Sensorless Brushless DC Motor Drive for Frequently Startup

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Abstract - This paper develops a sensorless BLDCM drive for frequently startup. The position information is based on detecting the zero-crossing point of the BEMF that can be directly obtained from the terminal voltage of the floating phase without voltage-dividing and filtering. As a result, this approach makes it possible to detect the rotor position over a wide speed range, especially at a lower speed. A fast startup procedure is also discussed because the induced BEMF signals are not present when motor is at rest. Experimental results shows that the schemes implemented are feasible and the performance achieved are satisfactory.

1. Introduction

BLDCM has been implemented in more and more wide range in recent years due to its outstanding advantages such as high efficiency, high power density, good controllability, and so on. A BLDC motor requires an inverter and a position detector to perform commutation. Conventionally, three Hall sensors are used as a position sensor for the BLDCM. However, the position of the Hall elements must be very precisely fixed, and the sensors themselves add a cost and reliability penalty.

In recent years, many position sensorless BLDCM drives that detect the rotor position and produce the commutation signal from the BEMF, have been studied. It is, however, difficult for a conventional sensorless drive to detect the BEMF in a lower speed because the BEMF is in proportion to the rotor speed. For this reason, the conventional one needs a complicated starting procedure, and the drive starting up frequently will cause plenty of copper loss, and over heat at last due to the long startup time and large startup current.

In this paper, a novel BEMF zero crossing points (ZCP) sensing method was presented to achieve reliable sensorless rotor position with relative concise and low cost circuit. The BEMF can be detected directly from the terminal voltage by properly choosing the PWM and sensing strategy. The PWM signals are only applied to high side switches and the BEMF is detected during PWM off time. Since no voltage-dividing or filtering of the BEMF signals is required, the position detection can be achieved over a wide speed range, especially at a lower speed. In this paper, principle of such a sensorless scheme is illustrated in detail. Meanwhile, thanks to the precise detection of BEMF ZCP, a quick motor startup procedure is achieved with concise logic.

2. Principle Of Sensorless Control

2.1 Relation between phase BEMF and commutation

Generally, a self-controlled BLDCM with trapezoidal BEMF waveforms is driven by a three-phase inverter with 6-step commutation. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conducting phase is called one step of two phase conducting. The conducting interval of each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60°, and the commutations occur at 30° delay from the corresponding zero-crossing points (ZCP) of the BEMF waveforms. Fig.1 shows the typical inverter configuration, Fig.2 shows the relation between phase BEMF and commutation.

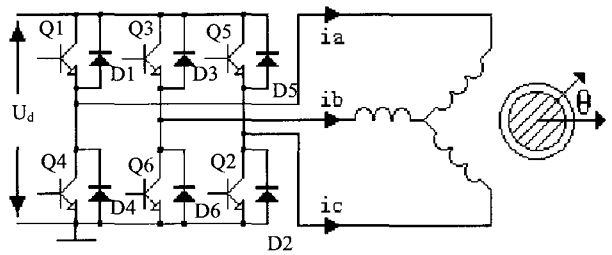

Fig. 1 Inverter configuration

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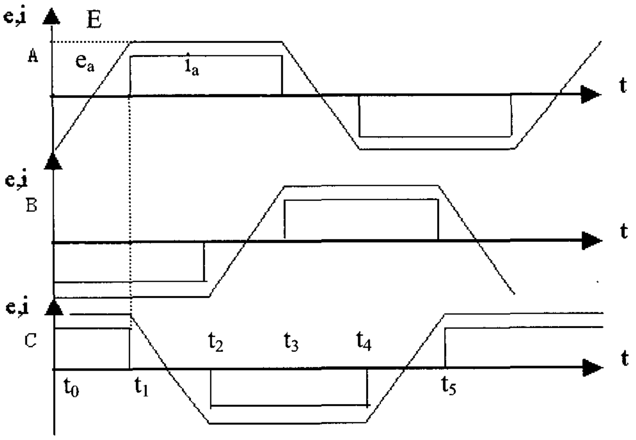

Fig. 2 Relation between BEMF and commutation instants

2.2 Obtain BEMF zero crossing information from the terminal voltage

If the proper PWM strategy is selected, the BEMF voltage referred to ground can be extracted directly from the terminal voltage of the floating phase. There are usually two ways of handling the PWM switching: 4-quadrant chopping and 2-quadrant chopping. In 2-quadrant chopping, only one of the two simultaneous-conducting switches is in PWM chopping. Taking the 2-quadrant pattern with high-side or low-side chopping pattern for example, in the high-side (low-side) chopping mode, the low (high) side switch is kept ON during the 120-degree interval and the high (low) side switches switch according to the pulsed signal. In the 4-quadrant chopping technique both of two switches corresponding to the two phases in ON mode are driven by the same signal: the two switches are turned-on and turned-off at the same time

In this paper, PWM on the high side is selected. Assuming at a particular step AC-, phase A and C are conducting current, and phase B is floating. The upper switch of phase A Q1 is controlled by the PWM and lower switch of phase C Q6 is on during the whole step. The terminal voltage of v_b is measured where the forward voltage of the switches and diodes are neglected.

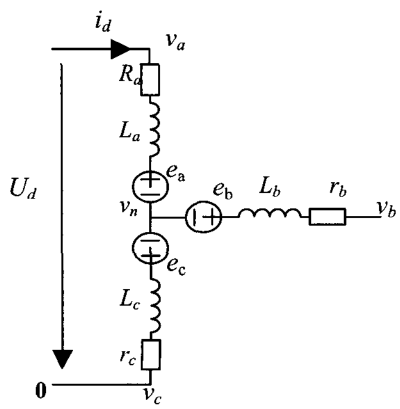

Fig. 3 Equivalent circuit of the step AC- during PWM

When Q1 is on, the current is flowing thought phase A and phase C. Then the equivalent circuit of the three phases for the step AC- is shown in Fig.3.

The following equations can be obtained from the equivalent circuit.

$$
\begin{aligned}
&v_a = U_d = r_a i_d + L_a p i_d + e_a + r_c i_d + L_c p i_d - e_c \\
&v_c = 0 \\
&v_n = r_c i_d + L_c p i_d - e_c \\
&v_b = v_n + e_b = r_c i_d + L_c p i_d - e_c + e_b
\end{aligned} \tag{1}
$$

In an ideal 3-phase symmetrical BLDCM, the winding impedances are equal to each other, i.e. $r_a = r_b = r_c$, $L_a = L_b = L_c$. Similarly, the three phase BEMFs are balanced, so that during this step AC-, there's e_c = $-e_b$ = E. Now the following equations can be induced

$$
\begin{aligned}
&v_n = \frac{U_d}{2} \\
&v_b = \frac{U_d}{2} + e_b
\end{aligned} \tag{2}
$$

Thus, the terminal voltage during PWM on is modulated by the BEMF.

When PWM OFF, Q1 is turned off, due to the operation of PWM control, the inductance of winding A and C maintains current i_d, flowing through D4 paralleled with the lower switch of phase A. In this case, the equivalent circuit is shown in Fig.4, and corresponding equations are list as follows.

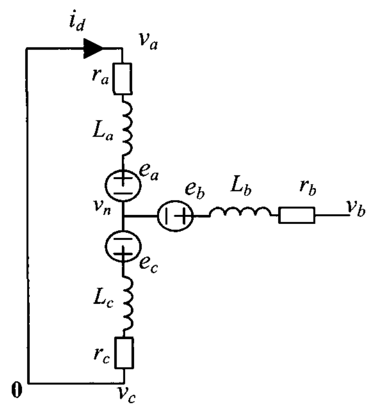

Fig. 4 Equivalent circuit of the step AC- during PWM off

$$
\begin{aligned}
&v_a = 0 = r_a i_d + L_a p i_d + e_a + r_c i_d + L_c p i_d - e_c \\
&v_c = 0 \\
&v_n = r_c i_d + L_c p i_d - e_c = 0 \\
&v_b = v_n + e_b
\end{aligned} \tag{3}
$$

When $e_b \geq 0$, $v_b = e_b$; and when $e_b < 0$, v_b is clamped to zero by D4.

From the above equations, it can be seen that during the off time of the PWM, which is the current freewheeling period, the terminal voltage of the floating phase is proportional to the BEMF voltage without any superimosed switching noise. It is also important to note that this terminal voltage is directly referred to the Ground instead of the floating neutral point. Moreover, since the BEMF is extracted from the terminal voltage, the zero crossing of the BEMF can be detected very precisely without low pass filtering and voltage dividing. Consequently, it is possible to detect the rotor position over a wide speed range, especially at a lower speed, and to simplify the starting procedure.

2.3 Unattenuated BEMF ZCP Detecting

A specially designed circuit as shown in Fig.5 can be applied to detecting the BEMF ZCP, wherein only the detecting circuit of phase B is example. A voltage comparator P has a non-inverting input connected to a node M, via a resistor R1 and forward diode D1 in series to the free end of phase B, and to the auxiliary +15V voltage supply by resistor R2. The comparator also has an inverting input connected to a node N, symmetrically to the non-inverting input, except a resistor R4 and forward D2 in series to the ground voltage GND. The output CompOut of the comparator P is connected to an input of latch D, controlled by an enable signal ValidComp. The output of the latch D is a BEMF ZCP detection signal, BemfZcp, connected to CPU. This circuit is repeated three times, each for each phase. Diode D1 blocks off the high rate terminal voltage (in fact, what we are interested in is around 0V) so that the comparator P is suitable to be implemented. Resistor R3 and R4 just provide a reference voltage for voltage comparison, and diode D2 is to compensate the forward voltage of D1.

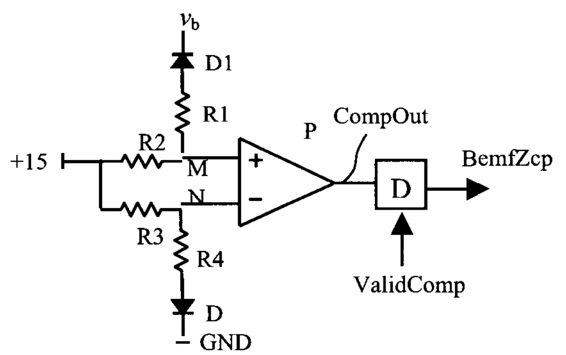

Fig. 5 Unattenuated BEMF ZCP detecting circuit

Fig.6 shows a voltage-time signal for the terminal voltage of the floating phase B during the step AC-, referenced to ground voltage GND and ignoring the commutation interval. The time axis is magnified to enable visibility of the PWM control. The voltage of the node M, u_M, the ValidComp signal for enabling the latch D and the output BemfZcp of the latch are also shown. The terminal voltage during PWM ON is modulated by the BEMF in phase B. During PWM off, when the BEMF is less than zero, the terminal voltage v_b is clamped to zero by D4. At an instant t_z, a BEMF zero crossing occurs. After t_z, the BEMF is positive. Instant t_z is thus the zero crossing point (ZCP) that needs to be detected.

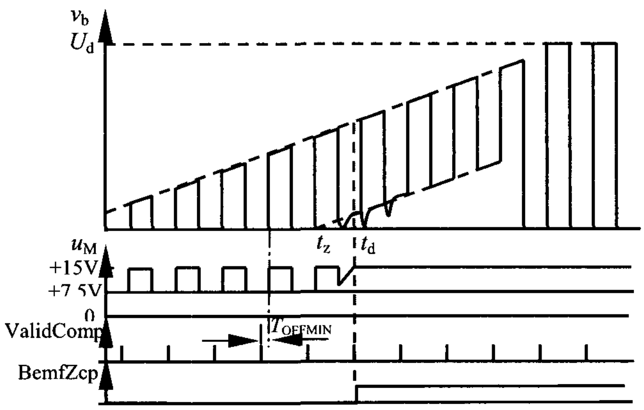

Fig. 6 Illustrative diagram of unattenuated BEMF ZCP detecting

It can be seen that during the PWM off period, the voltage v_b always goes to the ground level. This is due to the discharging procedure of the parasitic capacitance inherent in the switches and motor. So the value of the BEMF can only be meaningfully measured near to the end of a PWM off period. Since the control of the motor is performed by the CPU, the BEMF sampling instant can be easily timed, because the CPU knows when the end of each PWM off period will be.

Consequently, T_{OFFMIN}, as shown in Fig.6, must be provided to allow sampling the BEMF. The ValidComp signal is generated synchronously by the CPU according to the timer that is used to generate the PWM signals.

As shown in Fig.6, The BEMF has crossed the zero value at around instant t_z, while the positive BEMF value is detected as a change in signal BemfZcp when the next ValidComp signal comes at time t_d. Detection of BEMF ZCP is thus performed to the next cycle of PWM. For a 5kHz PWM, this will introduce a maximum error of only 200μs.

In addition, at the beginning of the step AC-, winding A remains connected to supply voltage U_d by PWM control of Q1, winding C becomes connected to ground GND. Due to the presence of inductive element, the current previously circulating in winding B i_b is maintained through diode D3 to supply voltage U_d, until all the energy stocked in winding B is dissipated. Consequently, before i_b decreased to zero, there is a short interval when all three phases are conducting current, and v_b equals to U_d, which is called commutation interval. The detection must be blocked during this interval in order to avoid being falsely triggered.

The commutation algorithm used is the standard BLDCM control algorithm as described before, in other word, the commutation is to be performed 30 electrical degrees after the BEMF ZCP. The delayed time can be computed from the interval between the last two consecutive BEMF ZCP or the previous two consecutive BEMF ZCP. The previous BEMF ZCP is intended for compensation in case of dissymmetrical motors. Also, the delayed time can be easily adjusted by software according to the motor characteristics, application environment and the speed. For some high-speed applications, commutation can be performed in advance to compensate for the delay caused by the motor winding inductance.

2.4 Startup without orientation

As discussed in above sessions, once the motor is operating, the rotor position can be detected from the BEMF ZCP. Nevertheless, when the rotation speed of the motor is very low, the BEMF is too low to accomplish the zero crossing detecting successfully. Especially, when the motor startup from rest state, the BEMF equals to zero, and therefore contains no any rotor position information at all. Thanks to the precise detection of BEMF as described above, a quick motor startup procedure is achieved with concise logic.

Fig. 7 shows the torque curves of the motor in relation to different phase of excitation, as well as the corresponding curves of the three BEMFs. For each excited phase, for example AB-, the rotor tends to dispose itself in coincidence with the stable equilibrium points t180. Moreover it is evident that by exciting the phase AB- while the rotor is at rest, either a forward motion, or a backward motion, or no motion at all may occur, as shown in Tab.1, where the (-) sign of the torque means that the torque will startup a motor in a backward direction of rotation. The sign of the BEMF of the floating phase C is also shown, when the rotor runs in forward motion as shown in Fig.7. And when the motor changes direction of rotation, the BEMF will change sign correspondingly. This means that upon an inversion of rotation, a "pseudo ZCP" is generated and this pseudo ZCP is useful for the startup algorithm of the paper.

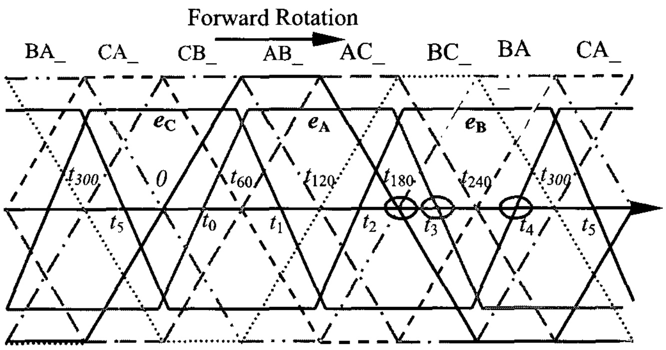

Fig. 7 Startup torque and BEMF

Table 1 Relation between torque and BEMF during startup

Rotor position	Torque	BEMF of phase C	Rotation direction
0~t1	+	+	Forward
t1~t180	+	-	Forward
t180~t4	-	-	Backward
t4~0	-	+	Backward
t180	0		Rest

As described previously, usually, the delay from phase BEMF ZCP to the next commutation is 30 electrical degrees to keep the phase current in phase with the corresponding BEMF. But in the startup, the delay will import a large amount of phase delay or commutating error. The reason is that the time of 30° is unknown at the first step. Since we don't know the position of the rotor before starting and a pseudo ZCP due to an inversion of rotation is used in this startup method as later discussed, when we have detected the first BEMF ZCP (include the pseudo ZCP), the only thing we do know is the interval between the first commutation and the first ZCP.

The procedure starts by exciting two predefined phases (it is irrelevant which phase is predefined and in the following description and in the set of examples which follows the phase AB- is supposed to be the predefined phase) to call the rotor toward the equilibrium point t180 as shown in Fig.7, for a preset time necessary to avoid parasitic detection and to accelerate the rotor, depending on its inertia characteristic. After that, the BEMF ZCP detecting, as described in the previous section, is enabled. Once the first BEMF ZCP (include the pseudo ZCP) of the floating phase C is detected from positive to negative (it is assumed that the output of BEMF ZCP detecting is positive when the speed is too low to detect the BEMF or when the rotor is at rest), the commutation is switched to the next phase immediately, which is called ZCP-commutation. After a number of consecutive ZCP occurred with the ZCP-commutation, the motor reaches a speed at which the ZCP is reliable without pseudo ZCP, it comes to switch to self-control. Once the motor is switched into self-control mode, the commutation signal is to be generated from the delay 30o after the corresponding ZCP, and the speed regulation is introduced too.

The different possible situation at startup according to Tab.1 and the relative behavior of the motor in performing the startup procedure is to be examined in detail following.

2.4.1 Startup of the rotor from 0~t1

By exciting the AB-phase for a preset time, the motor is accelerated in a forward direction of rotation due to the active torque, and the BEMF of phase C that is floating is positive. When the preset time has elapsed, the detection of the BEMF ZCP is enabled. A ZCP from positive to negative is detected when the rotor comes to t1, and the commutation occurs immediately, switching to the next phase AC-. The rotor accelerates in forward direction. Once the second BEMF ZCP detected at t2, the phase BC- is connected no phase delay. After several ZCP-commutation, it comes to self-control mode.

2.4.2 Startup of the rotor from t1~t180

By exciting the AB-phase for a preset time, the motor is accelerated in a forward direction of rotation due to the active torque, while the BEMF of phase C that is floating is negative. When the preset time has elapsed, the detection of the BEMF ZCP is enabled. There is no ZCP until the rotor comes to the equilibrium point t180. Due to the inertia of the motor and the load, the rotor wouldn't stop at the equilibrium t180. Once the rotor comes through the t180, the torque produced by the current AB- becomes passive. Therefore the motor stops and changes direction. Upon the change of direction of rotation of the rotor, the relative BEMFs also switch polarity. This presents a pseudo ZCP, the BEMF of phase C becomes positive. Then the rotor runs to t180 in backward until it comes through t180 again. Immediately the rotor running through t180, the rotor stops and changes direction to forward due to the active torque. A pseudo ZCP of phase C is detected from active to negative, and the ZCP-commutation is performed, switching to the next phase AC-. The rotor accelerates in forward direction. Once the BEMF of the floating phase B is detected positive, ZCP-commutation is switched to the next phase BC-. After several ZCP-commutation, it comes to self-control mode.

2.4.3 Startup of the rotor from t180~t4

By exciting the AB-phase for a preset time, the motor is accelerated in a backward direction of rotation due to the passive torque, while the BEMF of phase C that is floating is positive. When the preset time has elapsed, the detection of the BEMF ZCP is enabled. There is no ZCP until the rotor comes to the equilibrium point t180. Due to the inertia of the motor and the load, the rotor wouldn't stop at the equilibrium t180. Once the rotor comes through the t180, the torque produced by the current AB- becomes active. Therefore the motor stops and changes direction to forward. Upon the change of direction of rotation of the rotor, the relative BEMFs also switch polarity. This presents a pseudo ZCP, the BEMF of phase C becomes negative. Then the ZCP-commutation is done immediately to the next phase AC-, The rotor accelerates in forward direction. Once the BEMF of the floating phase B is detected positive, ZCP-commutation is switched to the next phase BC-. After several ZCP-commutation, it comes to self-control mode.

2.4.4 Startup of the rotor from t4~0

By exciting the AB-phase for a preset time, the motor is accelerated in a backward direction of rotation due to the passive torque, while the BEMF of phase C that is floating is negative. When the preset time has elapsed, the detection of the BEMF ZCP is enabled. A ZCP from negative to active is detected when the rotor comes to the points t4. Ignoring this ZCP, the conducted phase is still AB-, the following process is the same as startup of the rotor from t180~t4 as described above.

2.4.5 Startup of the rotor from t180

As we know, the rotor is at rest in an equilibrium point t180 of the excited phase AB-, it would not receive any acceleration because the applied torque will be null. This particular situation will be recognized by that there is no ZCP when the maximum startup time has elapsed. With reference to Fig.7, the new phase to be excited in order to obtain the maximum torque in forward direction will be a phase shifted by 120° from the preset phase, i.e. the phase BC-. Then the next commutation to BA-is to be performed once the BEMF ZCP of phase A is detected. After several ZCP-commutation, it comes to self-control mode.

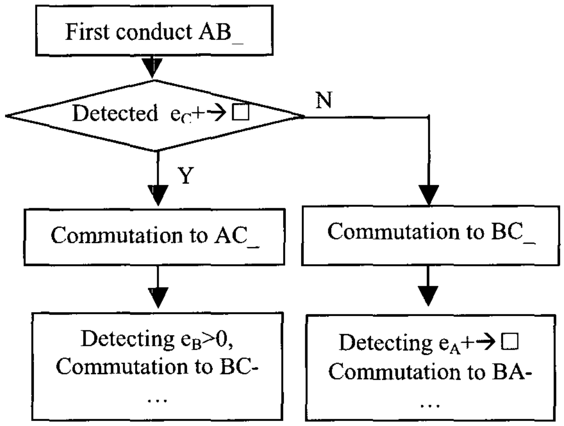

Fig. 8 Startup logic

From the above analysis, the startup logic can be obtained as shown in Fig.8.

It is evident that the initial rest position of the rotor from t1~0, there is a backward rotation at the startup instant. In practice, in the worst case, the maximum backward rotation of the rotor that may occur is about 180 electrical degrees.

3. Experimental Results

Based on the above control method, a sensorless BLDCM drive for frequently startup is developed. The experimental results both on the steady state operation and startup procedure are given below and described in detail. In this test, the switching frequency of the PWM is 5kHz. The BLDCM Model 90*ZW* is applied under test. The nominal parameters of it are listed in Appendix

3.1 Steady state waveforms

Fig.9 shows the stead state waveforms at high speed, where the top wave is terminal voltage va, referenced to ground voltage GND, the mid wave is the phase current ia, and the bottom wave is BEMF ZCP signal. The BEMF of the floating winding is extracted from the terminal voltage during the PWM off period, and each toggling edge of ZCP signal corresponds to the zero-crossing of the BEMF. The commutation occurs at 30° delay from the corresponding ZCP of the BEMF as Fig.9 demonstrated clearly.

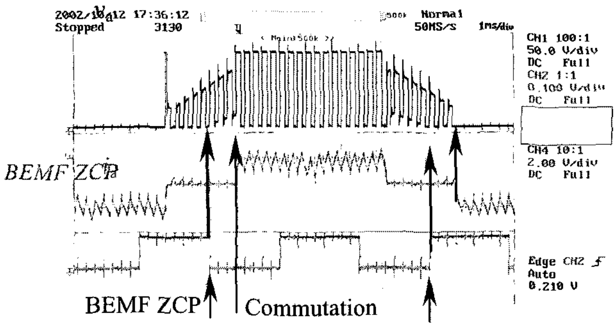

Fig. 9 Sequence of BEMF ZCP and phase commutation

As described before, unatteuatted BEMF ZCP detection has very good resolution. Thus it can be used in applications where the rotor speed is low, when the amplitude of BEMF is low. Fig.10 shows the waveforms at low speed, 100rpm. It can be seen that the features are satisfactory as well as that at high speed. The system can function very well even when the peak of BEMF is less than 1V. The motor speed can be extended to very wide range 60~3000rpm (1:50).

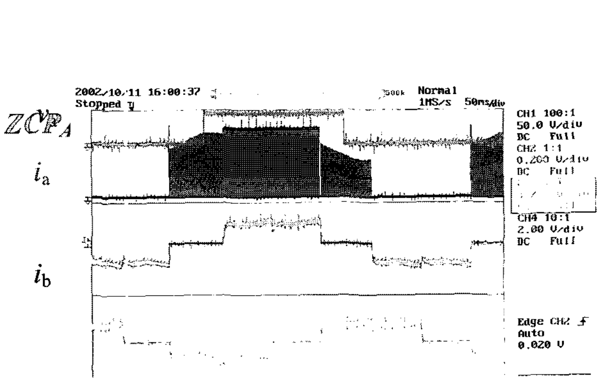

Fig. 10 Steady state waveform, at low speed=60rpm

3.2 Startup without orientation

The waveforms during startup procedure are shown in Fig.11 with different possible situation as described in Tab.1. At each of them, the top wave is terminal voltage va, the second wave is the phase current ia, the third wave is the phase current ib, the bottom wave is the BEMF ZCP signal. Each toggling edge of the ZCP signal corresponds to the zero crossing of the BEMF.

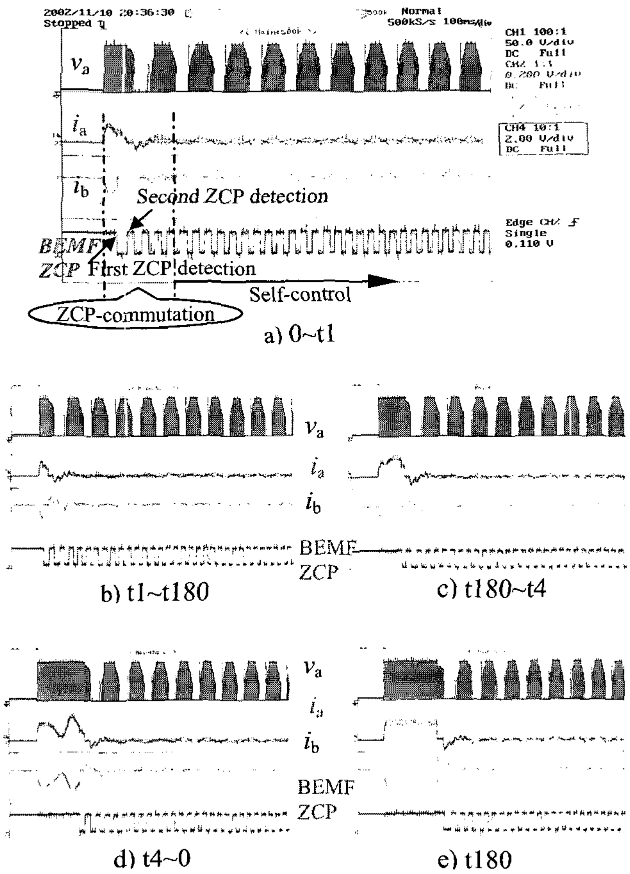

Fig. 11 Startup feature with different position

It shows clearly that the procedure starts by exciting the predefined phase AB-, the ZCP-commutation is to be performed once the first ZCP detected. After several consecutive ZCPs occurred with the ZCP-commutation, the motor is switched to self-control. Also, it can be seen that the phase currents decrease to a level much less than the previous period after the second ZCP detected, and decrease further when the motor comes to self-control. The startup time Ts is less than 250ms, where Ts is the interval between exciting the first predefined phase and the instant the second ZCP detected.

A drawback of this startup procedure is a possible backward rotation during the first exciting the pre-defined phase AB-. In practice, the maximum backward rotation of the rotor is about 180 electric degrees

4. Conclusion

A novel BEMF sensing method was presented in this paper with relative concise and low cost circuit. The BEMF can be detected during PWM off period because the terminal voltage of the floating phase is directly proportional to the BEMF during this interval. Since no voltage-deviding or filtering of the BEMF signals is required, the position detection can be achieved over a wide speed range (1:50). The capability of position sensorless drive at the low speed makes a great contribution to simplify the starting procedure. A quick motor startup procedure is achieved with concise logic. The test results show that the schemes implemented are feasible and the operation performances are satisfactory.

Appendix

The nominal parameters of the BLDCM

Model: 90*ZW*
Stator windings type: 3-phase 3-line, Y-connect
Pole pair p: 3
Rated output power P_N: 750W
Rated speed: 3000rpm (150Hz)
Armature resistance R_p: 3.3ohm
Back electromotive force coefficient K_e: 1.66V/Hz
Rated Torque Tn: 2.4N*m

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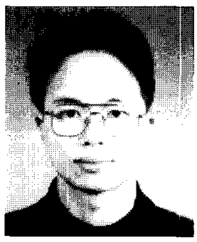

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