2010 International Conference on Electrical and Control Engineering

A Novel Starting Method of Sensorless BLDC Motors for Electric Vehicles

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Abstract—**A novel starting method of the brushless DC (BLDC) motors without position sensor for electric vehicles (EV) is proposed, including detecting of rotor position at standstill and a start-up method to accelerate the rotor up to a certain speed where the conventional position sensorless control methods based on the back EMF could work effectively. The whole starting procedure is accompanied with rotor position estimation, which can avoid the temporary reverse rotation and the starting failure of electric vehicles. The principle of the estimation is based on the variation of the current response caused by the magnetic saturation of the stator core of BLDC motor when the current flows along the magnetic axis. Further more, specific strategies of starting torque optimization and noise reduction are developed to start electric vehicles quickly and smoothly. This method is implemented with only one current sensor at the DC bus of the inverter and a low-cost general-purpose microcontroller, which becomes a simple, compact, low-cost, and effective solution for sensorless BLDC motors in the field of electric vehicles. It is demonstrated experimentally that a rapid and stable starting can be achieved by the proposed method.**

Keywords- BLDC; sensorless; electric vehicle; inductance saliency; starting; torque optimization

I. INTRODUCTION

Recently due to the advantage of energy-saving and environmental protection many kinds of electric vehicles (such as electric bicycle, electric wheelchair, and electric car) have been widely used. Brushless DC (BLDC) motors dominate the field of drive motors for electric vehicles, because of their simple structure, high efficiency, and excellent performance of speed regulation. Conventional brushless DC motors use position sensor to provide commutation signals, which will increase motor size, system cost and maintenance difficulty. Utilizing sensorless control technology will not only save the considerable cost and space for position sensor, but also simplify the procedures of system assembly and maintenance. Once sensorless control technology becomes mature, it will lead to a significant revolution in the electric vehicle industry.

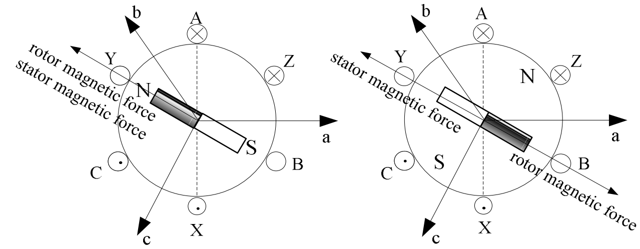
Among various sensorless control strategies for the BLDC motor, the sensorless control method based on the detection of zero crossing point (ZCP) of back-electromotive force (EMF) has been widely used in low-cost applications because of its simplicity. But when the motor is at standstill or at low speed, it is impossible or very difficult to get the position information from back-EMF. Therefore, a special starting method is generally needed. “Align and go” is one of the popular starting methods, which aligns the rotor of the BLDC motor to a certain position by energizing any two phases of the stator windings, then provide a rotating stator field with magnitude and frequency increasing gradually, to accelerate the rotor until the ZCP signal of back-EMF is available. This method will cause the reverse rotation of motor, which is not allowed for the starting of electric vehicles. On the other hand, the electrical and mechanical parameters such as the torque constant, the friction coefficient, and the inertia of the rotor should be considered for a stable starting performance. For electric vehicles, different road condition and passenger weight will lead to various load torque and some unexpected disturbance. Therefore open-loop starting method such as “align and go” is not suitable for electric vehicles.

This paper proposes a novel starting method using motor inductance saliency, which is applicable for electric vehicles. It consists of an initial rotor position estimation algorithm and a rotor acceleration algorithm with position feedback. The whole starting procedure is coupled with the detection of the rotor position, which can avoid reverse rotation and starting failure.

II. INITIAL ROTOR POSTION ESTIMATION

A. *The principle of inductance saliency*

In interior PM BLDC, the permanent magnet rotor has salient poles. The saturation of magnetic field depends on the relative location of rotor magnetic force and stator magnetic force, so the equivalent inductance of a stator winding varies due to the saturation effect.



(a) Demagnetization effect (b) Enhanced magnetic effect

Figure 1. Interaction of rotor and stator magnetic forve

978-0-7695-4031-3/10 $26.00 © 2010 IEEE
DOI 10.1109/iCECE.2010.784

Two kinds of interaction of rotor and stator magnetic force are shown in Fig. 1. One is demagnetization effect with equivalent inductance L_1 in Fig. 1(a), the other is enhanced magnetic effect with equivalent inductance L_2 in Fig. 1(b). The equivalent inductance will be smaller in a more saturated magnetic field, so $L_1 < L_2$. In conclusion, the equivalent inductance of field winding is relative to the rotor position.

B. *Initial rotor position estimation method*

In fact, winding inductance can not be measured directly. It can only be obtained by comparing the rate of change of the current flowing through the stator winding. In order to create different equivalent inductances when rotor position is fixed at standstill, voltage vectors with different directions will be applied to the stator windings.

For the three-phase BLDC motors, detection voltage vectors are implemented with three phase windings connected into the circuit simultaneously, shown as Fig. 2. There are six different detection voltage vectors applied alternately for a short constant time, which could be divided into three groups: V_1 (100) and V_4 (011); V_2 (110) and V_5 (001); V_3 (010) and V_6 (101). These detection voltage vectors should be applied group by group, but there is no restriction with regard to the order of the groups, for example, a sequence of "$V_6 \rightarrow V_3 \rightarrow V_5 \rightarrow V_2 \rightarrow V_4 \rightarrow V_1$" could work. As shown in Fig. 2, phase A is connected to the DC bus voltage, phase B and C to the ground, when applying voltage vector V_1 (100).

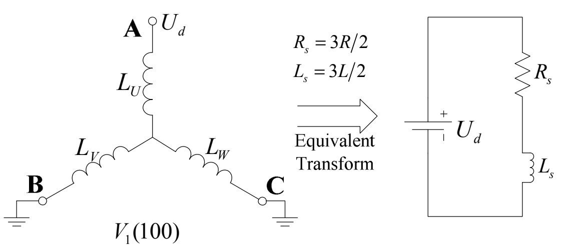


Figure 2. Implement of detection voltage vectors and quivalent circuit

Fig. 2 also shows the equivalent circuit of the motor when applying V_1. At standstill or low speed, back-EMF can be considered equal to zero, so the voltage equation on the stator windings is:

$$U_d = L_s \frac{di}{dt} + iR_s \tag{1}$$

In which, U_s, R_s, L_s represent respectively the DC-link voltage, the equivalent resistance and the equivalent inductance. The current response equation is listed as follow:

$$i(t) = \frac{U_d}{R_s}(1 - e^{-\frac{R_s}{L_s}t}) = \frac{U_d}{R_s}(1 - e^{-\frac{t}{\tau}}) \tag{2}$$

As described in (2), the rate of change of current response is determined by time constant τ ($\tau = L/R$). So at a certain time point T_s (T_s is smaller than the time of magnetic saturation), the current value is inversely proportional to the equivalent inductance of stator windings. In conclusion, when the detection voltage vector has the same direction with the rotor magnetic flux, the equivalent inductance is minimum, and the current sampled at time point T_s reaches the maximum value.

C. *Optimal time duration of detection voltage vectors*

The time duration of the detection voltage vectors is a crucial parameter which should be decided to distinguish the current difference when applying six detection voltage vectors.

According to (2), when applying the same voltage vector to the windings with unequal inductances, the current difference can be expressed as follow:

$$\Delta i(t) = i_1(t) - i_2(t) = \frac{U_d}{R_s}(e^{-\frac{1}{\tau_2}} - e^{-\frac{1}{\tau_1}}) \tag{3}$$

By differentiating (3) according to time, the time duration T_s is equal to the average time constant of stator windings τ_1 when the current difference is maximum. So the optimal time duration should be set near to the motor time constant.

III. ROTOR POSITION CLOSED-LOOP STARTING

After the initial rotor position has been identified with the proposed method, the motor starts to be accelerated from the standstill to a certain speed where the motor reveals sufficiently large back EMF. This paper proposes a novel start-up method with rotor position tracked continuously.

The rotor is accelerated with a rotating magnetic field generated by six drive voltage vectors in a certain sequence. In order to track the rotor position without position sensor, two short detection voltage vectors will be injected behind the drive voltage vector in every acceleration cycle. The rotor will move ahead by a certain angle under the effect of drive voltage vector, and two detection voltage vectors will find out whether the new rotor position is in the expected sector.

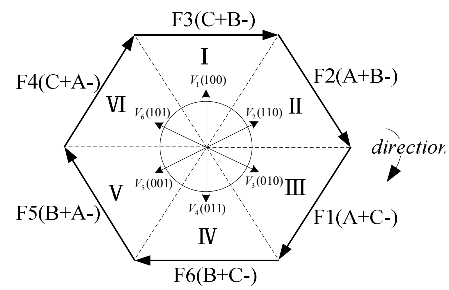


Figure 3. Sequence of voltage vectors in the start-up procedure

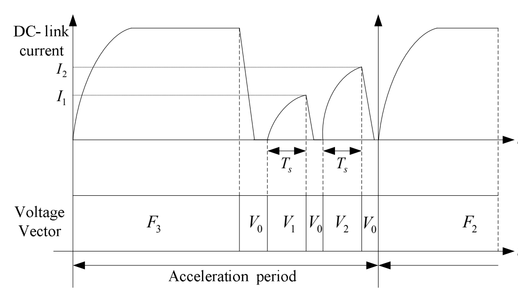


Figure 4. DC-link current waveform and voltage vectors

Fig. 3 illustrates the sequence of voltage vectors and the principle of rotor acceleration in the start-up procedure. The whole region of rotor position is divided into six sectors (Ⅰ-Ⅵ), which corresponds to different detection voltage vector (V_1-V_6) that generates the maximum current response. When rotor is in sector Ⅰ, firstly a long drive voltage vector F3 is applied, thereafter two short detection voltage vectors V_1 and V_2 are injected . Comparing current responses I_1 and I_2, if $I_1 > I_2$, the rotor is still in sector Ⅰ, F3 should be imposed in the next round; if $I_1 < I_2$, the rotor has moved to sector Ⅱ, then drive voltage vector in the next round should be F2. The current waveform in DC-link and the voltage vectors for this case are depicted in Fig. 4. In the figure shown, a zero vector (V_0) is imposed between every two nonzero voltage vectors, whose purpose is to make DC-link current drop to zero, and avoid mutual interference of current responses.

IV. SPECIAL STRATEGIES FOR ELECTIC VEHICLES

Considering some unique features of electric vehicles, such as huge inertia, specific strategies are developed to improve the performance of the proposed starting method.

A. *Optimization of starting torque*

1) Impact of drive voltage vector on starting torque: This paper utilizes a series of drive voltage vectors with step-up frequency and voltage in the starting process, shown as Fig. 5, which not only optimizes current commutation, but also reduces the number of detection voltage vectors applied. By setting up appropriate parameters of step-up frequency and voltage, maximum starting torque can be obtained, and electric vehicles will start up quickly and smoothly.

2) Impact of detection voltage vector on starting torque: During one acceleration cycle of the proposed starting procedure, five voltage vectors (including one drive voltage vector, two detection voltage vectors and two zero voltage vectors) are applied. Only drive voltage vectors produce effective electromagnetic torque. Detection voltage vectors and zero voltage vectors have a negative impact on the starting torque due to the occupation of the PWM inverter and reducing the total time of drive voltage vectors. Further more, detection voltage vectors may generate negative electromagnetic torque, which contribute to rotor vibration and Back-EMF zero-crossing signal error. To avoid that problem, detection voltage vectors are implemented with low DC-voltage by decreasing the PWM duty, shown as Fig. 5.

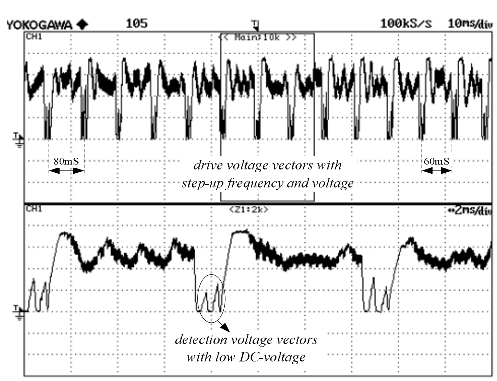


Figure 5. DC-link current waveform utilizing the strategy of starting torque optimization

B. *Noise reduction*

The enormous starting noise without hall position sensor is a serious problem. Considering that stator windings of BLDC motors are inductive, winding current after commutation can not rise up to the level before commutation immediately, which will result in dramatic fluctuation of electromagnetic torque. This is the essential cause of motor vibration and noise. So this kind of vibration and noise can not be completely eliminated, but can be weakened by implementing voltage vectors with 100% PWM duty at the beginning of commutation, which makes the current grow fast and promote the electromagnetic torque to a higher level quickly.

V. EXPERIMENTAL STUDY AND RESULTS

A. *Experiment plaform*

Experiments have been done to verify the feasibility of the proposed method. The experimental subject is an electric motorcycle with rated power of 350W and battery voltage of 48V, whose original controller is replaced by a sensorless controller utilizing the proposed starting method. System architecture of experiment platform is shown in Fig. 6. The system cost is cut down drastically by using Freescale's 8-bit microcontroller MC68HC908 as CPU and only one sensing resistor on the DC bus.

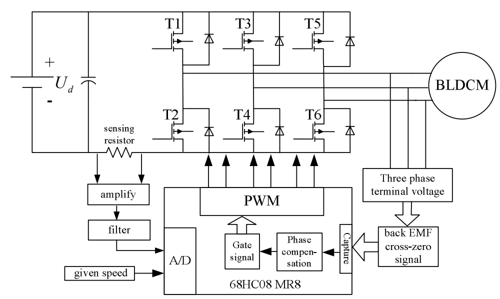
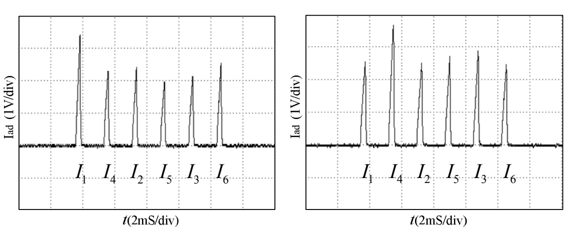


Figure 6. Experimental system configuration

B. *Results of initial rotor position estimation*

During initial rotor position estimation, the DC-link current has a six-pulse waveform under the effect of six detection voltage vectors, in sequence of "$V_1 \rightarrow V_4 \rightarrow V_2 \rightarrow V_5 \rightarrow V_3 \rightarrow V_6$". Fig. 7 shows the waveforms of DC-link current when the real rotor position is in two different sectors. It indicates that the difference between six current responses is clear enough to reflect the information of rotor position, and each rotor position sector corresponds to a certain detection voltage vector which generates the maximum current response.



(a) sector Ⅰ (b) sector Ⅳ

Figure 7. Current response when applying six detection voltage vectors

Fig. 8 show the results of the initial rotor position estimation and it reveals that the estimation error is at maximum +/- 15 electrical degrees. Hence it could be said that the estimation resolution is 30 electrical degrees, which is qualified as the commutation signal for BLDC motors.

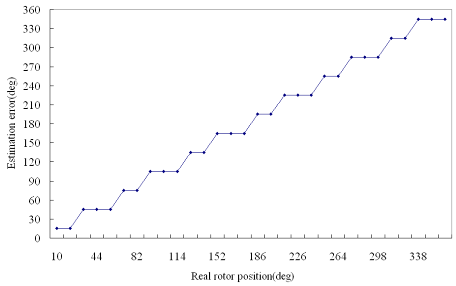


Figure 8. Result of initial rotor position estimation

C. *The whole starting procedure*

The whole starting procedure can be divided into three steps: initial rotor position estimation, rotor acceleration with its position feedback and switching to the sensorless operation based on back-EMF.

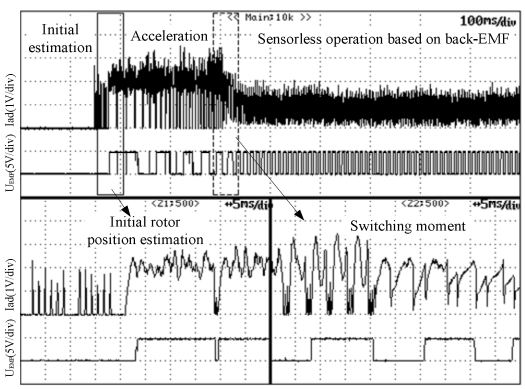


Figure 9. DC-link current waveform and back EMF cross-zero signal in the whole starting procedure

Fig. 9 shows the waveform of DC-link current and the back EMF zero-crossing signal in the whole starting process. As can be seen, initial rotor position estimation is repeated several times to ensure the validity of estimation. The back-EMF zero-crossing signals have been stable before switching to "back-EMF running", and have no mutation after switching, which means a successful starting is achieved.

D. *Experiment with no load and full load on electric vehicles*

Fig. 10 shows the waveform of DC-link current and back EMF zero-crossing signal in the no-load starting process, which lasts for 300mS only; Fig. 11 shows result of starting experiment with full load on the electric motorcycle, which lasts for about 600mS. The frequency of back EMF zero-crossing signal increases steadily, which indicates that the rotor speed is rising smoothly and no reverse rotation or starting failure occurs.

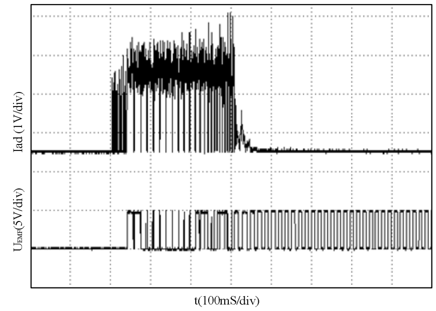


Figure 10. Experimental result of no-load starting

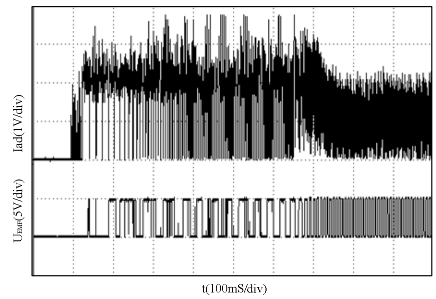


Figure 11. Experimental result of full load electric vehicle start-up

VI. CONCLUSION

This paper presents a novel starting method of BLDC motors without position sensor for electric vehicles. The initial rotor position estimation algorithm can identify the rotor position with a resolution of 30 electrical degrees. The whole starting procedure is accompanied with rotor position detection, which avoids reverse rotation and starting failure. In addition, by utilizing specific strategies such as torque optimization and noise reduction methods, the electric vehicles could start up more rapidly and smoothly. The proposed method can be implemented with a low-cost general-purpose microcontroller to provide a simple, compact, low-cost, and effective solution for BLDCM drives in the application of electric vehicles.

However, compared to the performance with position sensor, the starting torque of sensorless control is not sufficient, and the motor vibration and noise can not be eliminated completely during start-up procedure, which would be focused on in future research.

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