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Sensorless Control for High-Speed BLDC Motors With Low Inductance and Nonideal Back EMF

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Abstract*— The position sensorless control of high-speed brushless DC motors with low inductance and non ideal back electromotive force (EMF) in order to advance the reliability of the motor system of a magnetically balanced control moment gyro for space application. The commutation angle error of the established line-to-line voltage zero-crossing points detection method is analyzed. Based on the characteristics measurement of the non ideal back EMF, a two-stage commutation error compensation method is proposed to achieve the reliable and -accurate high commutation in the operating speed region of the proposed system. The commutation angle error is rewarded by the transformative line voltages, the hysteresis comparators, and the appropriate design of the low-pass filters in the both speed region, respectively. High-precision commutations are achieved especially in the high-speed region to drop off the motor loss in steady state. The simulated and experimental results show that the proposed method can achieve an effective damages effect in the whole operating speed region.

***Keywords*—BLDC motor; sensorless motor control; Non ideal back EMF.**

I. INTRODUCTION

The improvement and accessibility of very high-energy density brushless materials has contributed to an increased use of the brushless dc motor (BLDC) in high recital applications. Brushless DC motors have the advantage of higher power density than other motors, which results in condensed and tough structures. Owing to these features, BLDC motors have become trendier in the applications where efficiency is a critical problem, or where spike caused by mechanical commutation are not approved. A BLDC motor requires an inverter and a rotor position sensor to achieve commutation process because a permanent magnet synchronous motor does not have brushes and commutators in DC motors. However, the position sensor presents quite a few disadvantages from the standpoint of drive's cost, machine size, reliability, and noise protection. As a result, many research have been reported for sensorless drives that can control position, speed, and torque devoid of shaft-mounted position sensors

Position sensors can be entirely eliminated, thus dropping further cost and size of motor assembly, in those applications in which only changeable speed control (i.e., no positioning) is required and system dynamics is not particularly challenging (i.e., slowly or, at least, predictably varying load). In fact, some direct methods, such as back-EMF and current sense, provide, in most cases, enough information to estimate with sufficient precision the rotor location and, therefore, to control the motor with synchronous phase currents. A PM brushless drive that does not need position sensors but only electrical measurements is called a sensorless drive

The BLDC motors provide an arresting aspirant for sensorless operation because the nature of its excitation essentially offers a low-cost way to remove rotor position information from motor-terminal voltages. In the excitation of a three-phase BLDC motor, except for the phase-commutation periods, only two of the three phase windings are conducting at a time and the no conducting phase carries the back-EMF. The various sensorless control strategies are; the open phase current sensing method, the third harmonic of back-EMF detection method, the back-EMF detection method and the open phase voltage sensing method. All these methods do not provide a high performance at low speed ranges .To solve this problem, a new sensorless control method utilizing an unknown input observer is used. The unknown input observer has been widely researched, especially in the fault detection field. However, this observer has not been adopted in sensorless BLDC motor control application. Hence, this paper presents a new sensorless control method incorporating an un known input observer that is independent of the rotor speed

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for a BLDC motor drive. As a result, this paper proposes a highly useful new solution for a high speed sensor less BLDC motor drive with low inductance back emf, which can effectively estimate a line-to-line back-EMF

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II. BLDC Motor Drive

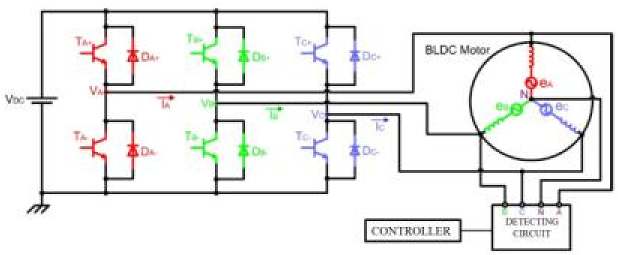

Figure 1.Typical sensorless BLDC motor drive

Fig.1, shows a sensorless BLDC motor drive, which consists of a dc source which is reversed and then fed to the BLDC motor, the detect circuit is used determine the back emf which is sent as information to the controller. The controller provides the signals for the inverter control which in turn controls the BLDC motor.

Generally, a brushless DC motor consists of a permanent magnet synchronous motor that converts electrical energy to mechanical energy, an inverter corresponding to brushes and commutators, and a shaft position sensor as shown in Fig.1. In this figure, each of the three inverter phases are highlighted in a different colour, including the neutral point: red phase A, green phase B, blue phase C, and pink neutral point N. The stator iron of the BLDC motor has a non-linear magnetic saturation typical characteristic, which is the basis from which it is possible to determine the initial position of the rotor. When the stator winding is energized, applying a DC voltage for a certain time, a magnetic field with a fixed direction will be established. Then, the current responses are different due to the inductance difference, and this variation of the current responses contains the information of the rotor position. Therefore, the inductance of stator winding is a function of the rotor position.

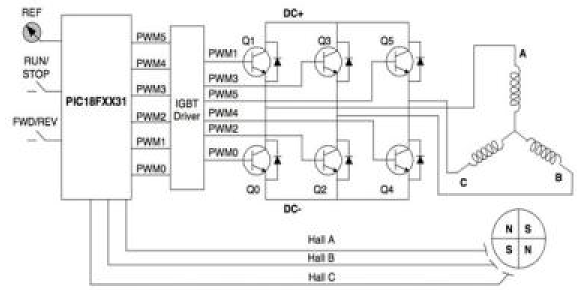

Figure 1(a) Power Stage Motor topology

The analysis of the circuit depicted is based on the motor model for phase A (highlighted in red colour), illustrated in Fig. 2, and the following assumptions are considered:

- The motor is not saturated.
- Stator resistances of all the windings are equal (R_S), self-inductances are constant (L_S) and mutual inductances (M) are zero.
- Iron losses are negligible.

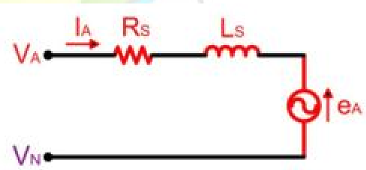

Figure 2. Equivalent circuit of the BLDC motor for phase A

Then, the voltage function of the conducting phase winding might be expressed as indicated in Equation (3):

$$V_{DC} = I \,.\, R_S + L_S \frac{dI}{dt} + e \quad (1)$$

Where $V_{DC}$is the DC-link voltage, $R_S$and $L_S$are the equivalent resistance and inductance of stator phase winding respectively, and e is the trapezoidal shaped back-EMF.

The torque equation is given by:

$$T_e = \frac{e_a.i_a + e_b.i_b + e_c.i_c}{\omega_m} \quad (2)$$

Where v_a, v_b, and $v_c$are phase voltages. $R_s$is a stator resistance. i_a, i_b, and $i_c$are phase currents. $L_s$is a stator inductance. M is a mutual inductance. Where, here in after L represents L_s– M. e_a, e_b, and $e_c$are phase back-EMFs. $\omega_m$is a mechanical angular velocity. Fig. 2 shows that the torque ripple can be minimized and the stable control is achieved when the phase current with square wave form is injected into the part where the magnitude of back-EMFs is fixed.

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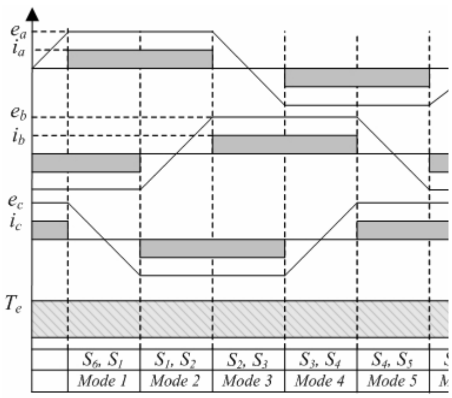

Figure3. Waveforms of a back-EMF, a phase currentand a torque of BLDC motor.

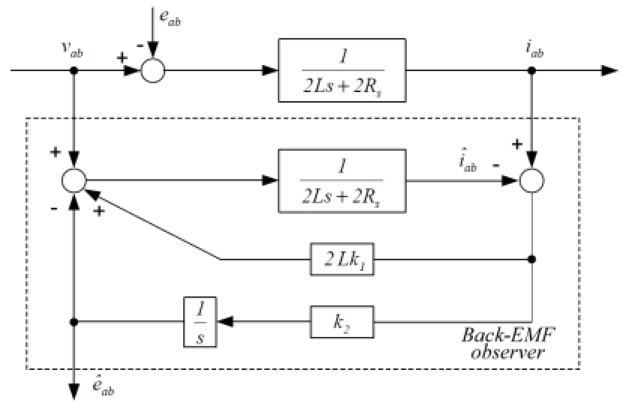

Figure. 4. Block diagram of the proposed back-EMF observer.

III. Sensorless Control Method

The sensorless control method is based on the fact that the rotor position can be detected by the trapezoidal back-EMF of BLDC motors. Since a back-EMF of the BLDC motor is not measured directly, it is estimated by the unknown input observer. This unknown input observer is constructed by aback-EMF regarded as an unknown input and state of the BLDC motor drive system. The sensorless control method using the unknown input observer can be obtained as follows:

A. *First Line-to line back-EMF estimation using the unknown input observer*

Since the neutral point of the BLDC motor is not offered, it is difficult to construct the equation for one phase. Therefore, the unknown input observer is considered by the following line-to-line equation:

$$i_{ab} = -\frac{2R_s}{2L} i_{ab} + \frac{1}{2L} v_{ab} + \frac{1}{2L} e_{ab} \tag{3}$$

In (3), $i_{ab}$and v_{ab}can be measured, therefore they are "known" state variables. On the other hand, since e_{ab}cannot be measured, this term is considered as an "unknown" state.

Fig. 4 shows a block diagram of theproposed back-EMF observer.Therefore, the equation of whole observer including all of three phases is as follows:

$$\frac{d}{dt}\begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \\ \hat{i}_{bc} \\ \hat{e}_{bc} \\ \hat{i}_{ca} \\ \hat{e}_{ca} \end{bmatrix} = \begin{bmatrix} -\frac{2R_s}{2L} & -\frac{1}{2L} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{2R_s}{2L} & -\frac{1}{2L} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{2R_s}{2L} & -\frac{1}{2L} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \\ \hat{i}_{bc} \\ \hat{e}_{bc} \\ \hat{i}_{ca} \\ \hat{e}_{ca} \end{bmatrix} + \begin{bmatrix} \frac{1}{2L} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{2L} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{2L} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_{ca} \end{bmatrix} + \begin{bmatrix} k1 & 0 & 0 \\ k2 & 0 & 0 \\ 0 & k3 & 0 \\ 0 & k4 & 0 \\ 0 & 0 & k5 \\ 0 & 0 & k6 \end{bmatrix} \begin{bmatrix} i_{ab} - \hat{i}_{ab} \\ i_{bc} - \hat{i}_{bc} \\ i_{ca} - \hat{i}_{ca} \end{bmatrix} \tag{4}$$

B. *Commutation function*

The sensorless control method that decides commutation instances of switching devices by detecting ZCP of back-EMF has been commonly used. However, this method cannot detect ZCP at a low-speed range. In order to solve this problem, the sensitive commutation function defined by using the line-to-line back-EMF observer is proposed to improve the performance of the sensorless control scheme as shown in Fig. 4 and the commutation functions (CF) are defined as below:

$$\text{Mode 1 and 4: } CF(\theta_1) = \frac{\hat{e}_{bc}}{\hat{e}_{ca}}, \tag{5}$$

$$\text{Mode 2 and 5 } CF(\theta_2) = \frac{\hat{e}_{ab}}{\hat{e}_{bc}}, \tag{6}$$

$$\text{Mode 3 and 6: } CF(\theta_3) = \frac{\hat{e}_{ca}}{\hat{e}_{ab}}, \tag{7}$$

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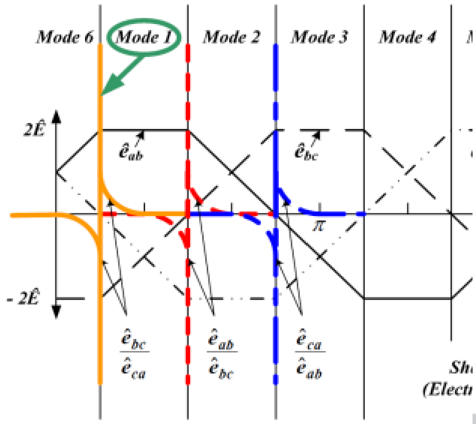

Figure5. Proposed commutation functions.

As shown in Fig. 5, the commutation function for the mode conversion from mode 6 to 1 is represented by the fractional equation consisted of the numerator($\hat{e}_{bc}$) having a constant negative magnitude and thegradually decreasing denominator ($\hat{e}_{ca}$). Before modechange, this commutation function instantaneouslychanges from negative infinity to positive infinity and this moment is considered as the position signal so that this feature can be certainly distinguished from noises by selecting a relevant threshold magnitude. Although a similar commutation function has been reported, the commutation functions of the proposed scheme have the characteristic of less noise sensitive.

C. The estimation of speed and position

If the estimated magnitude of a back-EMF is defined, the rotor position and the speed can be calculated by simple arithmetic. The relationship between the speed and the magnitude of a back-EMF in BLDC motors is:

$$E = K_e \omega_e \quad (8)$$

Where E is a back-EMF magnitude, $K_e$is a back-EMF constant, and $\omega_e$is an electrical angular velocity.

As shown in Fig. 6, the magnitude of the back-EMF is estimated by the maximum magnitude of the line-line back-EMF that the unknown input observer offers. Therefore, the speed can be calculated by using the estimated magnitude of the back-EMF as follows:

$$\widehat{\omega}_e = \frac{\hat{E}}{K_e}, \quad (9)$$

$$\widehat{\omega}_m = \frac{2}{P}\widehat{\omega}_e \quad (10)$$

where$\widehat{\omega}_m$is an estimated mechanical angularvelocity and P is the number of poles.

The rotor position is obtained by integrating the motor speed:

$$\hat{\theta} = \int \widehat{\omega}_e \, dt + \theta_0 \quad (11)$$

where$\theta_0$is the initial position of rotor.

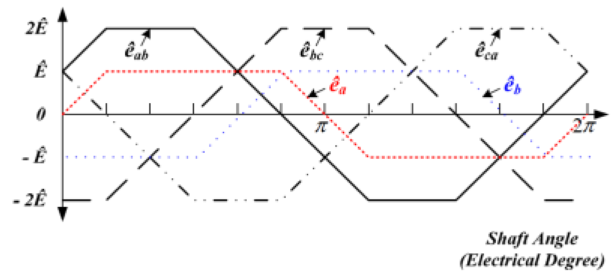

Figure. 6. Relation between the estimated line-to-line back-EMFs and the estimated back-EMFs.

D. Overall structure of the proposed sensorless scheme

Fig. 7 illustrates the overall structure of the proposed sensorless drive system. The line-to-line voltage is calculated based on the DC-link voltage and switching status of the inverter. As described above, the back- EMF observer provides the estimated line-to-line back-EMF. The commutation function the speed and the rotor position are calculated from the estimated line-to-line back-EMFs. The commutation signal generation block generates commutation signals based on the calculated rotor position and the commutation function. Each phase current is controlled by the hysteresis current controller using the commutation signals.

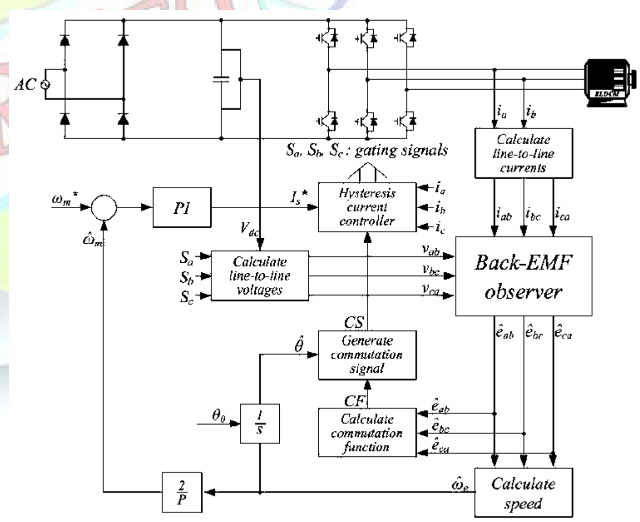

Figure.7. The overall block diagram of the proposed sensorless drive system.

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IV. SIMULATIONMODEL

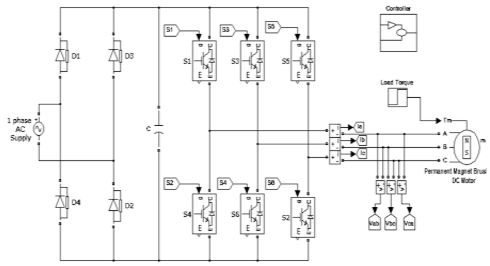


Figure 8.Simulink model of sensorless BLDC motor drive.

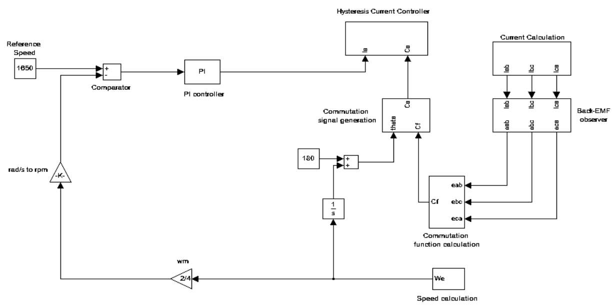


Figure 9.Simulink sub-model – Controller.

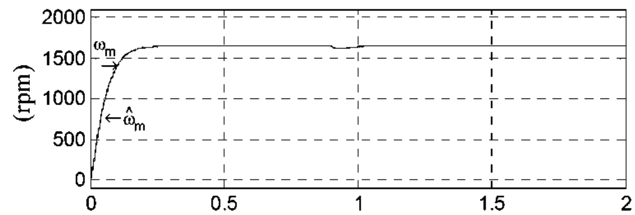
Fig. 8 shows the MATLAB/SIMULINK model of a sensorless BLDC motor drive. It consists of a three phase inverter, BLDC motor, controller, voltage and current measurements. The entire sensorless control is masked inside the controller as a sub-model which is shown in Fig..

Simulations have been performed on the BLDC motor that has the ratings and parameter as shown in Table.

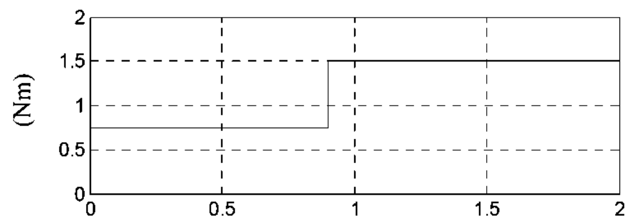
TABLE I. RATINGS AND PARAMETERS OF BLDC MOTOR

Parameter	symbol	Value
Rated voltage	V	310(V)
Rated torque	T_e	1.5(Nm)
Rated speed	N_r	1650(rpm)
Stator resistance	R_r	7.3(ohm)
Stator inductance	L	0.02(H)
Rotor inertia	J_m	23.16x10-4(kg.m2)
Back-EMF constant	K_e	0.25(V/rad/sec)
Number of pole pairs	P_n	2

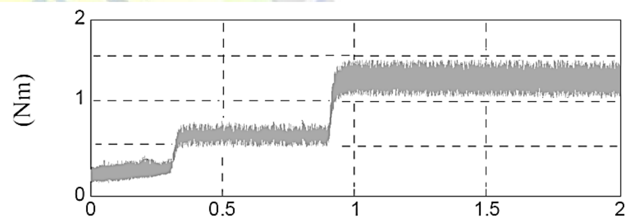
V. RESULTS AND DISSCUSSION



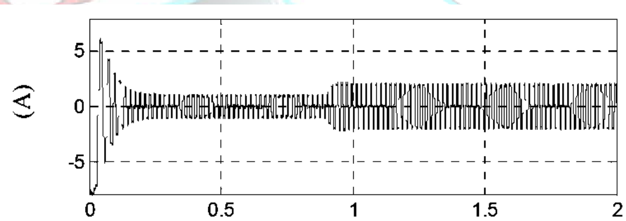
(a) Rotor speed.



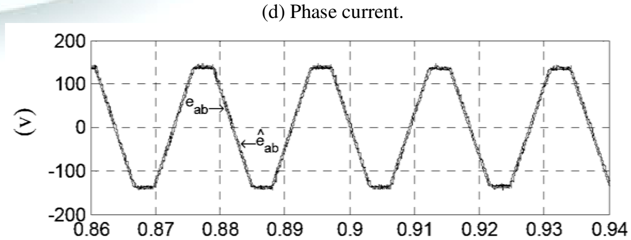
(b) Load torque.



(c) Electromagnetic torque.



(d) Phase current.



(e) Line-to-line back-EMF.

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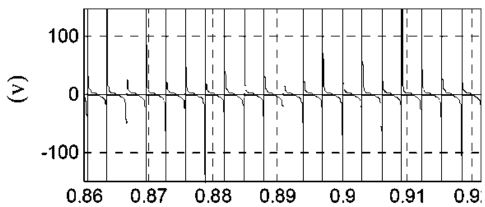
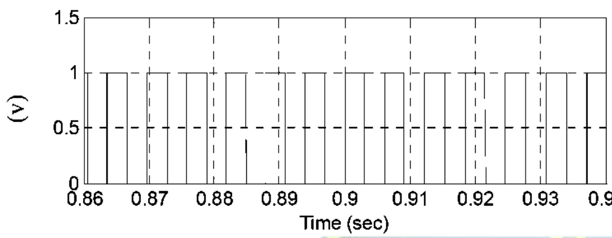
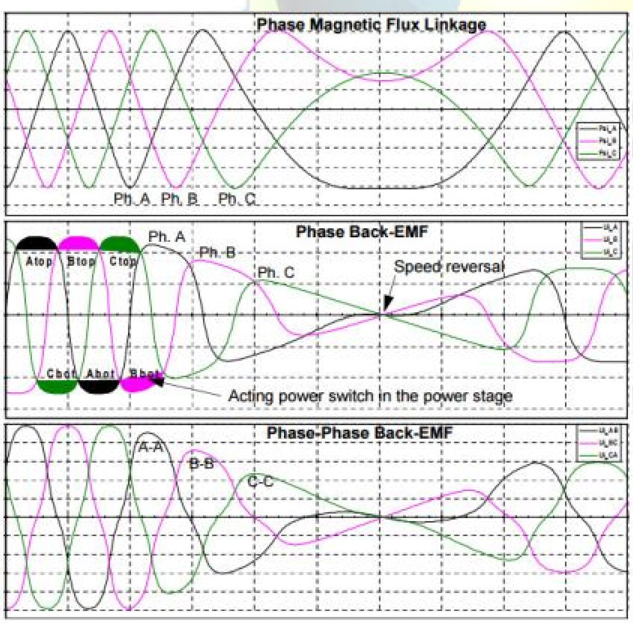


(f) Commutation function.



(g) Commutation signal.

Fig. 10. Response waveforms under step change of load torque. (Speed reference: 1650 rpm, Load: 0.75 → 1.5N.m).



(h) Back Emf and Magnetic Flux

TABLE II. OUTPUT RESPONSE OF SPEED AND TORQUE

Parameter	symbol	Set value	Time response
Rotor speed	N_m	1650 rpm	0.3 sec
Torque	T_e	0.75 N.m(0 sec)	0.3 sec
		1.5 N.m (0.9 sec)	0.1 sec

This paper evaluates the robustness of the sensorless algorithm under variation of speed and load. To test the dynamic behavior of the drive under load fracas, weassertadynamicloadof0.75N.mand1.5N.mtothemotorat0sand 0.9 with the reference speed of 1650 rpm As shown in Fig.10, the speed drops slightly while the phase current increases to reject the disturbance. Note also that the estimated speed tracks the actual speed quite well through the transient. In this profile, the commutation signals are generated when the magnitude of the commutation function is bigger than the threshold magnitude definedby5V. The time response of the speed and the electromagnetic torque is shown in Table . It is clearly verified from this test that the proposed sensorless drive algorithm has good transient response under various speed operating conditions.

VI. CONCLUSION

The sensorless control of a BLDC motor using an unknown input observer technique was modeled and simulated in MATLAB/SIMULINK. The simulation results show that this method can estimate a rotor speed in real time for precise control and can make precise commutation pulse even in transient state. The actual rotor position as well as the machine speed was estimated even in the transient state from the estimated line-to-line back-EMF. Thus the validity of this method is confirmed.

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