HIGH-SPEED PERFORMANCE PREDICTION OF THREE-PHASE ELECTRONICALLY-COMMUTATED PERMANENT-MAGNET MOTORS

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Abstract
Drive characteristics of three-phase electronically-commutated permanent-magnet (ECPM) motors for high-speed operation in traction applications is investigated in this paper. A dynamic simulation model using the Matlab / Simulink environment combines the features of the three-phase ECPM motor and its supplying full-bridge inverter in order to predict the high-speed performance for various drive conditions. The solution is given for a 120^o-conduction mode of the inverter with provision for selecting a commutation-angle advance. Simulation results show that the ECPM motor can successfully achieve high-speed constant-power operation at more than three times the base speed.

1. INTRODUCTION

In electric traction applications, wide-range speed control of propulsion-system motor drives is necessary. Hence, when the motor speed is lower than the base speed, the drive is required to provide a constant output torque. On the other hand, when the speed is higher than the base speed, constant-power operation is preferred because it can significantly reduce the cost and size of the motor drive.

In general, constant-torque operation can be easily achieved in any electronically-commutated permanent-magnet (ECPM) motor drives. The base speed is imposed by the inverter DC-link voltage, the maximum torque requirement determining the inverter VA rating. When the speed increases above the base speed, the dynamically-induced stator-phase back-emf becomes close to the stator-phase voltage (limited by the inverter DC-link voltage), resulting dramatic reduction in stator-phase current and electromagnetic torque. Thus, ECPM motor drives with constant DC-link voltage usually suffer from difficulty to achieve high-speed operation.

This paper investigates the torque-speed characteristic extension by the commutation-angle advance technique [1] for a three-phase ECPM motor drive with quasi-squarewave 120^o-conduction-mode inverter supply. A simulation model combining the features of both the ECPM motor and the supplying voltage-source inverter is used to predict the drive performance for high-speed constant-power operation.

2. SIMULATION MODEL FOR HIGH-SPEED OPERATION

The essential elements of the three-phase ECPM motor drive under consideration are the surface-mounted PM rotor and the star-connected stator-armature winding in which the power electronic inverter supplies 120^o-conduction-mode quasi-squarewave bidirectional current. The main motor specifications are given in Table 1.

Table 1. Main specifications of the three-phase ECPM motor under consideration

DC-link inverter voltage	U = 145 V
maximum current	I_{max} = 5 A
phase resistance	R = 2.98 Ω
phase inductance	L = 0.0114 H
back-emf constant	k_e = 0.156 V·s / rad
number of pole pairs	p = 2
moment of inertia	$J = 8.5\times10^{-4}$ kg·m^2
viscous damping coefficient	$B = 1.45\times10^{-6}$ Nm·s/rad

The dynamic behaviour of this three-phase ECPM motor drive is described by a set of five first-order differential equations:

$$e_k = k_e\,(d\theta/dt)\cos(\theta - 2\pi\,(k\text{-}1))/\,3) \\ \quad = v_k - Ri_k - L di_k/dt, \quad k = 1, 2, 3, \qquad (1)$$

$$d^2\theta/dt^2 = p\,(m_e - B(d\theta/dt) - m_r)/\,J, \qquad (2)$$

$$m_e \;= p\,k_e\,(i_1\cos\theta\; + i_2\cos(\theta - 2\pi/3) \\ \quad - (i_1 + i_2)\cos(\theta - 4\pi/3)), \qquad (3)$$

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; θ, 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; m_e, m_r, the electromagnetic and load torque, respectively; B, J, the viscous damping coefficient and moment of inertia (of the motor and mechanical load).
The drive system model of Eqs. (1)-(3) embodies the 120^{o} switching pattern of the three-phase full-bridge inverter with six transient commutation periods and other six conduction intervals for the 360^{o} of each stator-winding energization cycle. Hence, the following simplifying assumptions have been made in the above system model: (i) eddy-current and hysteresis effects are neglected; (ii) there is no saliency, and therefore equivalent phase inductances are constant and independent of rotor position; (iii) power-electronic devices in the inverter circuit are ideal.
At speeds higher than the base speed, where stator-phase voltage (limited by the inverter DC-link voltage) and dynamically-induced back-emf of the ECPM motor are of similar values, the torque output of the drive decreases since the stator-phase current magnitude is low. This situation can be rectified to some extent by switching-on each stator phase earlier, i.e. by introducing a commutation angle advance δ_c , here defined as the angular position of a stator-phase commutation with respect to zero-crossing (toward positive values) of the corresponding phase back-emf. Thus, the phase current rise is faster, since the phase voltage is counteracted my a lower back-emf at commutation.
The time-stepping dynamic simulation for high-speed operation of the ECPM motor was implemented in Matlab/Simulink environment (Fig.1) and performed with constant DC-link voltage for various commutation angle advances and drive conditions.

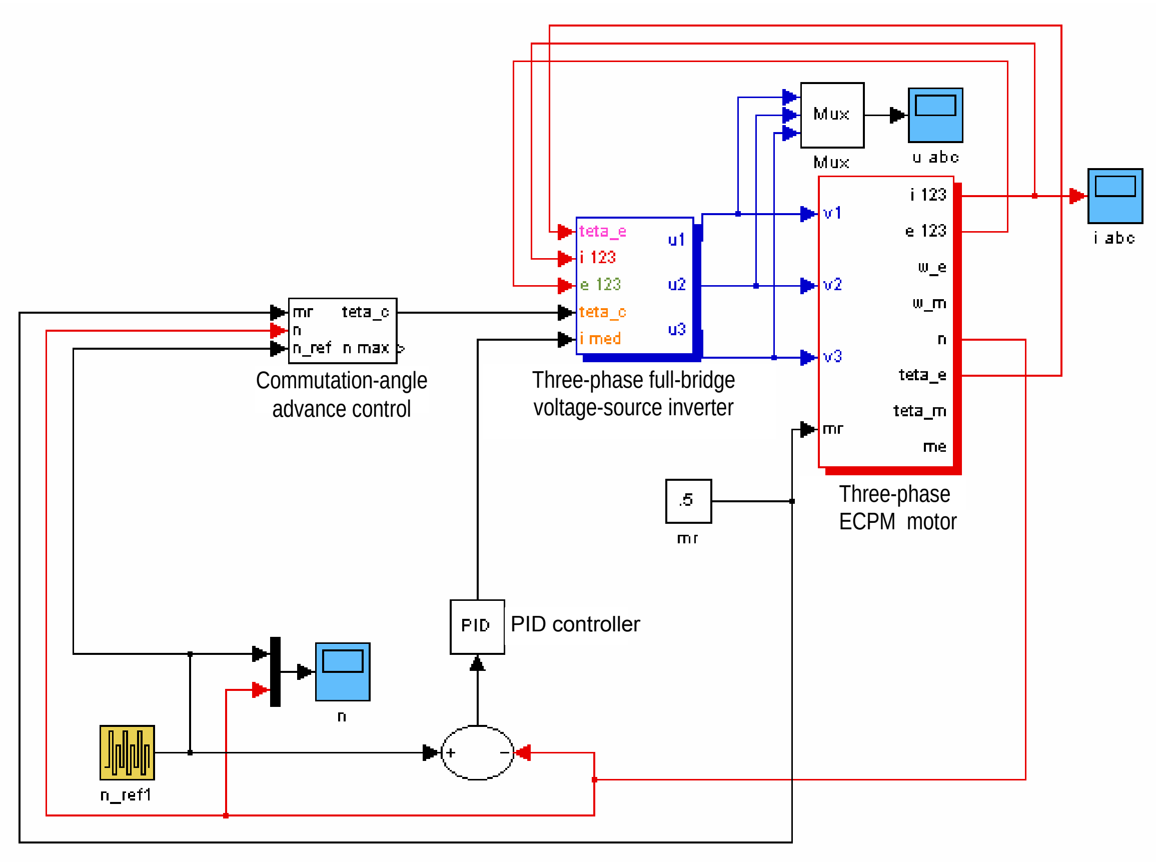

Fig. 1. Matlab/Simulink diagram for the dynamic simulation of the ECPM motor high-speed operation.

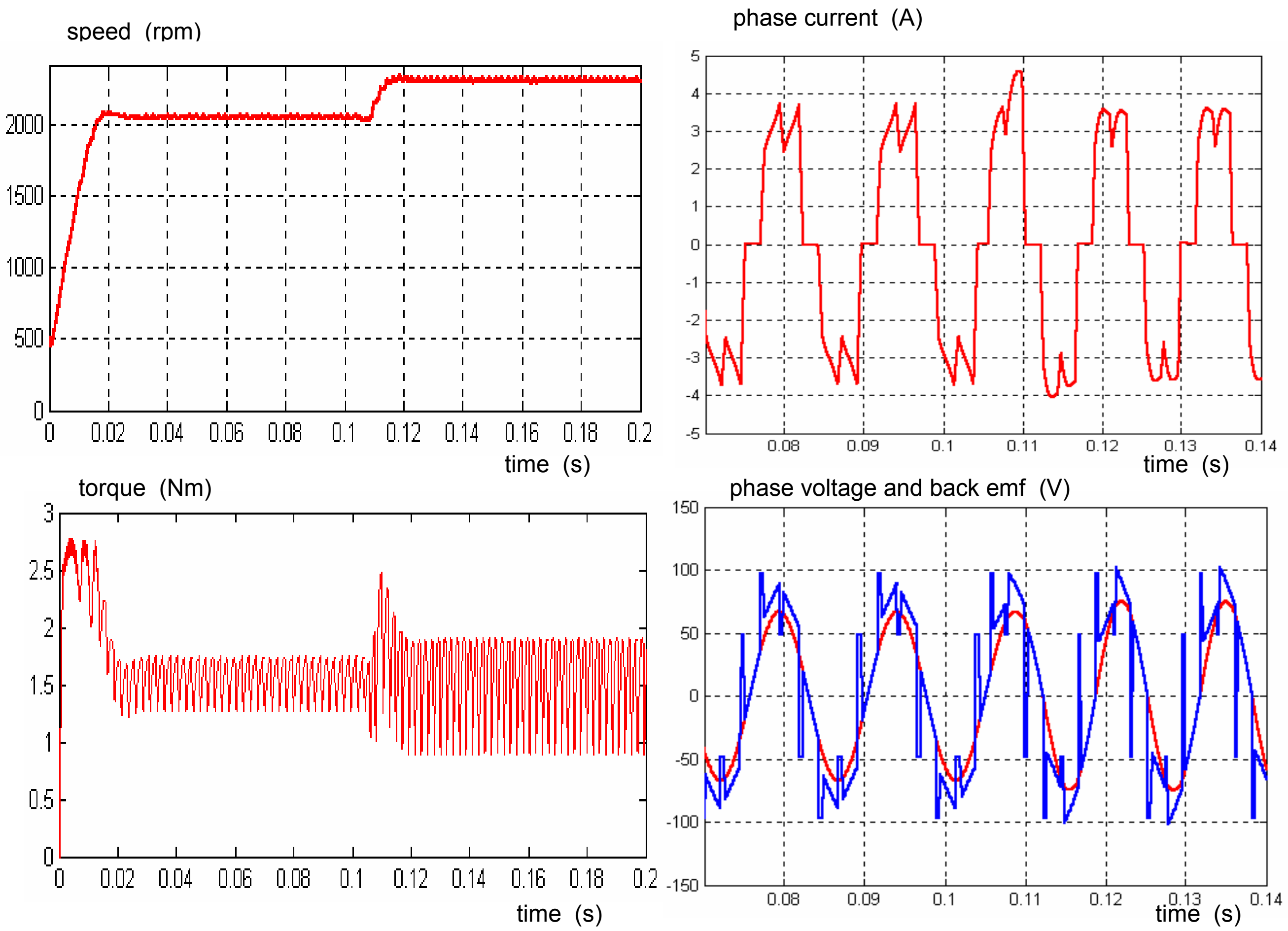

Fig. 2. Dynamic simulation results for transient and steady-state behaviours of the three-phase ECPM motor drive operating under constant load (m_r = 1.5 Nm) and with commutation-angle advance shifted (at high speed) from 0° to 30°.

3. HIGH-SPEED PERFORMANCE PREDICTION

High-speed characteristics of the three-phase ECPM motor drive, such as torque vs. speed, torque ripple, stator-phase currents and voltages, are predicted for 120°-conduction-mode inverter pattern by using the simulation model described above.

Fig. 2 shows the dynamic simulation of the ECPM motor drive operating, at constant load, with the commutation-angle advance set to zero from standstill to the high-speed range, and further on, in the constant-power region, with 30° advanced commutation. An improvement in the high-speed operation limit, but also in the torque ripple, when using the commutation-angle advance technique, is obvious.

Torque-speed characteristics for no-load high-speed operation of the ECPM motor under various commutation-angle advance conditions are displayed in Fig. 3. These torque-speed curves have served as a reference for predicting the optimal commutation-angle advances for related loads and speeds (Fig. 4). It is clear from Fig. 4, that high-speed torque performance is improved as the commutation-angle advance increases up to a threshold value for each particular motor speed and load.

As shown in Fig. 5, the ECPM motor drive can provide both constant-torque and constant-power operations. For the constant-power high-speed behaviour of the motor, as defined by the computed torque-speed envelope in Fig. 5, the commutation-angle advance should be increased as a nonlinear function of the speed (Fig. 6). Simulation results show that the ECPM motor can successfully achieve high-speed constant-power operation at more than three times the base speed without exceeding the drive voltage and current ratings.

Fig. 7 compares the high-speed performance of the ECPM motor drive, at constant load condition, for two commutation-angle advances, i.e. 40° and 60°, respectively. It should be pointed out that the ECPM motor drive exhibits higher phase-voltage (first-harmonic) amplitude and torque ripple, as the commutation angle is advanced.

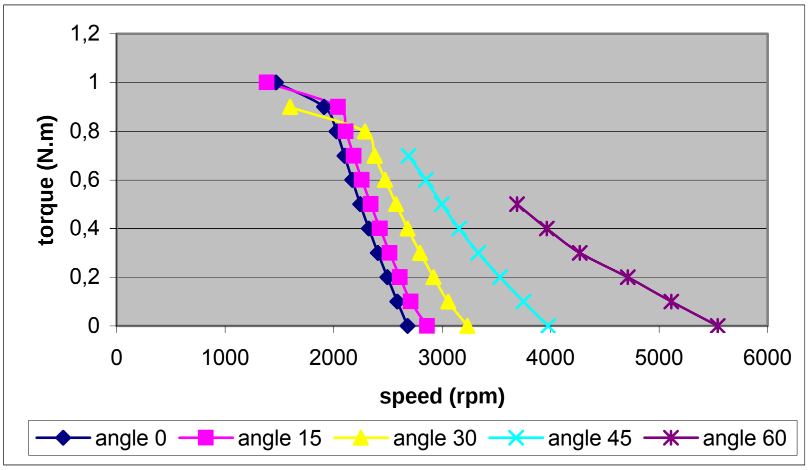

Fig. 3. Torque-speed characteristics of the three-phase ECPM motor drive operating at high speeds under no-load and various commutation-angle-advance conditions.

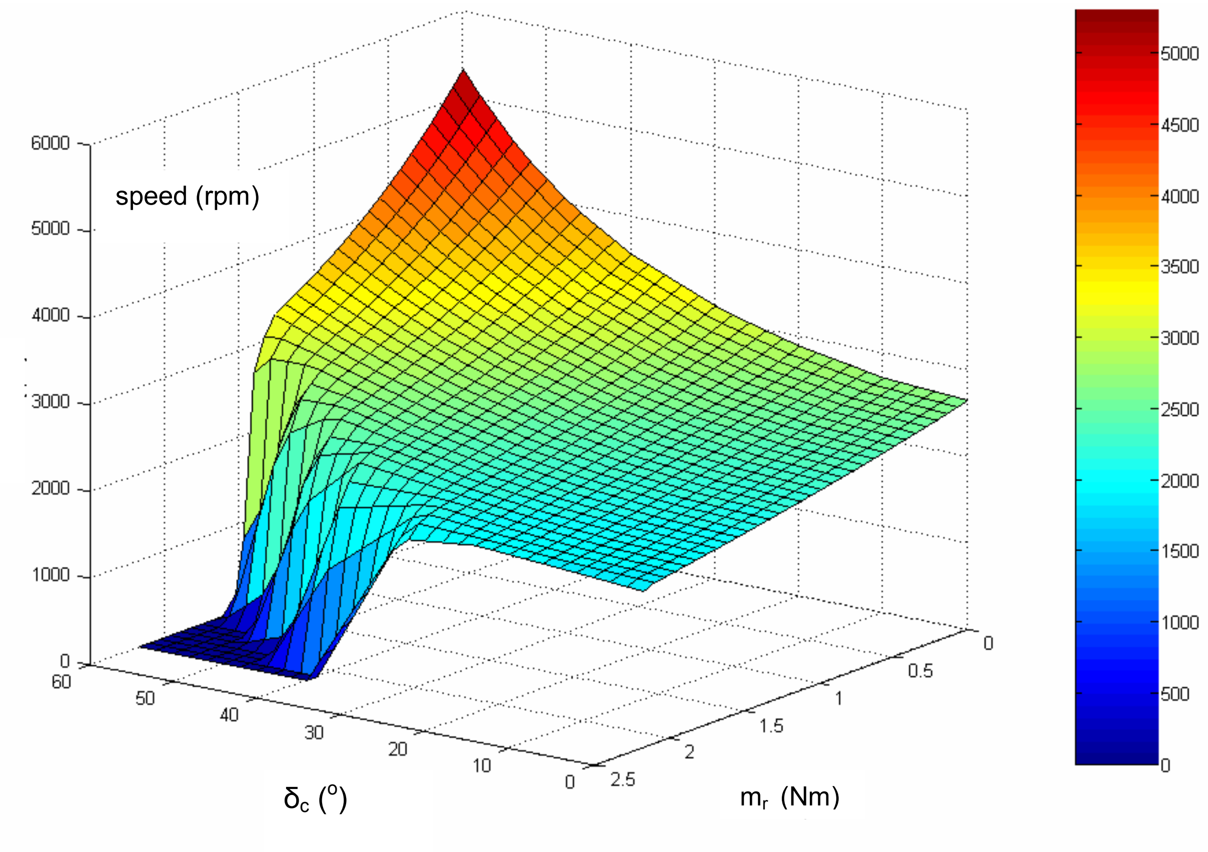

Fig. 4. Constant-torque (up to the base speed) and constant-power (above the base speed) operating limits of the three-phase ECPM motor drive under various load, speed and commutation-angle-advance related conditions.

4. CONCLUSIONS

The paper presented a simulation approach for three-phase ECPM motor drives to predict their high-speed performance at various drive conditions for traction applications. The real-time adjustment of the commutation-angle advance to achieve constant-power operation is a conceptually simple control technique for improving performance of an ECPM motor drive in high-speed range. It lends itself to efficient look-up table control using data specific to both the ECPM motor type and the desired torque-speed profile.

The solution given here for a full-voltage 120°-conduction mode of the supplying inverter covers both steady-state and transient behaviours of three-phase ECPM motor drives, and extends the torque-speed characteristic far away from the usual limit speed. However, it also exacerbates the output torque ripple.

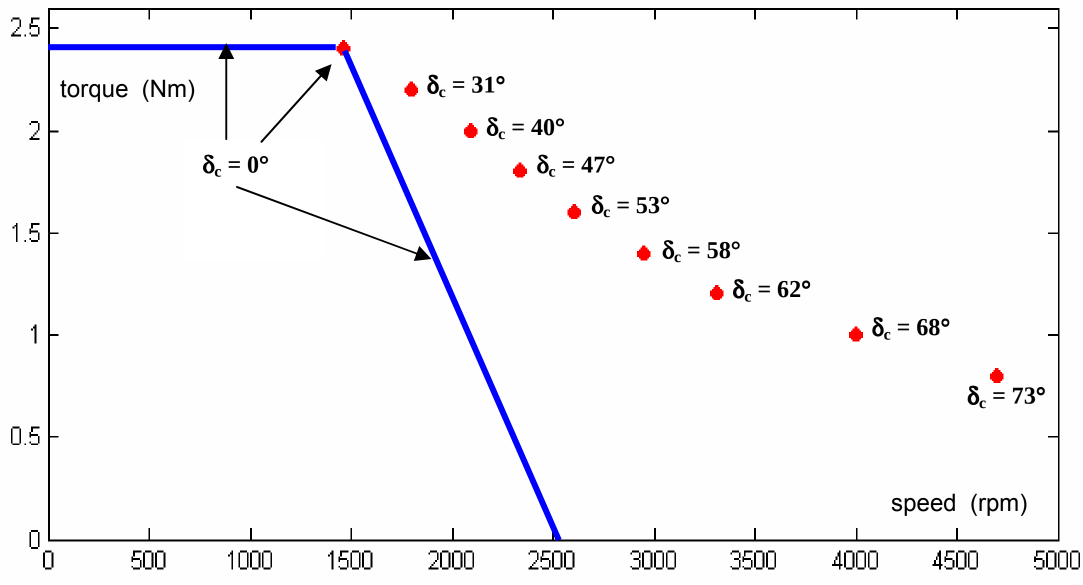

Fig. 5. Torque-speed characteristics of the three-phase ECPM motor drive operating under full-load and various commutation-angle-advance conditions.

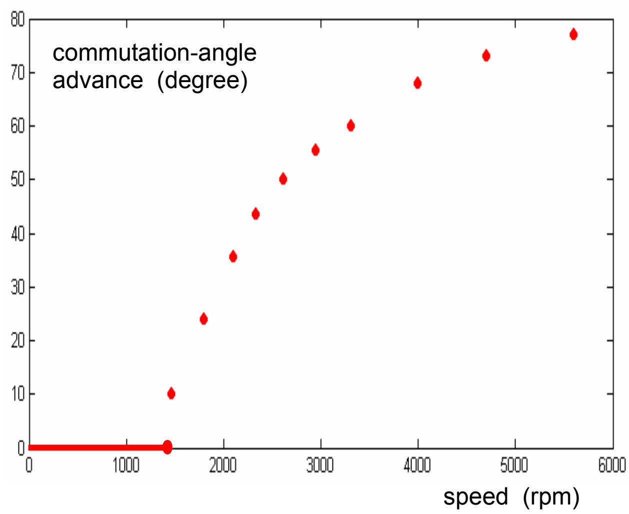

Fig. 6. Speed-dependent commutation-angle advance leading to constant-power high-speed operation of the three-phase ECPM motor drive.

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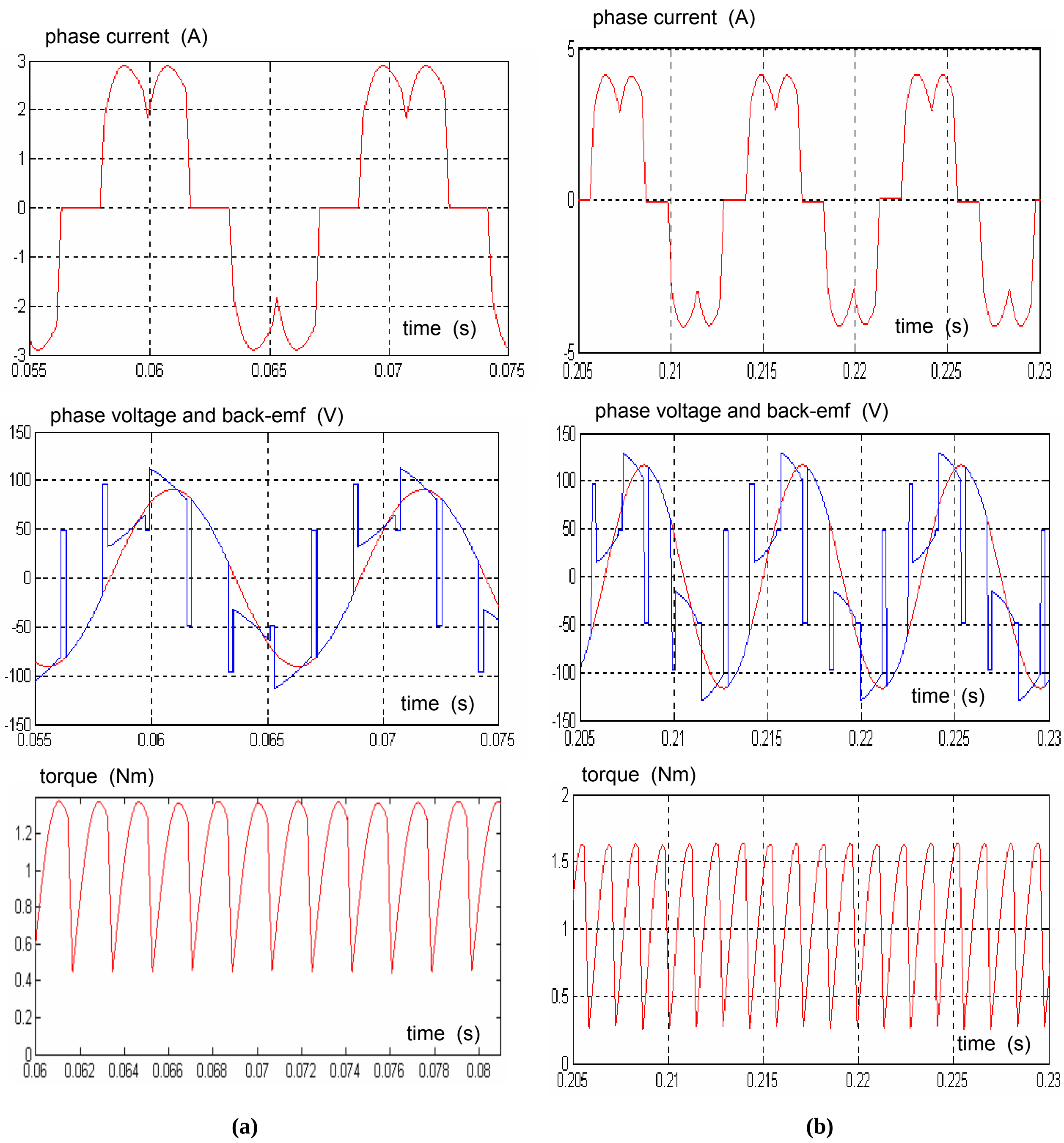

Fig. 7. Simulation results for steady-state high-speed operation of the three-phase ECPM motor drive at constant load (m_r = 1 Nm) and with commutation-angle advance of (**a**) 40° and (**b**) 60°, respectively.