A New Sensorless Starting Method for Brushless DC Motors without Reversing Rotation

Yen-Chuan Chang and Ying-Yu Tzou, *Member, IEEE*

Power Electronics Systems and Chips Lab.
Advanced Power Electronics Center
Department of Electrical and Control Engineering
National Chiao Tung Univ., Hsinchu, Taiwan

***Abstract*—This paper presents a new sensorless starting method for brushless DC motors without reversing rotation for unidirectional applications. The method can detect the rotor position at standstill and a specific start-up method is then used to accelerate the motor up to a middle-speed where conventional sensorless control algorithms based on the back-EMF can work properly. The proposed scheme employs only one current sensor at DC-link side of the inverter, and can be applied to a motor without knowing its parameters and additional position sensors. As compared with previous approaches, the presented technique can simplify the sensorless position detection procedure and lower the cost. The proposed initial rotor position detection technique has a resolution of 30 electrical degrees, and does not cause any rotor vibration during the detection process. The sensorless starting scheme has been implemented on a single-chip DSP controller (TMS320LF2407A) and experimental results reveal that the starting procedure can work smoothly without temporarily reversing rotation.**

***Index Terms*—brushless dc motor, initial rotor position detection, sensorless start-up control.**

I. Introduction

Permanent magnet synchronous motors (PMSMs) are widely used in various applications on account of high efficiency, high power density, and maintenance free. The conventional PMSM drive systems require Hall effect sensors or encoders to provide necessary information on rotor position and shaft speed. However, these Hall effect sensors are subjected to temperature variations, magnetic field interruptions, need to be specially installed, and unfitted for slim type small motors. Therefore, in recently year, sensorless techniques are used to develop reliable, low cost control strategies for PMSMs.

A common problem associated with the sensorless motor control system is its starting performance. Most sensorless control methods are based on back-EMF or flux-linkage estimation. However, when motor is at standstill or low speed, the measured signal is too small to make precise position estimation. Therefore, there should be a specific starting process in sensorless drive systems. The commonest solution to the problem is the open-loop start-up method by injecting current which is ramped up from low to high frequency. However, with an unknown initial rotor position and combined with possible large static friction, the motor may start to rotate in company with temporary reversing rotation or even unable to startup. Another solution to the problem is to start the motor from a pre-determined rotor position [1]. The procedure is to excite two phases of the three-phase windings for a preset time. The permanent magnet rotor will then rotate to align with the direction corresponding to the induced magnetic filed. With a known commutation logic and initial rotor position, an open loop control scheme is then applied to speed up the motor from standstill. However, during the alignment process there may sometimes cause a reversing rotation or even temporary vibrations, and this is unacceptable for some applications such as electrical vehicles.

To solve the above issues, the alignment process is improved by various initial rotor position estimation techniques. Most initial rotor estimation methods are based on the saturation effect of stator iron core due to the permanent magnet [2]-[3]. In reference [4]-[5], the initial position is identified by comparing the d-axis current after applying voltage pulses. Reference [6] detects the initial rotor position by the time periods of discharge of stator windings, which are excited before discharge. Another initial position detection method combines an iterative sequence of voltage pulses with a fuzzy logic processing of the current response and phase currents derivation based on the DC-link current measurements [7]. The procedure in [8] is based on the large-and-small relationship between the maximum line-to-line emfs (electromotive forces) induced in the armature windings when two windings are excited by the DC voltage source of the inverter. However, these methods have drawbacks being complicated or have to sense the three-phase currents and voltages.

In this paper, a simple initial rotor position detecting method without position sensors is proposed to fulfill a low-cost sensorless motor drive system. The principle of the method is based on the detection of variations of the DC-link current responses by the injection of properly applied voltage vectors. The measured dc-link current is a function of rotor position due to its magnetic field distribution. A simple searching scheme is developed to justify its initial position with a resolution of 30 electrical degrees. Therefore, this method does not need any previous knowledge of the motor

This work was supported by the National Science Council, Taipei, Taiwan, R.O.C. Project no. NSC 95-2221-E-009-338-MY3.

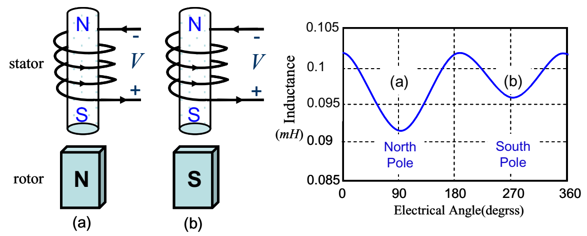

Fig. 1. Stator inductance as a function of rotor flux and stator current.

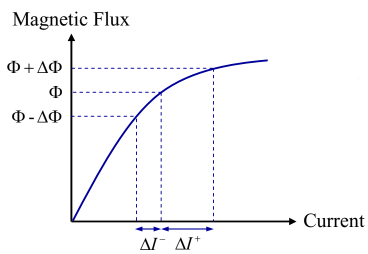

Fig. 2. Nonlinear magnetization characteristics of the stator core.

parameters, and is robust to motor parameter variations. Besides, the estimation process does not cause any rotation during detection process, and is suitable for various applications. After the initial rotor position is determined by the proposed method, a specific starting method is used to speed up the motor to reach a speed at which the rotor position estimation is sufficiently accurate and then the motor is switched to a sensorless speed regulation loop.

II. Initial Rotor Position Estimation

A. Basic Principle

For a surface-mounted PMSM, it is more difficult to detect the initial rotor position than for a salient-pole PMSM, because it has no salience. In order to solve the problem, the magnetic saturation effect of the stator iron core is used. In a PMSM motor, the rotor is permanent magnet and the inductance of the stator windings is function of rotor flux [9]. When the stator windings are aligned with the north or south pole, the inductance will decrease due to the saturation effect. Moreover, when applying a DC voltage to the stator wildings and produces a current which induces magnetic field aligned with the rotor field shown in Fig. 1(a). The magnetic flux will be increased and the stator saturation is increased, too. This results in the decreasing of stator inductance and requires more current to generate the flux $\Delta\Phi$ as shown in Fig. 2. On the other hand, when the induced magnetic field is against the rotor field as shown in Fig. 1(b), the current decreases the magnetic flux by the coil, decreases stator saturation, and slightly increases the inductance compared with no stator current. Consequently, we can identify the position of magnetic pole from the variation in inductance.

A PMSM motor can be modeled as a three-phase R-L circuit. When applying a DC voltage to the windings, the rising time of the current reflects the time constant of the stator windings, which is smaller for smaller inductance as

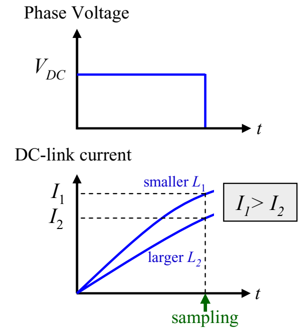

Fig. 3. DC-link Current response with different inductance.

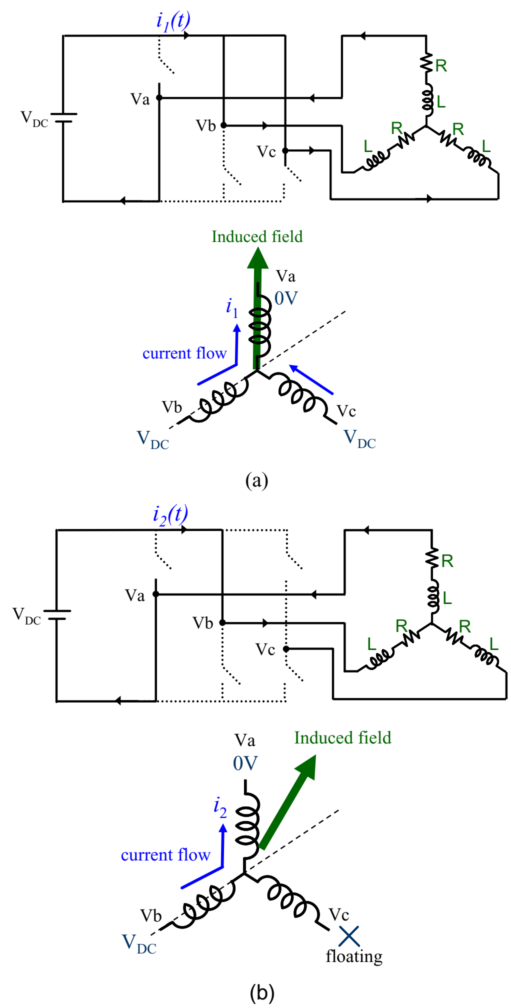

Fig. 4. Current paths of two exciting configurations.

shown in Fig. 3. Since the inductance in the windings is a function of rotor flux, the rotor position reflects the difference of time constant. Therefore, the relative position between a rotor magnet and a stator winding can be determined by the measurement of the current at the end of the voltage vector. Fig. 4(a) and (b) shows two excitation configurations and the current in the stator induce two different directions of magnetic field. When observing the peak value of DC-link current i_1 and i_2 at the sampling time, if i_1 is larger than i_2, then it can be deduced that the rotor

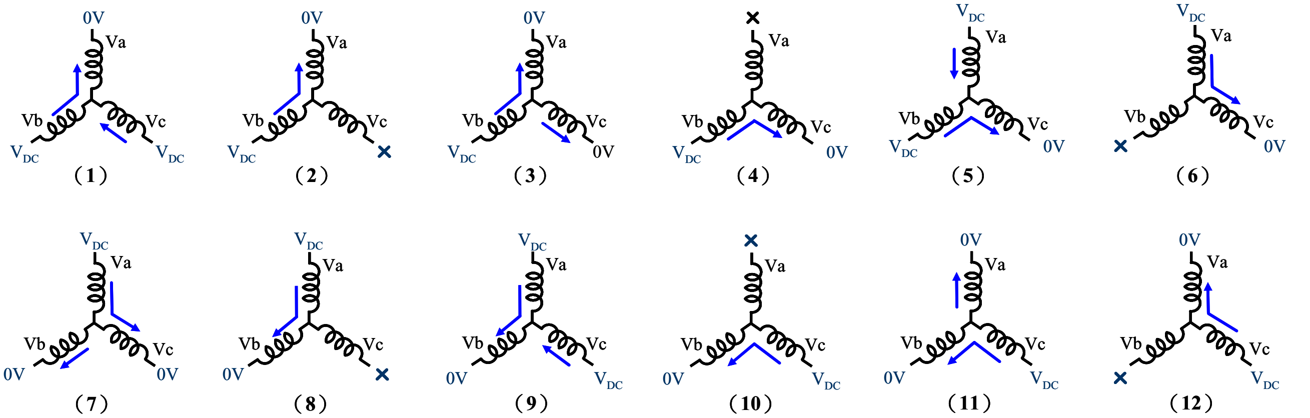

Fig. 5. Twelve excitation configuration.

field is near the field induced by i_1, because of the smaller stator inductance.

B. Initial Rotor Position Estimation Method

Based upon the principle mentioned above, there are twelve excitation configurations can be applied as shown in Fig. 5. The initial rotor position can be determined by comparing the peak amplitude of the twelve DC-link current. Fig. 6 shows the twelve voltage vectors in the estimation process. The voltage vector which maximum value of the DC-link current occurs represents where the permanent magnetic pole is located. For example, Fig. 7 shows the DC-link current response after twelve voltages exciting. There is a maximum peak current value while the exciting configuration is (2) in Fig. 5. Therefore, the permanent magnetic pole is aligned with the magnetic field induced by the exciting configuration (2) in Fig. 5. According to the method, initial rotor position can be detected every 30 electrical degrees, which is enough accuracy to start-up the motor without temporary reversing rotation. The flowchart of the whole estimation procedure is represented in Fig. 8.

C. Injection Timing Control of Voltage Vectors

The initial rotor position estimation is based on the DC-link current response when the voltage vectors applied, therefore the amplitude and the output time of the voltage vectors are important. However, we can determine only the output time of them because the amplitude is decided by the DC-link voltage. The configuration of the applied voltage is divided in two groups. One is shown in Fig. 5 (1), (3), (5), (7), (9), (11), and the other is in Fig. 5 (2), (4), (6), (8), (10), (12). The main differences of them are the equivalent resistance and inductance. For example, the equivalent resistance and inductance in Fig. 4 (a) are 1.5*R* and 1.5*L*, whereas they are 2*R* and 2*L* in Fig. 4(b). To have an identical peak current at the end of the voltage vector, the turn-on time of the voltage vectors should be different. The current response $i_1(t)$ and $i_2(t)$ in Fig. 4(a) and 4(b) can be expressed as

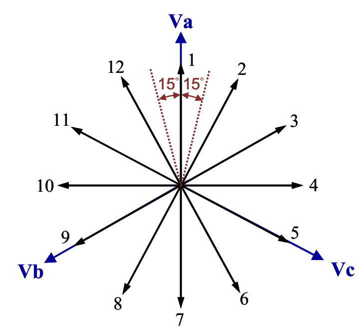

Fig. 6. Voltage vectors in the estimation process.

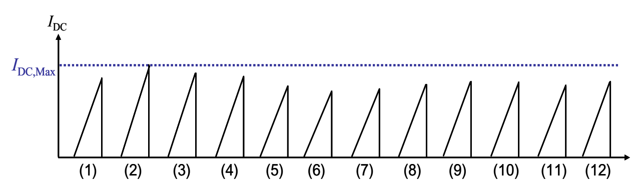

Fig. 7. DC-link current response after twelve exciting voltage vectors.

$$i_1(t) = \frac{V_{DC}}{1.5R}(1 - e^{-\frac{R}{L}t_1}) \tag{1}$$

$$i_2(t) = \frac{V_{DC}}{2R}(1 - e^{-\frac{R}{L}t_2}) \tag{2}$$

where t_1 and t_2 are the turn-on time of the voltage vectors in Fig. 4(a) and (b) respectively. To equalize the peak current response, then

$$i_1(t) = i_2(t)\,. \tag{3}$$

Thus, we can obtain

$$t_2 = -\frac{L}{R}\ln\left(\frac{4e^{-\frac{R}{L}t_1} - 1}{3}\right). \tag{4}$$

As shown in (4), the relationship between the output timing of the voltage vectors can be determined.

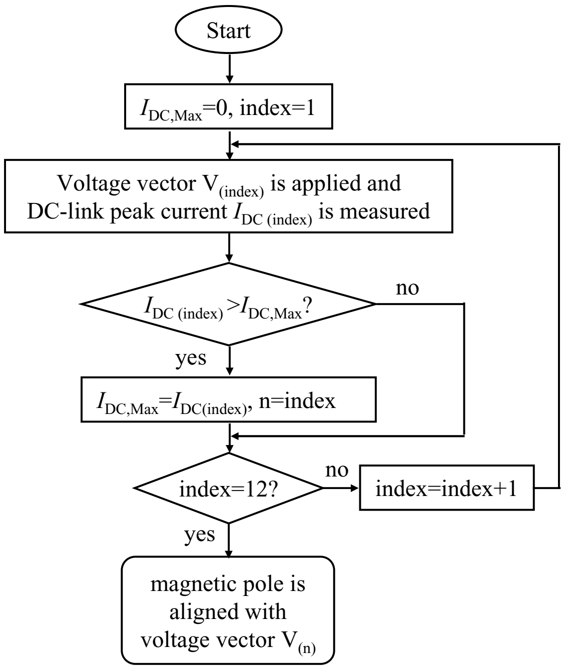

Fig. 8. Flowchart of the initial rotor position detection procedure.

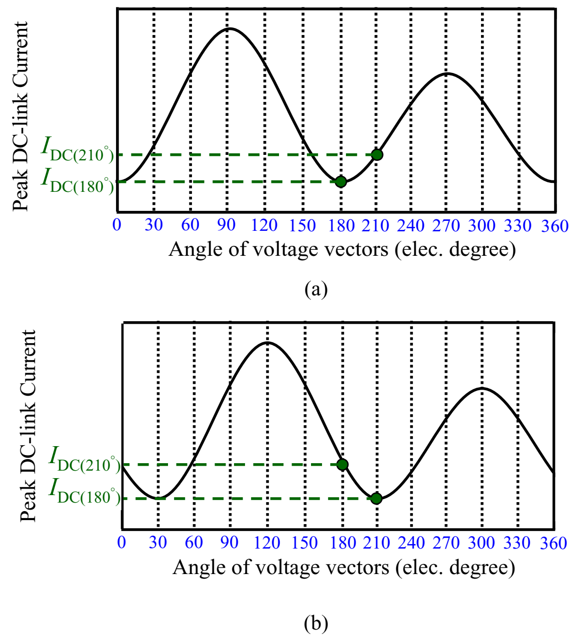

Fig. 9. Peak DC-link current for voltage vectors when the rotor position is at (a) 90 degrees and (b) 120 degrees.

III. Starting Procedure

Most sensorless control schemes based on the back-EMF detection can work properly when operating at medium to high speed control range in steady-state condition. However, it fails when the motor is at standstill or low speed. Therefore, a specific starting method should be used to accelerate the motor to a certain speed which sensorless algorithms can work reasonably.

In this paper, a starting method is presented based on the initial rotor position detection. When starting a motor, the injection of the voltage vectors should be maintain 90 degrees advanced the permanent magnet field in order to get the maximum torque. Once the initial position of the rotor is identified, the starting voltage vector can be determined. However, we have to update the rotor position in the accelerating process. But the detecting method mentioned formerly may produce a reverse torque when motor is rotating. Therefore, a specific starting procedure should be used. For example, when the initial rotor position is at 90 degrees, two voltage vectors that induce magnetic field of 180 degrees and 210 degrees are applied. At this time, the relationship of peak DC-link current $I_{DC(180°)}$ and $I_{DC(210°)}$ is $I_{DC(180°)} < I_{DC(210°)}$ as shown in Fig. 9(a). Then, the motor starts and while the rotor position is around 120 degrees, it becomes $I_{DC(180°)} > I_{DC(210°)}$ as shown in Fig. 9(b). After that, two voltage vectors of 210 degrees and 240 degrees are applied. In this way, the torque can maintain positive in the accelerating process. The starting method can smoothly accelerate the motor without reversing rotation. Besides, it does not rely on the motor parameters and is easily implemented.

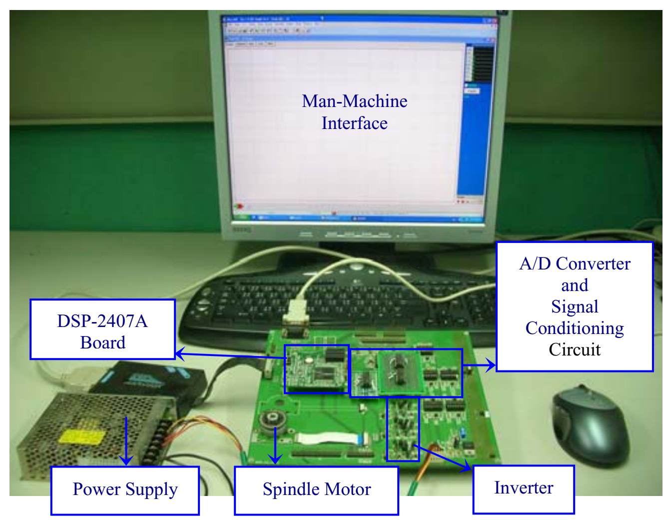

Fig. 10. A view of the implemented experimental system.

IV. Experimental Results

A. System Configuration

Fig. 10 shows the experimental system constructed to verify the proposed method. The DC-link voltage of the inverter is 12 V and the tested motor is a DVD spindle motor. The parameters are shown in Table I. A DSP (TMS320LF2407A) is used to implement the starting algorithms, closed-loop speed sensorless control and communication with PC via RS232 to monitor the position and speed of the motor. The actual motor position is calculated by linear Hall effect sensor signals. The current in the DC-link of the inverter is measured by a current sensing resistor.

TABLE I
PARAMETERS OF THE TESTED MOTOR

3-phase permanent magnet synchronous motor	
Type	Y-connection, 12 poles
Rated voltage	12 V
Stator resistance	0.5 Ω
Stator inductance	0.102 mH
Back-EMF constant	0.423 mV/rpm
Rotor inertia	1.056×10^{-6} kg·m^2
Mech. time constant	0.27 sec

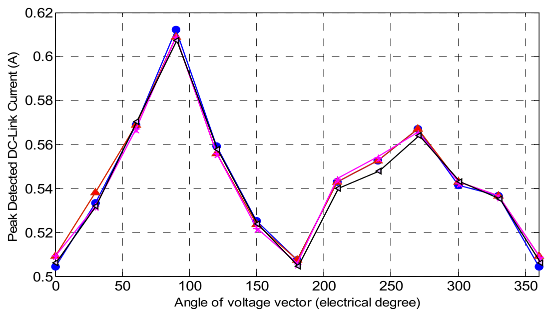

Fig. 11. Measured peak DC-link current when the rotor position is at 90 degrees.

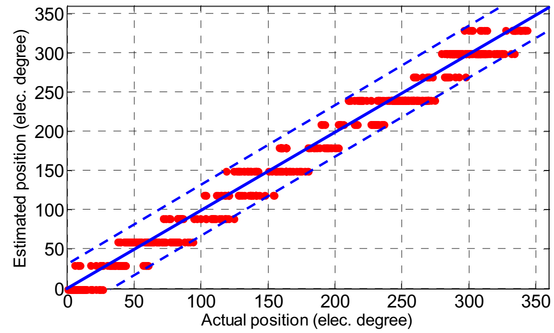

Fig. 12. Statistics of estimated rotor position under variations of real rotor position.

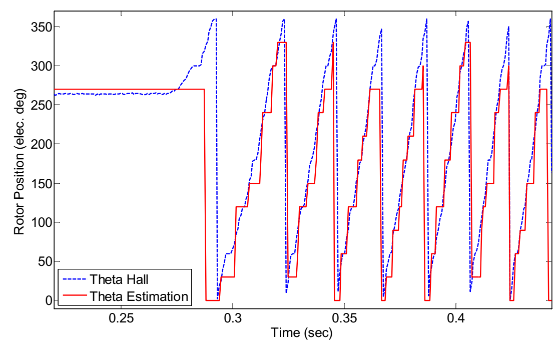

Fig. 13. Start-up response.

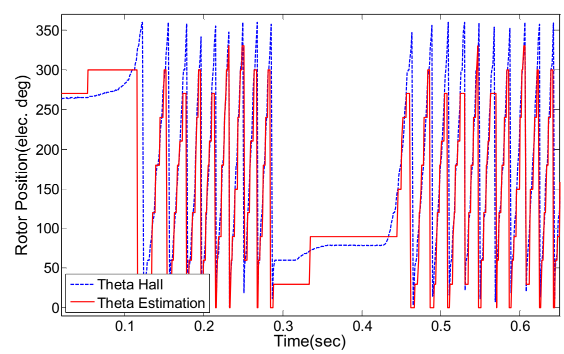

Fig. 14. Start-up response with mechanical disturbances.

B. Experimental Results

In the estimation process, the time duration of the voltage vector in Fig. 4(a) is 10 μs because the current difference between the first and second is larger than 40 *m*A which is enough to differentiate from each other. The time interval between the twelve voltage vectors is 1 *m*s. Fig. 11 shows the peak DC-link current value with different directions of the voltage vectors. The motor is at standstill and the permanent magnetic field is at 90 electrical degrees. Thus, there is a maximum peak value when the direction of the applied voltage vector is 90 degrees.

In order to ensure the estimated position is within a specified accuracy at any possible initial positions, a statistical study of the rotor position estimation with given initial position has been carried out. Fig. 12 shows the statistics of the estimated rotor position as a function of its real position. The statistics lies on the boundary between the two dash lines, and it shows that the maximum estimated error is about 30 electrical degrees. This is enough to start a motor without reversing rotation since it still have a positive torque even in the worst estimation case.

Fig. 13 shows the start-up response with the proposed starting method. It can be seen that the accelerating procedure is smoothly and does not rotates reversely at the beginning. Fig. 14 shows that there is an external disturbance which stops the rotor during the start-up process. The motor can re-accelerate after the abnormal disturbance. Fig. 15 shows a typical closed-loop sensorless speed control response from standstill to 3000 rpm. The proposed starting method is used to implement a completely sensorless control system from standstill to high speed.

V. CONCLUSION

This paper presents a new sensorless starting method for brushless dc motors using only one current sensor for the dc-link current detection. This method does not need any previous knowledge of the motor parameters, and is robust to motor parameter variations. As compare to the previous approaches, the presented technique has advantages of simplifying the detection procedures, lowering the realization cost, and improving the starting torque. Experiment results show that the proposed technique has a

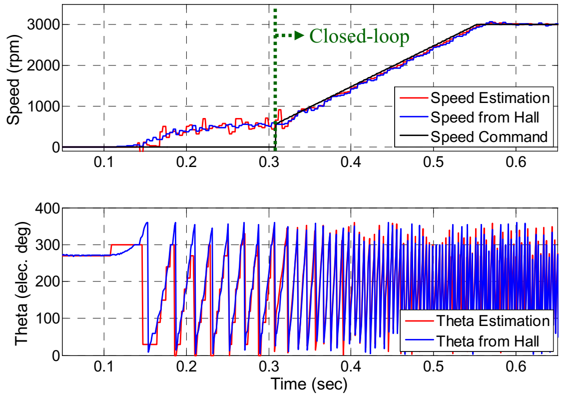

Fig. 15. Sensorless speed control from standstill to 3000 rpm with the proposed start-up method.

resolution of 30 electrical degrees, and does not cause any rotor vibration during the detection and starting process. With the proposed method, the motor can be smoothly accelerated and without a backward starting vibration. The proposed method can also be used for restarting control under large static friction or external disturbances. This Hall sensorless starting method can be used for motor drives employed brushless permanent magnet motors, such as smart fan drivers, spindle drivers, compressor drivers, jogging machine drives, cooling machine drives, and electrical bicycles, etc.

References

[1] S. Ogasawara and H. Akagi, "An approach to position sensorless drive for brushless DC motors," *IEEE Trans. Ind. Appl.*, vol. 27, pp. 928-933, Sept.-Oct. 1991.

[2] W. J. Lee and S. K. Sul, "A new starting method of BLDC motors without position sensor," *IEEE Trans. Ind. Appl.*, vol. 42, pp. 1532-1538, Nov.-Dec. 2006.

[3] G. H. Jang, J. H. Park, and J. H. Chang, "Position detection and start-up algorithm of a rotor in a sensorless BLDC motor utilising inductance variation," *Electric Power Appl., IEE Proc*., vol. 149, pp. 137-142, Mar. 2002.

[4] S. Nakashima, Y. Inagaki, and I. Miki, "Sensorless initial rotor position estimation of surface permanent-magnet synchronous motor," *IEEE Trans. Ind. Appl.,* vol. 36, pp. 1598-1603, Nov.-Dec. 2000.

[5] K. Tanaka, T. Yuzawa, R Moriyama, and I. Miki, "Initial rotor position estimation for surface permanent magnet synchronous motor," *IEEE IAC*, vol.4, pp. 2592-2597, Sept.-Oct. 2001.

[6] Yen-Shin Lai, Fu-San Shyu, and Shian-Shau Tseng, "New initial position detection technique for three-phase brushless DC motor without position and current sensors," *IEEE Trans. Ind. Appl.*, vol. 39, pp. 485-491, Mar.-Apr. 2003.

[7] M. Tursini, R. Petrella, and F. Parasiliti, "Initial rotor position estimation method for PM motors," *IEEE Trans. Ind. Appl.*, vol. 39, pp. 1630-1640, Nov.-Dec. 2003.

[8] J. Sugawara, T. Kaimori, and S. Nishikata, "A novel and simple initial rotor position detecting method for PMSMs," *IEEE PEDS*, pp. 612-617, 2005.

[9] P. B Schmidt, M. L. Gasperi, R. Glen, and A. H. Wijenayake, "Initial rotor angle detection of a nonsalient pole permanent magnet synchronous machine," *IEEE IAC*, vol. 1, pp. 459-463, Oct. 1997.