC drives are fed with 120° square wave current waveforms, requiring a 60° resolution in rotor position sensing.

In BLDC drives using DTC schemes a high-resolution position estimating strategy is needed to increase the initial low-resolution position from the sensors such as the Hall effect ones. Several methods have been proposed to estimate the position in BLDC drives with Hall sensors [1], [2], [3], [4], [5], [6], [7], [8]. The techniques presented in [1], [8] are based on hybrid filters, they use differential equations which are involved in the estimation of the synchronous-frame terms used to control the torque. In [2], [13], [14] a linear extrapolation technique, like zero order or first order *Taylor* algorithm, is applied to increase the low-resolution position signal. The estimation method is based on average velocity (using linear extrapolation) to obtain an increased position resolution [7]. The drawbacks of these methods consist in the fact that they used the sector average speed, which is very noisy due to Hall sensors misalignments. Another technique used to estimate the rotor position is the *tracking method*, as in [15]. This method estimates the BEMF from the physical parameters of the motor and later on, the position is determined. This method requires a precise knowledge of the motor parameters, which are normally temperature dependent. To improve the rotor position estimation, other methods are used state observers [4], [12], [16], [17], [18], [19], Kalman filters [9], Model Reference Adaptive Systems (MRAS) based observers [21], or Luenberger observers [10]. The observers are used to replace sensors in the control systems, where sensors are difficult to use. The tracking observers [11], characterized by low-resolution position as input, usually use the vector-cross-product phase detection method. The input of the observer is the quantized vector from low-resolution transducer with Hall-effect sensors. By applying a *harmonic decoupling method* in order to increase the controller performance [5], [6], [7], [11] the tracking methods [4], [19] are improved.

This paper describes a position observer which uses a harmonic decoupling with respect to the position estimation and presents a new controller design in the discrete time domain. Experimental testing is used to illustrate the VTO behavior in the entire speed domain. This high-resolution estimated position is used like an input to a look-up table containing the memorized phase BEMF of a BLDC motor to estimate the torque and to perform the DTC control.

2. ROTOR POSITION ESTIMATION USING A VTO

The high-resolution rotor position estimation is obtained through the digital signal processing of the low-resolution transducer output. The low-resolution position signal is transformed into a spatially quantized rotating vector. The complex model of low-resolution position vector can be regarded as an addition between a fundamental component and a series of spatial harmonics which determine the discrete nature of the low-resolution position vector [4]-[6]:

$$\begin{aligned}\overline{H}_{\alpha\beta} &= e^{j(\theta_e-\pi/6)} + \sum\nolimits_{k=0}^{\infty}\{-(6k-1)^{-1}\cdot\\ &\cdot e^{-j[(6k-1)\theta_e+\pi/6]} + (6k+1)^{-1}\cdot e^{j[(6k+1)\theta_e-\pi/6]}\} = ,\\ &= \overline{H}_{\alpha\beta,(1)} + \overline{H}_{\alpha\beta,harm}\end{aligned} \tag{1}$$

where $\overline{H}_{\alpha\beta,(1)}$ is the decoupled position vector obtained by subtracting the vector harmonics from the quantized position vector.

The fundamental frequency component $\overline{H}_{\alpha\beta,(1)}$ is equal to the angular speed of the shaft and determines the continuous position of the motor. The goal of the decoupling method is to remove these higher harmonics components, which give the discrete nature of the quantized vector $\overline{H}_{\alpha\beta}$, and keep the fundamental component which provides the high-resolution position information.

In this paper, a subset of the additional harmonics, such as the 5th, 7th, 11th and 13th, was decoupled (*truncated harmonics decoupling*), $\overline{H}_{\alpha\beta,(5,7,11,13)}$. As a result, a continuous waveform is obtained, but with a significant ripple from un-decoupled high order harmonics components $\overline{H}_{\alpha\beta,undec}$:

$$\overline{H}_{\alpha\beta} = \overline{H}_{\alpha\beta,(1)} + \overline{H}_{\alpha\beta,(5,7,11,13)} + \overline{H}_{\alpha\beta,undec} \tag{2}$$

After the harmonics decoupling process, a simple PLL structure is used to estimate the rotor position based on a mechanical model of the BLDC motor. To avoid inaccuracies in position information due to the position estimation a PI controller is used to correct the estimated position [3]. The VTO structure has two inputs: the quantized vector containing position information and a torque feed-forward input to the mechanical model [6].

This observer is a state observer with three states. Therefore, the system can be enlarged by inserting a third state that is the estimated torque load $\hat{T}_l$. The state-space equations of the PLL tracking observer are:

$$\begin{cases} d\hat{\omega}/dt = (1/\hat{J})[-\hat{B}\cdot\hat{\omega} + K_1(\theta-\hat{\theta}) + \hat{T}_e + \hat{T}_l] \\ d\hat{\theta}/dt = \hat{\omega} + K_2(\theta-\hat{\theta}) \\ d\hat{T}_l/dt = K_3(\theta-\hat{\theta}) \end{cases}, \tag{3}$$

where $\hat{\omega}$ is the estimated angular speed, θ is the quantized position, $\hat{\theta}$ is the estimated position, $\hat{B}$ is the estimated damping friction coefficient, $\hat{J}$ is the estimated total inertia, $\hat{T}_e$ is the estimated electromagnetic torque and K_1, K_2, K_3 are the observer gains.

The matrices of the state-space mechanical model are:

$$X = \begin{bmatrix}\hat{\omega}\\ \hat{\theta}\\ \hat{T}_l\end{bmatrix}, A = \begin{bmatrix} -\frac{\hat{B}}{\hat{J}} & -\frac{K_1}{\hat{J}} & \frac{1}{\hat{J}} \\ 1 & -K_2 & 0 \\ 0 & -K_3 & 0\end{bmatrix}, U = \begin{bmatrix}T_e\\ \theta\end{bmatrix}, B = \begin{bmatrix}\frac{1}{\hat{J}} & \frac{K_1}{\hat{J}} \\ 0 & K_2 \\ 0 & K_3\end{bmatrix} \tag{4}$$

The eigenvalues are the roots of the characteristic equation $|A_d - p\cdot I_3| = 0$, where $A_d = I_3 + A\cdot T_s$ is the discrete form of matrix A and T_s is the sampling period.

By comparing the terms of the characteristic equation with the terms from the general expression of the characteristic equation, then the coefficients of matrix $K = [K_1\ K_2\ K_3]^T$ is obtained:

$$|A_d - p\cdot I_3| = (s-p_\omega)(s-p_\theta)(s-p_{Tl}), \tag{5}$$

where p_ω, p_θ, p_{Tl} are the observer poles that are real for best observer behavior and less than unity to guarantee the observer stability.

Therefore, the gains of the observer can be expressed as:

$$\begin{cases} K_1 = (1/T_s^2)[(p_\omega p_\theta + p_\theta p_{Tl} + p_{Tl} p_\omega) - \\ \quad -(3-2\alpha T_s) + K_2 T_s(2-\alpha T_s)] \\ K_2 = (1/T_s)(3-\alpha T_s - (p_\omega + p_\theta + p_{Tl})) \\ K_3 = (1/T_s^3)[(1-\alpha T_s)(1-K_2 T_s) + K_1 T_s^2 - p_\omega p_\theta p_{Tl}] \end{cases}, \tag{6}$$

where $\alpha = \hat{B}/\hat{J}$.

Assuming that the difference of the reference position vector and the estimated position vector is very small, the position estimation error ε, can be approximately detected from the following cross product:

$$\left\|\overline{H}_{\alpha\beta,undec}\times\overline{H}_{\alpha\beta,(1)}\right\| = \sin(\theta-\hat{\theta}) \approx \theta-\hat{\theta}=\varepsilon_{\theta} \qquad (7)$$

The block diagram of the entire structure proposed in this paper is presented in Fig. 1.

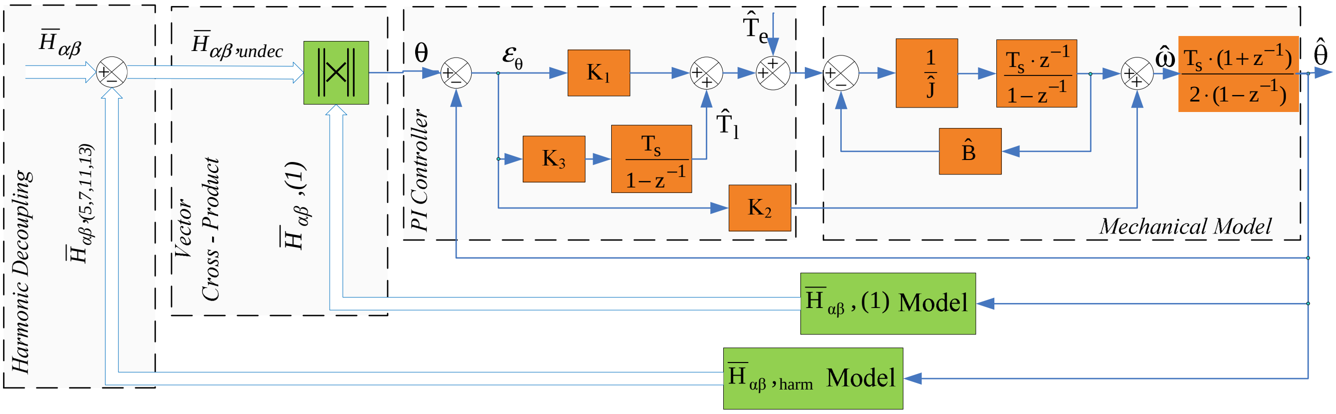

Fig. 1. Block diagram of the vector-tracking position observer.

3. EXPERIMENTAL RESULTS

A drive prototype for home appliance applications, consisting in a trapezoidal BEMF machine with star-connected stator windings, a full bridge insulated gate bipolar transistor (IGBT) inverter and a 32-bit floating-point digital signal processor (DSP) in which the aforementioned control algorithm resides, has been built and tested.

The BLDC motor (*p=4* number of poles, star connection) has the following parameters as given in Table I. The motor has been loaded using a permanents magnets DC machine that operates in generator mode. The inverter switching frequency is set to 10 kHz and the dead-time is 2.5 µs.

Table 1.**Values of the BLDC motor prototype.**

Rated parameters	**Symbol**	**Value**	**Unit**
Rated voltage	U_n	160	V
Rated current	I_n	5	A
Rated speed	n_n	2000	rpm
Stator resistance	R	0.63	Ω
Stator inductance	L	0.00468	H
Total inertia	J	0.00824	$kg\cdot m^2$

The flowchart of the algorithm is presented in Fig. 2. After the three phase frame to stationary frame transformation and trigonometric function were applied to the position synchronous components, the quantized six step position vector was obtained. The decoupled waveform was obtained by subtracting harmonics, such as the 5th, 7th, 11th and 13th, from the quantized position input signal. The algorithm has a 100 µs sampling period.

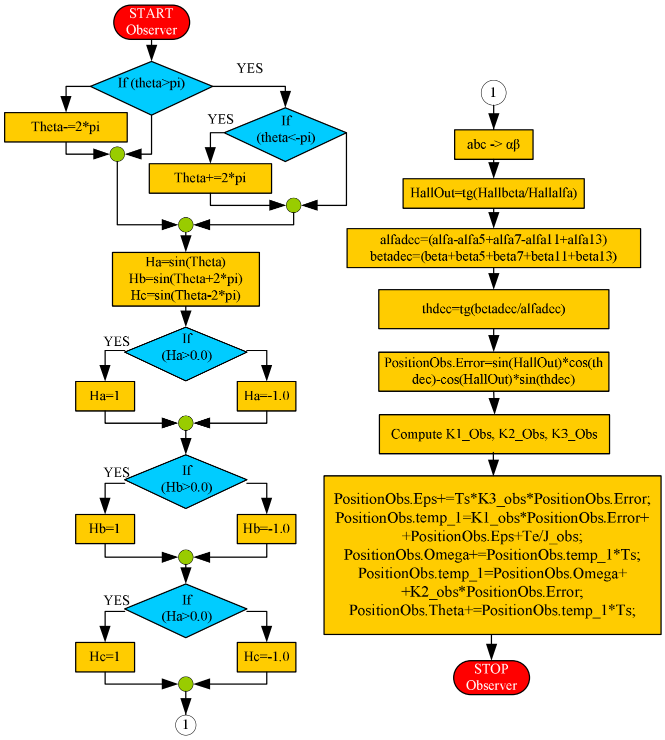

Fig. 2. Flowchart of the vector-tracking position observer.

For VTO performances evaluation, the authors experimented a DTC structure for the BLDC motor [8], [20]. The block diagram of this structure is shown in Fig. 3. As is presented, the estimated position provides Space Vector Modulation (SVM) and the BEMF Look Up Table (LUT) position information. There can be seen two independent closed-loops: torque and flux. The electromagnetic torque is calculated from the estimated BEMF, phase currents and estimated angular speed. The stator flux is calculated from the phase voltages and the phase currents. The differences between the prescribed and the estimated variables (flux and torque) are set as inputs in two hysteresis comparators. Further, the hysteresis comparators outputs are set as inputs to the SVM logic table.

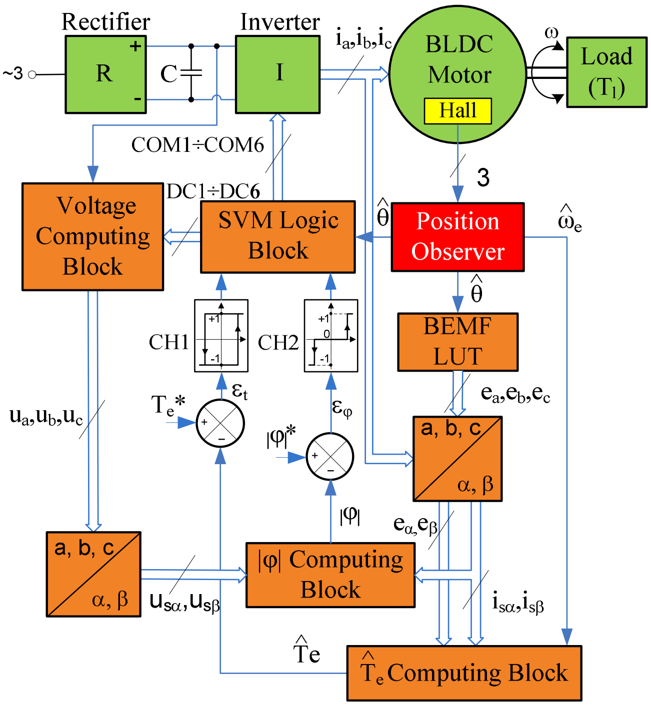

Fig. 3. Block diagram of the DTC structure.

The experimental results have been obtained for the following working conditions: start-up (Fig. 4), steady-state (Fig. 5) and step variation of the reference speed (Fig. 6).

A looking-glass is made at start-up (see Fig. 4) to show the actual convergence of the observed position toward the measured position. However, the error presents high-frequency oscillations (equal to six times the electrical frequency) due to the low-resolution position measurement.

The VTO is based on a mechanical model of the physical system; therefore erroneous knowledge of inertia *J* affects the VTO dynamics, but does not affect its steady-state tracking properties.

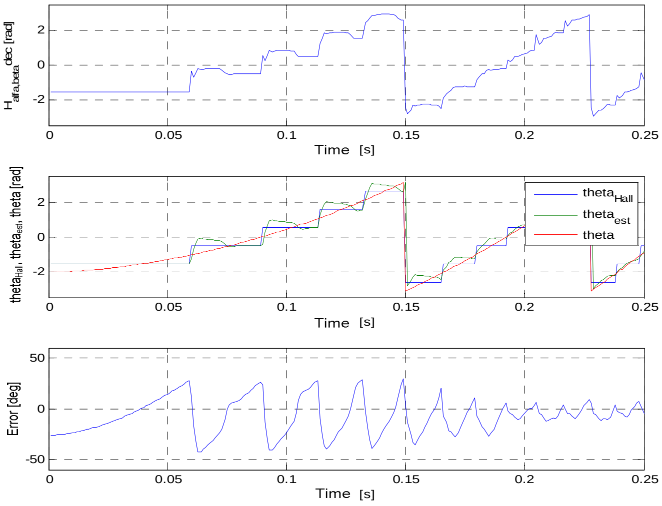

Fig. 4. Start-up performances of the drive system using the VTO.

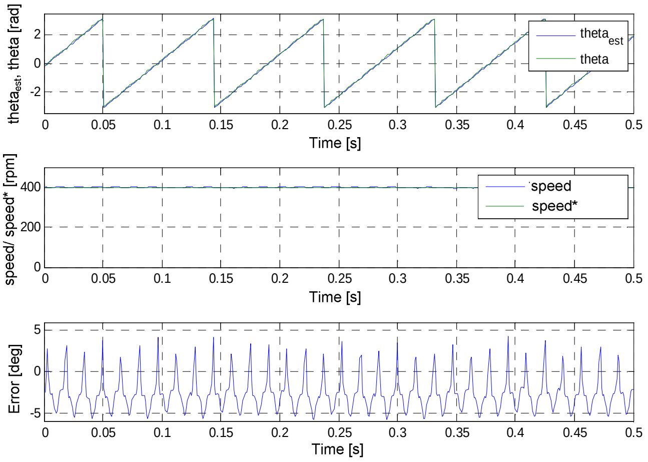

Fig. 5. Steady-state performances of the drive system using the VTO.

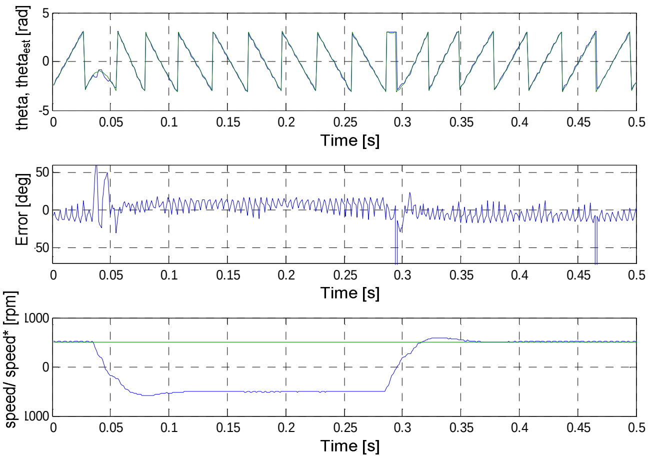

Fig. 6. Dynamic performances of the drive system using the VTO.

4. CONCLUSIONS

Such a drive attempts to overcome some limitations of traditional BLDC drives which use a low-resolution position transducer. The most innovative feature of the control algorithm is its controller design. The experimental results show that when using the VTO, the best steady-state and dynamic performances of estimation process are achieved.

The results are highly satisfactory for torque estimation (in DTC of BLDC motor drives based on Hall-effect position sensors). The proposed observer was tested with a motor control strategy and the response is a good one, and the error is also acceptable.

The start-up error at low loads can be eliminated by forcing the start-up of the BLDC drive (similar to sensorless control), by creating a constant frequency magnetic field in the stator without position sensing.

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