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Anti-reverse rotation startup method for sensorless brushless DC motor

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Abstract: In order to start up the brushless DC motor (BLDCM) without reverse rotation and smoothly switch the running state of the motor, a novel startup and smoothly switching method for a sensorless BLDCM is presented. Based on the saturation effect of the stator iron, six short voltage pulses are applied to determine the initial rotor position and the rotor can be found within 60°. After that, a series of short and long voltage pulses are used to accelerate the motor and the variation of the response current is utilized to detect the rotor position dynamically. When the motor reaches a certain speed at which the back-electromotive force (EMF) method can be applied, all the power devices are turned off and the running state of the motor is smoothly switched at the moment determined by the relationship between the terminal voltage waveform and the commutation phases. The experimental results verify the feasibility and validity of the proposed method.

Key words: brushless DC motor; sensorless control; anti-reverse rotation; back-electromotive force; switch

The sensorless control technology of the brushless DC motor (BLDCM) based on the back-electromotive force (EMF) detection method has been widely used in the industrial and commercial fields. As we know, the magnitude of the back-EMF is proportional to the motor speed, so the back-EMF detection method cannot be applied properly when the motor is at standstill or at low speed. In order to solve this problem, many methods have been developed. One of them, often referred to as a 3-step startup method[1], is used to align the rotor first in a predetermined direction, and then accelerate the motor in an open-loop scheme before the back-EMF method is applied. This startup method is easy to implement but tends to be affected by the load and may temporarily cause reverse rotation which is not allowed in some applications. Because of the drawbacks mentioned above, another kind of startup method based on the saturation effect of the stator iron is developed[2-3], in which the response current of the stator winding under short time voltage pulses is utilized to detect the rotor position[4-6].

In this paper, the short pulse sensing method, which is also based on the saturation effect of the stator iron and will not cause any reverse rotation or vibration during the startup process, is presented to locate and accelerate the rotor. The structure diagram of hardware implementation is illustrated in Fig. 1, in which the current sensor is used to amplify the terminal voltage of the sense resistor R_i and the resistance network is used as the voltage divider. The terminal voltage which reflects the back-EMF information is sampled by the A/D converter integrated in the micro-controller.

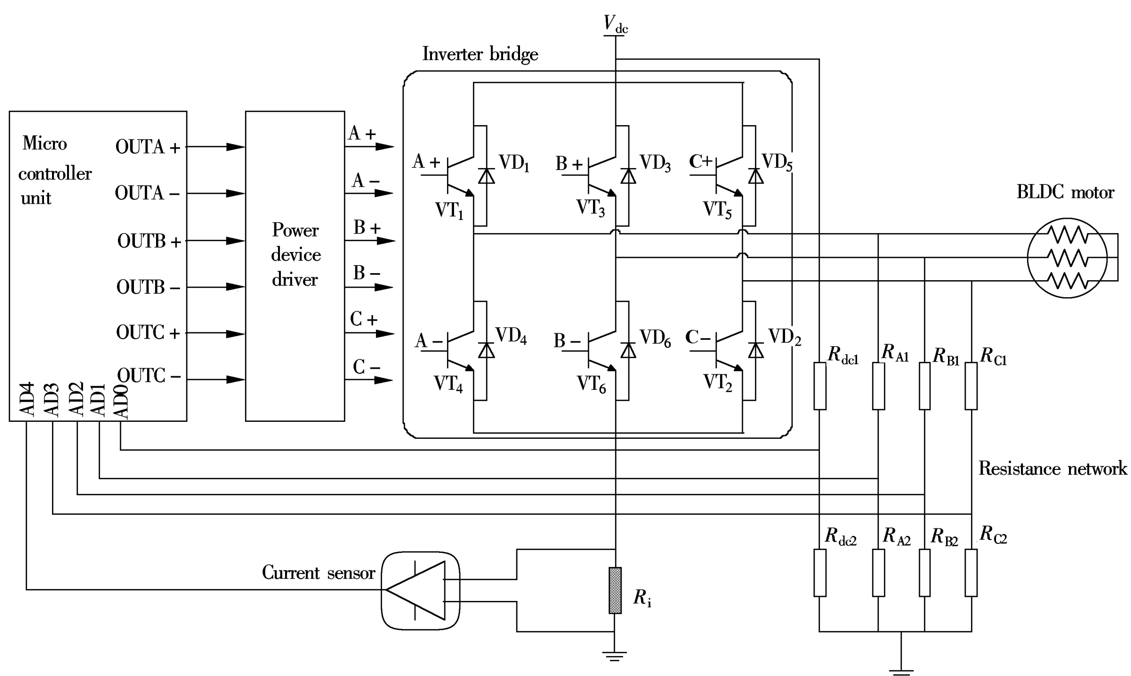

Fig. 1 The structure diagram of the drive circuit

Two of the three phase windings are energized every time and the rotor position can be determined dynamically. The selection of the switching moment between the startup and the back-EMF control process is a key point, because an improper switching moment may cause the motor to go out of step or to stop. In this paper, the relationship between the

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terminal voltage and the commutation phases, when all the power devices are turned off, is analyzed and used to determine the optimal switching moment.

1 Operation Principle

The stator iron of the BLDCM has non-linear magnetic saturation characteristics. When the stator winding is energized, a magnetic field with a fixed direction is established, as shown in Fig. 2(a). If the north pole of the rotor is in the same direction as that of the stator winding field, the inductance of the stator winding will decreases due to the saturation effect of the stator iron. On the contrary, if the north pole of the rotor is in the opposite direction from that of the winding field, the saturation decreases and the inductance increases accordingly. This variation is illustrated in Fig. 2 (d) from which we can see that the inductance of the winding stator is a function of the rotor position.

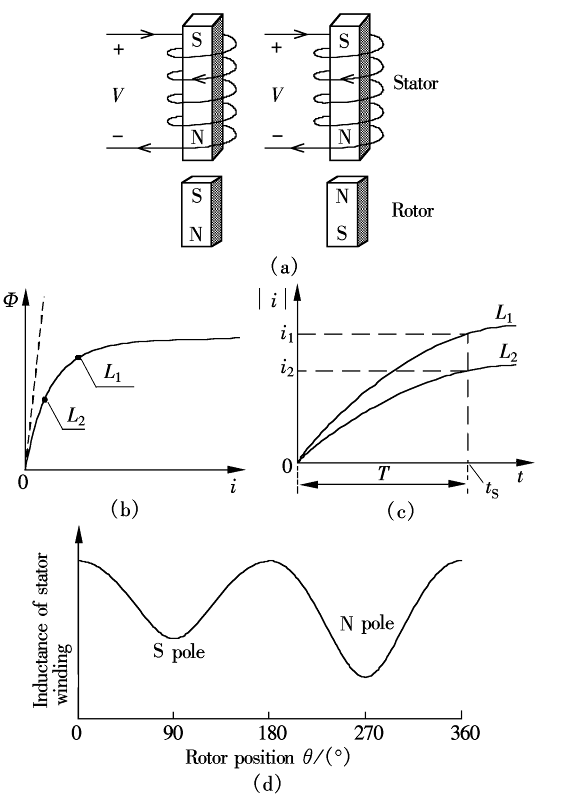

Fig. 2 The saturation effect of the stator iron. (a) Magnetic field synthesis; (b) Typical magnetization curve; (c) Current response due to inductance variation; (d) Stator inductance vs. rotor position

Therefore when a DC voltage is applied to the stator winding for a certain time, the current responses will be different due to the variations in inductance as shown in Figs. 2(b) and (c). In Fig. 2(b), the slope of the curve represents the inductance, so we can derive that $L_1 < L_2$ and under this condition at the same sampling moment t_S in Fig. 2(c) $i_1 > i_2$.

Through the above analysis, by comparing the current response, we can obtain the information of the rotor position.

2 Initial Rotor Position Detection and Speedup Method

Based on the operation principle mentioned above, six voltage pulses are injected into the phase windings and the peaks of the response current are compared with each other to determine the rotor position.

As shown in Fig. 1 and Fig. 3(a), the high-side power device VT_1 and the low-side power device VT_6 are activated first, which can be denoted as A + B −. The resultant magnetic field is represented by F_{16}. Then the high-side power device VT_3 and the low-side power device VT_4 are activated, and are denoted as B + A −, and F_{34} represents the resultant magnetic field. If the north pole of the rotor is in the same direction as that of the resultant magnetic field F_{16} and in the opposite direction from that of F_{34}, the peak of the response current of A + B − state is greater than that of B − A +. This condition can be denoted by a binary number 1, and contrarily denoted by 0. Thus the north pole of the rotor is found within 180°. By using a similar procedure to B + C −, C + B −, C + A − and A + C −, the rotor position can be narrowed down to 60°, which is sufficient enough for proper commutation, as shown in Fig. 3(b). This scope can be represented by three binary numbers illustrated in Fig. 4.

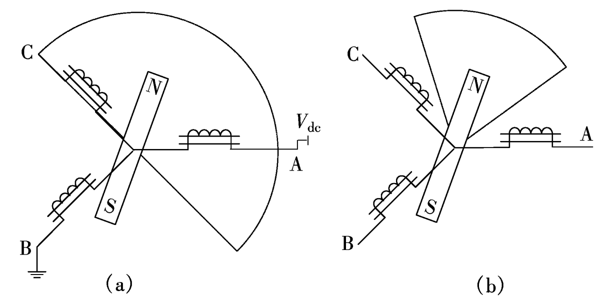

Fig. 3 The schematic diagram of initial rotor position detection. (a) Energized stator winding and rotor position within 180°; (b) Rotor position within 60°

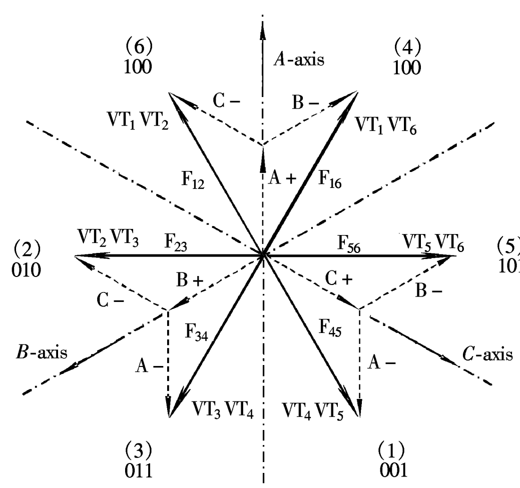

Fig. 4 The switching states diagram

When the initial rotor position is identified, the motor is accelerated to a certain speed. The previous algorithm of position detection will not work effectively in this process, because it is difficult to inject six pulses during a commutation period when the rotor is moving quickly; another reason is that three of the six pulses produce negative torque.

In order to solve these problems, a voltage pulse train composed of successive short and long pulses is adopted, which not only generates positive torque to speed up the motor but also provides information concerning rotor position.

Supposing the north pole of the rotor is located at sector 4(100) and the motor rotates counter-clockwise, the states A + C − and B + C − at this moment can produce positive torque. In Fig. 5, the short pulse and the long pulse correspond to A + C − and B + C −, respectively.

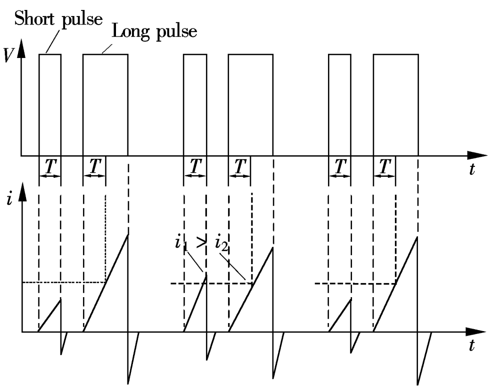

Fig. 5 The voltage pulse train and the current response

When the current response of short voltage pulse i_1 is greater than that of long voltage pulse i_2 for the same sample period T, the commutation occurs; i. e., the short pulse becomes B + C − and the long pulse becomes B + A −. If the response of the short voltage pulse is still less than that of the long pulse, the voltage pulse train stays the same as before.

This is because the north pole of the rotor first gets close to the direction of the magnetic field produced by the short pulse when the motor is rotating; the closer they get, the smaller the inductance becomes, as shown in Fig. 2(d). The current response of the short pulse becomes larger and exceeds that of the long pulse at some moment. This phenomenon repeats itself every 60°, so it can be used to determine the commutation time. Repeating this procedure can assure that the motor accelerates to a speed at which the back-EMF method can be applied. The experimental result is shown in Fig. 6.

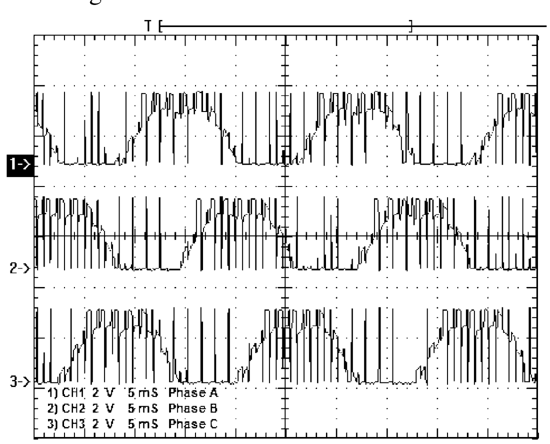

Fig. 6 The terminal voltage of three phases during speedup process

3 Smoothly Switching Method

When the motor is accelerated to a certain speed, the back-EMF detection method can be applied. In order to prevent the motor from vibration or losing step, it is very important to select the proper switching moment for a reliable operation of the BLDCM. In this paper, the relationship between the terminal voltage waveform and the commutation phases, when all the power devices are turned off, is analyzed. This can be used to determine the best switching moment.

As we known, because of the inertia, the motor will not stop immediately when the drive circuit is turned off. There is a voltage induced in the phase windings of the stator due to the rotation of the magnetic field of the rotor and this voltage reduces gradually with the decrease in speed. If we pick out a short time interval right after the turn-off moment, the terminal voltage has obviously not decreased yet, as illustrated in Fig. 7, where t_0 is the turn-off moment of power devices, t_1 is the moment that the timer starts, t_2 is the switch moment, and t_3 is the commutation moment. This waveform of the terminal voltage is related to the commutation phases. For example, the flat part of the waveform corresponds to the conduction state of the low-side power device of the inverter (120 electrical degrees), the 120 electrical degrees of the center of the salient part corresponds to the conduction state of the high-side power device of the inverter and the concave point corresponds to the commutation moment.

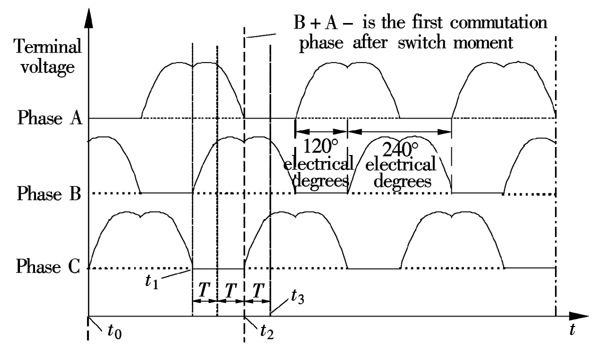

Fig. 7 The terminal of three phases after all power devices are turn off

Based on the analysis above, the timer of the MCU starts at t_1 and stops at t_2, as shown in Fig. 7. Supposing that the time interval is $2T$, then one half of it is equal to a commutation period T corresponding to 60°. The switching moment is also t_2 and the first commutation phase that is energized after switch is B + A −. After delaying 60°, the next commutation phase C + A − is energized.

Fig. 8 shows the experimental waveform in which channel 1 to channel 3 are the terminal voltages of the three pha-

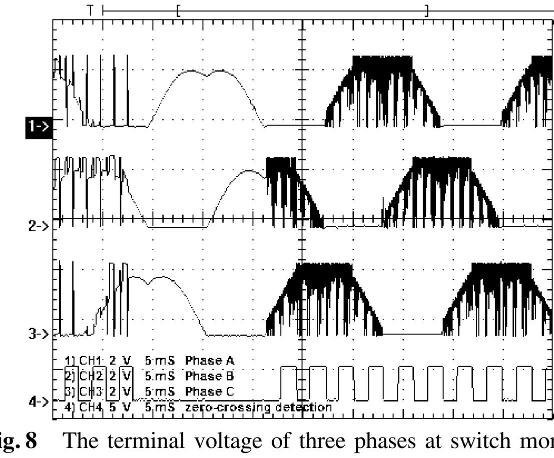

Fig. 8 The terminal voltage of three phases at switch moments

ses in the switching process, and channel 4 represents the back-EMF detection waveform whose rising edge is just the zero-crossing point. The duty cycle of the PWM modulation signal after switch is 50%, which is convenient for the speed regulation.

4 Conclusion

In this paper, an anti-reverse-rotation startup and smooth switching method of a sensorless brushless DC motor is presented. By using this method, the rotor position at standstill can be estimated with a resolution of 60° and the motor is accelerated to a certain speed at which the back-EMF detection method can be applied. The hardware implementation of the driving circuit is simple. Only one current sensor and a resistance network are required. It is very suitable to use in the low-cost applications. The experimental results verify the feasibility and validity of the proposed method.

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无位置传感器无刷直流电机无反转起动方法

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摘要: 为了实现无位置传感器无刷直流电机的无反转起动及平滑切换,提出了一种新的无位置传感器无刷直流电机起动及切换方法. 该方法依据电机定子铁芯饱和效应,采用6个短时电压脉冲检测转子初始位置,可将转子定位在60°范围内,然后采用长短电压脉冲相结合的方式加速电机同时利用电流响应的变化动态检测转子位置,当转速上升到可以检测到反电势过零点时,关闭电机驱动电路,根据端电压波形和导通相之间的对应关系确定切换时刻,可将电机平滑切换至反电动势换相运行方式. 样机试验结果验证了上述方法的可行性和有效性.

关键词: 无刷直流电机;无位置传感器控制;无反转起动;反电势法;切换

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