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Sensorless high-speed BLDC machine using hardware-RFO

Jian-Xin Shen, He Hao, Meng-Jia Jin, Wei-Zhong Fei, (2012)

Abstract: *High-speed permanent magnet (PM) brushless dc (BLDC) motor often needs a continuous rotor position signal for dynamic phase-advancing control, whist such kind of position signal cannot be directly obtained from the conventional Hall effect sensors or via the traditional back-EMF-based sensorless control strategy. Furthermore, during high-speed operation, the inverter free-wheeling diodes may conduct for more than 30 elec-deg, obscuring the back-EMF zero-crossings. Hence, the traditional back-EMF-based sensorless control strategy becomes unworkable. To overcome these problems, a new sensorless control method is proposed in this paper. It uses full hardware to observe the flux vector which is excited by rotor magnets. Thus, it can provide the rotor position which is the same as the phase angle of the observed flux vector. The proposed sensorless control method is validated with a 2Kw, 85000rpm PM BLDC motor system.*

Keywords: Brushless motor, electric drive, control system.

1. Introduction

Numerous sensorless control techniques have been proposed for permanent magnet (PM) brushless dc (BLDC) drives, mostly focusing on low and moderate-speed operations. However, there are new problems in high-speed situations. By way of example, the technique of detecting the back-EMF zero-crossings is a common method [1]. However, the effect of winding inductance becomes significant in high-speed motors, hence, the free-wheeling diodes of the inverter may conduct for such a long time that the phase back-EMF zero-crossings are obscured, resulting in failure of the sensorless control [2], [3].

On the other hand, the effect of winding inductance can make the phase current retarded from the back-EMF, especially when the motor speed is high. Therefore, phase-advancing control, i.e., advanced firing of the inverter, is often employed, while the advancing angle should be dynamically adjusted according to the motor speed and load condition. In such a case, continuous rotor position information is needed. However, if Hall effect sensors are used, only six key rotor positions can be detected, which are not readily applicable to dynamic phase-advancing control.

This paper presents a sensorless control technique based on full hardware rotor-flux-observer (RFO), which is not influenced by the free-wheeling diode conduction during high speed operation, meanwhile can provide continuous rotor position information for phase-advancing purpose. The RFO-based sensorless control technique has been used previously for the sensorless control of PM brushless ac (BLAC) drives [4]-[5], in which the motor phase voltage is calculated by a DSP from the inverter switching status and the measured DC link voltage (u_{dc}), as $u=S*u_{dc}$. S is the switching variable. It is either 1(when the upper switch is on) or 0 (when the lower switch is on). However, in a BLDC motor, there always exists a non-energizing phase, whose winding terminal is floating and the phase voltage cannot be calculated, since neither the upper nor the lower switch is on, S is neither 1 nor 0 and is varying between 1and 0. Therefore, the proposed RFO uses hardware to measure the voltage and current, and observe the flux vector.

An experimental control system, as shown in fig.1, is built to validate the control technique with 2kW, 85000rpm high-speed sensorless PM BLDC motor, which is used for an electric assisted turbocharger. The 2-pole permanent magnet ring of the BLDC motor is magnetized in parallel, providing a sinusoidally distributed airgap field and sine-wave back-EMFs. Also, a high-strength non-magnetic titanium alloy retaining sleeve is used to support the contents of the rotor for its safe and reliable operation across the load, speed and temperature ranges [6]. In addition, a copper shield is fixed around the magnet ring in order to minimize the rotor eddy current losses [7]-[9].

Figure 1: Photo of experimental control system

2. Principle of Rotor-Flux-Observer-based sensorless operation

The RFO is based on the motor two-axis $\alpha-\beta$ model. Fig.2 is the phasor diagram of the PM brushless motor [4], in which both voltage and current vectors (**U** and **I**) are illustrated. Each vector has an α–component and a β–component,

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \mathbf{C}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \mathbf{C}\begin{bmatrix} u_{ag} \\ u_{bg} \\ u_{cg} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \mathbf{C}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

where

$$\mathbf{C} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \quad (3)$$

u_a, u_b, u_c are the motor phase voltages, which cannot be directly sensed if the motor winding neutral point is not led out. u_{ag}, u_{bg}, u_{cg} are the motor terminal voltages from the winding terminals to the dc supply ground, and i_a, i_b, i_c are the motor phase currents. These can be measured with voltage and current sensors, respectively. Furthermore, the transformation of the matrix **C** can be implemented with simple hardware. Therefore, at any time, the vectors **U** and **I** can be obtained.

It is known that

$$\mathbf{U} = \frac{d\mathbf{\Psi}_s}{dt} + R \cdot \mathbf{I} \quad (4)$$

where R is the winding resistance, and $\mathbf{\Psi}_s$ is the stator flux-linkage vector. Thus, $\mathbf{\Psi}_s$ can be observed from

$$\mathbf{\Psi}_s = \int (\mathbf{U} - R \cdot \mathbf{I})dt \quad (5)$$

In other words, $\mathbf{\Psi}_s$ can be obtained with two hardware integrators, for which the inputs are $(u_\alpha - Ri_\alpha)$ and $(u_\beta - Ri_\beta)$, whilst the outputs are $\mathbf{\Psi}_{s\alpha}$ and $\mathbf{\Psi}_{s\beta}$, respectively.

$\mathbf{\Psi_f}$ is the magnet-excited flux-linkage vector, i.e., the rotor flux vector. It aligns with the rotor d-axis. Its phase angle is just the rotor position θ_r. Hence, if $\mathbf{\Psi_f}$ is observed, the rotor position can be calculated. It is known that

$$\mathbf{\Psi}_f = \mathbf{\Psi}_s - L_s \cdot \mathbf{I} \quad (6)$$

where $L_s = L - M$ in a surface-mounted permanent magnet BLDC motor, and L is the winding self-inductance, whilst M is the mutual inductance.

(6) can also be implemented with simple hardware, its outputs being the α-component and β-component of the $\mathbf{\Psi_f}$ vector ($\psi_{f\alpha}$ and $\psi_{f\beta}$), respectively.

A DSP system is then used to sample the analogue signals of $\psi_{f\alpha}$ and $\psi_{f\beta}$ through A/D converters, and then calculate the rotor position as

$$\theta_r = \arctan\frac{\psi_{f\beta}}{\psi_{f\alpha}} \quad (7)$$

Moreover, in order to cripple the influence of the pure integration in (4), which amplifies any

DC offset or error in the measured voltages and currents until saturation is reached [4], the flux observer needs to be improved, by applying a high-pass filter to each input of the integrators [10]. Since the combination of the high-pass filter and the integrator is equivalent to a low-pass filter, in practice, the integrators are replaced with low-pass filters, which can be easily implemented with Op-Amps, capacitors and resistors.

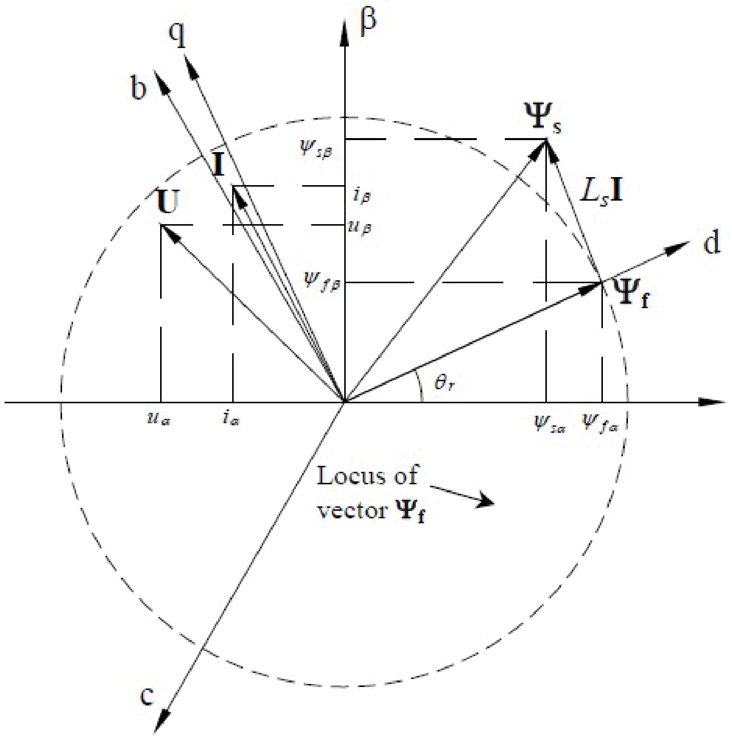

Figure 2: Phasor diagram of BLDC motor

3. Experimental Validation

An experiment system of the RFO-based sensorless controller, associated with a 2kW, 85000rpm high-speed PM BLDC motor, is set up. Fig.3 shows the captured waveforms, under the rated operation condition, of the phase current (i_a), terminal voltage (u_{ag}), phase voltage (u_{an}), α- and β-components of voltage vector (u_α and u_β), of current vector (i_α and i_β), of stator flux-linkage vector ($\psi_{s\alpha}$ and $\psi_{s\beta}$), and of magnet-excited flux-linkage vector ($\psi_{f\alpha}$ and $\psi_{f\beta}$). $\psi_{f\alpha}$ and $\psi_{f\beta}$ are displayed on an oscilloscope as X- and Y- inputs, forming the locus of the $\boldsymbol{\psi}_f$ vector, as shown in fig.4. Though the locus is not an ideal circle, it brings little error to the calculated rotor position, as the waveform of rotor position (θ_r) in Fig.3, is almost an ideal saw-tooth wave. This proves that the proposed sensorless control strategy is workable and reliable.

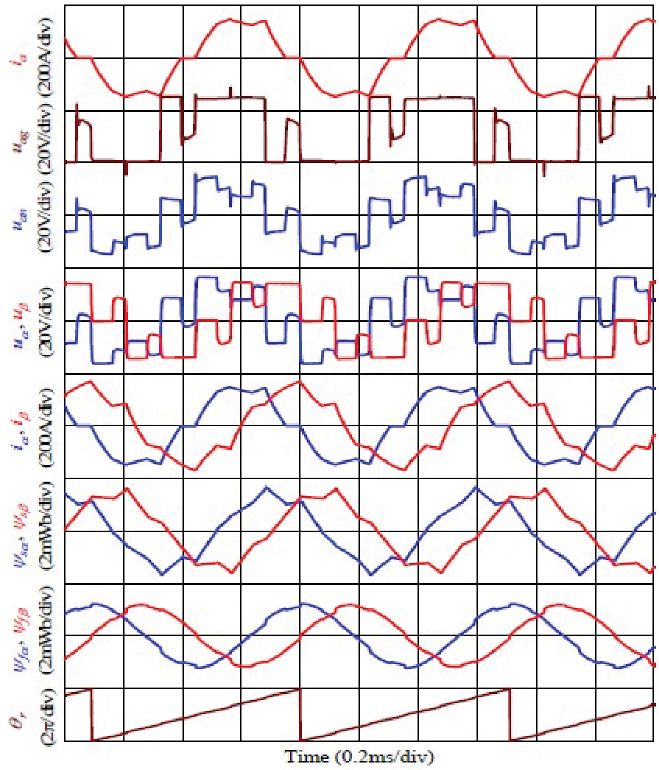

Figure 3: Measured waveforms under rated operation condition, motor speed being 85000rpm

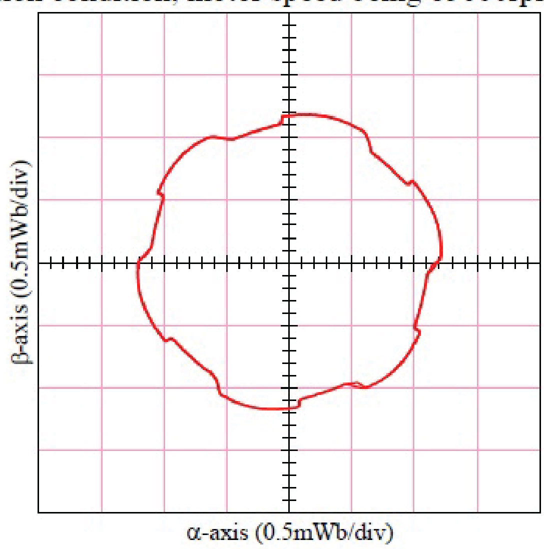

Figure 4: Captured locus of rotor flux vector

4. Conclusion

This paper presented a novel sensorless control method of high speed PM BLDC motor. The principle of the rotor-flux-observer-based sensorless operation was introduced. The experimental results show good performance of the full hardware flux observer up to the rated speed of 85000rpm, as well as reliable operation of the sensorless control technique at such a high speed.

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Shen, Jian-Xin

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