Back - EMF Estimation Approach for Sensorless Operation of Small Electronically-Commutated Permanent-Magnet Motors

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Abstract – In the paper, a new sensorless rotor-position detection and switching-signal generation scheme using a back-EMF estimation algorithm for a small three-phase electronically-commutated permanent-magnet (ECPM) motor is proposed. The validity of this sensorless commutation technique for small ECPM motor operation is confirmed by simulation and experiments.

Index Terms – electronically-commutated permanent-magnet motor, back-EMF estimation algorithm, dynamic simulation, sensorless operation, experimental set-up.

I. INTRODUCTION

In the last years, there is an increasing trend in small-size appliances to move towards using electronically-commutated permanent-magnet (ECPM) motors. Commonly, this kind of small motors comprises a PM rotor, a three-phase wound stator fed from a DC power source through a full-bridge MOSFET inverter, and three digital Hall-effect rotor-position sensors whose output signals are decoded in a control logic block for providing proper switching pattern of the inverter. Six-step two-phase-on feeding scheme is frequently used for the inverter-driven three-phase ECPM motor to continually synchronize the stator-phase energization with the rotor-PM MMF wave [1].

Previous work has led to various indirect rotor-position detection techniques being developed for small ECPM motors in an attempt to eliminate the necessity for a separate position sensing device with its attendant concerns over cost, reliability and space requirement [2]. Some of these techniques use the motional back EMF induced in the stator winding by the rotor-PM excitation flux, and are implemented commercially:

? direct back-EMF detection, based on sensing first the instant at which the back EMF in the non-energized stator phase crosses zero and, then, 30° phase shifting to properly yield the gating signals for the inverter power switches [3]; it suffers from some phase-shift errors during the acceleration and deceleration periods;

? back-EMF integration method, in which the commutation signals are obtained by comparing the modulus of the integrated back-EMF waveform with a pre-set threshold voltage [4]; it has the disadvantage that the optimal values of threshold voltage and integration constant are difficult to determine.

In this paper, a back-EMF estimation algorithm for sensorless operation of a small three-phase ECPM motor is proposed. Thus, crossing points of two phase back-EMF waveforms (i.e. zero-crossing points of line back-EMF waveforms) in the stator winding are obtained through predictive algorithm from measured phase currents and voltages, and then used to generate the sensorless commutation signals for the inverter-driven three-phase ECPM motor without additional phase shifting. Effectiveness of the proposed sensorless commutation technique is verified by simulation and experiments.
motor in the right direction, and to bring it up to a certain speed where the phase back EMFs in the stator winding can be estimated.

**II. PROPOSED SENSORLESS COMMUTATION TECHNIQUE**

The small ECPM motor under consideration is of commercial Maxon type, having a two-pole PM rotor with diametrical magnetization, a slotless armature with three-phase star-connected airgap winding and quasi-squarewave voltage supply via a full-bridge six-switch inverter. The main motor specifications are given in Table 1. The dynamic behaviour of the small three-phase ECPM motor is described by a set of five first-order differential equations:

\[ e_k = k_e (d\theta/dr) \cos(\theta - 2\pi (k-1))/3 \]
\[ = v_k - Ri_k - L\dot{i}_k / \tau, \quad k = 1, 2, 3, \tag{1} \]
\[ d^2\theta/dr^2 = p (T_e - B(d\theta/dr) - T_L) / J, \tag{2} \]
\[ T_e = p k_e (i_1 \cos \theta + i_2 \cos(\theta - 2\pi/3) - (i_1 + i_2) \cos(\theta - 4\pi/3)), \tag{3} \]

where \( e_k, i_k, v_k, k = 1, 2, 3, \) denote the stator-phase back EMFs (of sinusoidal waveform), currents and voltages, respectively; \( k_e \) the back-EMF constant; \( \theta \), the rotor position (electrical angle); \( R, L \) the stator-phase resistance and equivalent inductance, respectively (which are both assumed constant); \( p \), the number of pole pairs; \( T_e, T_L \) the electromagnetic and load torque, respectively; \( B, J \) the viscous damping coefficient and moment of inertia (of the motor and mechanical load), respectively.

If the stator-phase currents and voltages are measured at a fixed, sufficiently small (i.e. 20 \( \mu \)s) sampling period \( t_s \), Eq.(1) can be converted into a discrete-time form and performed to estimate the back EMFs at the actual \( n \)th sampling instant:

\[ \hat{e}_k(n) = v_k(n) - Ri_k(n) - L(i_k(n) - i_k(n-1)) / t_s, \]
\[ k = 1, 2, 3, \tag{4} \]

\( i_k(n-1) \) being the phase current measured at previous \( (n-1) \)th sampling instant. This real-time estimation algorithm of the phase back EMFs was implemented in Matlab/Simulink environment, leading to the waveforms of Fig. 1, displayed in relationship with the proposed switching signal pattern of the inverter. Thus, the commutation instants of inverter switches correspond to the crossing points of two phase back EMFs (for example, the six-step commutation sequence of the inverter begins with the crossing point of phase back-EMFs \( \hat{e}_2 \) and \( \hat{e}_3 \)). It can also be seen from Fig. 1, that in each of the six commutation sectors of the inverter switching pattern, there is always one phase back EMF having the biggest values, another one of the smallest values and the third one of intermediary values (for example, the first sector of the six-step inverter commutation sequence reveals \( \hat{e}_1 > \hat{e}_2 > \hat{e}_3 \)).

Based on prior observations, a new sensorless six-step commutation scheme was developed and simulated (Fig. 2) by comparing the estimated phase back EMFs and, accordingly, generating the switching signals in the inverter without additional phase shift.

A set of simulation results given in Fig. 3 shows the sensorless operation characteristics of the considered small ECPM motor under no-load and step-load conditions. It is proved by this real-time simulation test

<table>
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<tr>
<th>TABLE 1. MAIN SPECIFICATIONS OF THE SMALL THREE-PHASE ECPM MOTOR UNDER CONSIDERATION</th>
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<tr>
<td>rated voltage ( U = 18 ) V</td>
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<tr>
<td>maximum current ( I_{max} = 3.3 ) A</td>
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<tr>
<td>phase resistance ( R = 0.63 ) O</td>
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<tr>
<td>phase inductance ( L = 0.15 \times 10^{-3} ) H</td>
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<tr>
<td>back-EMF constant ( k_e = 0.0382 ) Vs/rad</td>
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<tr>
<td>number of pole pairs ( p )</td>
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<tr>
<td>moment of inertia ( J = 8.5 \times 10^{-6} ) kg( \cdot )m(^2)</td>
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<tr>
<td>viscous damping coefficient ( B = 1.45 \times 10^{-5} ) Nm/s/rad</td>
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</table>
that the proposed sensorless commutation scheme works quite well not only at steady-state but also during transient.

Since the back EMF is not generated at zero speed, the procedure proposed in [5] to start the motor from standstill was used in both simulation and experimental tests. Thus, a pre-set current is conducted for a sufficient time through two chosen stator phases in order to ensure the alignment of the rotor to the reference axis of the magnetic field produced by the two energized phases. Once the rotor position is definite, the motor start-up in the desired sense is achieved by generating a sequence of six inverter gating signals in accordance with the switching pattern for the correct rotation. After completion of this six-state open-commutation cycle, the back-EMF estimation algorithm for self-commutation of the motor replaces the starting procedure.

The proposed sensorless commutation technique involving back-EMF estimation based on stator-phase currents and voltages can be mainly affected by measurement errors. In order to check the ability of the technique to perform in the presence of both current and voltage measurement errors, a real-time simulation test was carried out by introducing (in several periods of 0.3 ms) offset and magnitude errors in the measured terminal quantities (Fig. 4). As emphasized by the simulation results of Fig. 4, the proposed sensorless commutation scheme is quite robust with respect to current and voltage measurement errors.

III. EXPERIMENTAL RESULTS

To prove the practical use of the proposed sensorless commutation technique for the small ECPM motor, some experiments under various operational conditions have been performed. The picture of the experimental set-up is shown in Fig. 5. It comprises: a PIC assembly (Motorola) of three-phase MOSFET bridge-inverter and motor controller; the small three-phase ECPM motor under test with the specifications of Table 1; a small DC generator with load resistors, which is mechanically coupled to the ECPM motor to serve as its dynamic load; a star resistor network to sense the stator-phase voltages; wide-bandwidth transducers to measure the stator-phase currents; a PC incorporating a data acquisition board (National Instruments); a low-cost 8-bit microcontroller (Philips) for real-time implementation by programmed software of the proposed sensorless commutation scheme for the small ECPM motor.
Fig. 5. Experimental set-up for testing the proposed back-EMF estimation algorithm for sensorless operation of the small three-phase ECPM motor.

Fig. 6 gives some typical experimental results for the steady-state sensorless operation of the tested ECPM motor under no-load (a) and full-load (b) conditions. As it is seen from the measured and estimated steady-state waveforms in Fig. 6, the ECPM motor sensorless commutation algorithm based on real-time back-EMF estimation performs well under both unloading and loading tests.

The sensorless starting procedure for the ECPM motor involving rotor pre-positioning and open-loop commutation transient stages [5] is suitably achieved by software in the microcontroller.

IV. CONCLUSION

This paper has developed a new sensorless commutation scheme using a stator-phase back-EMF estimation algorithm for a small three-phase ECPM motor.

The proposed algorithm implies no modifications to the motor, avoids the limitations of other back EMF-based sensorless approaches and requires less computational effort than full-order observer methods. Its effectiveness under steady-state and transient conditions was verified by real-time simulation and experiments.

REFERENCES