A Novel Twelve-Step Sensorless Drive Scheme for a Brushless DC Motor

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This paper presents a novel twelve-step sensorless drive scheme for a three-phase brushless DC motor, which combines the traditional six-step 120° and 180° conduction modes and has varied active angular period. The proposed scheme is implemented on a single FPGA-chip. Several experiments for various active angle periods from 124° to 168.75° are undertaken. The experimental results show that the torque constant is larger for the larger active angular period.

Index Terms—**Back EMF, brushless DC motor, sensorless drive, zero-crossing.**

I. INTRODUCTION

THE six-step 120° and 180° drive schemes are widely applied to small three-phase brushless DC motors (BLDCMs) [1]–[3]. Although 180° drive scheme can produce larger torque output, it is hard to be implemented as a sensorless drive way, since the windings of all three phases are always conducted so that the induced back electromotive force (EMF) is impossible to detect, and then the commutation periods cannot be determined. As a result, most sensorless drives are based on the six-step 120° drive scheme and has been shown suitable for the speed control of the motor [4]. However, the main limitation of the 120° sensorless drive is the smaller torque constant in comparison with the 180° drive. Saha *et al.* [5] proposed a 150° and a 165° sensorless drive scheme by the left extension of the 120° sensorless drive scheme. This paper tries to propose a universal method that can be used to develop a sensorless drive scheme with varied active angular period from 120° to about 170° (i.e., the conducting period of one phase can be more than 120° but less than 170° in electrical angle).

II. TRADITIONAL SIX-STEP 120° AND 180° DRIVES

The traditional six-step 120° drive system conducts any two phases and leaves the third phase floating for an interval of 120 electrical degrees (see Fig. 1). It is then possible to detect the back EMF of the floating phase by measuring its terminal voltage. The voltage curve of the back EMF with respect to the voltage of the neutral point will cross zero at the multiple-60 electrical degrees. It can be seen from Fig. 1 that the phase commutations are at $(30 + 60k)$ electrical degrees, where $k = 0, 1, \ldots$; i.e., 30° delay from the zero-crossings. Let $T_{\mathrm{zc}}(k)$ be the interval time between the $(k-1)$th and the kth zero-crossing points of the back EMF, which is the estimate of the time passing 60 electrical degrees at that moment [3], [4]. Note that the Hall signals in the motor with three Hall sensors are synchronous with the back EMFs of the armature terminals [6], [7], so that the position resolution of a sensorless motor is the same as that of a motor with Hall sensors.

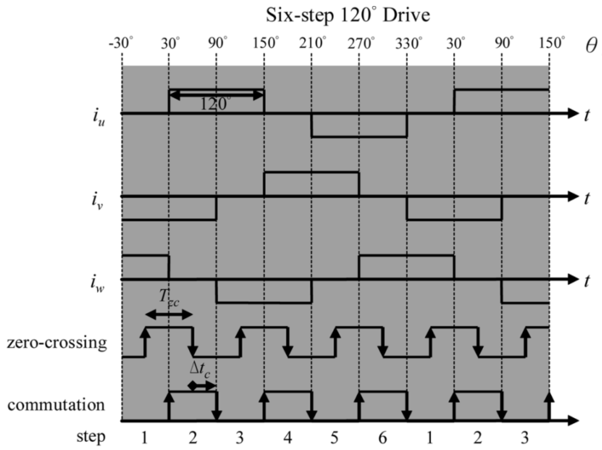

Fig. 1. Traditional six-step 120° sensorless drive scheme.

The 120° sensorless drive scheme is then implemented by commuting the conducting phases with the delay $\Delta t_c(k)$ from the kth zero-crossing point (see Fig. 1), where

$$\Delta t_c(k) = \frac{1}{2} T_{\mathrm{zc}}(k). \tag{1}$$

On the other hand, the three phases are always conducted in the six-step 180° drive scheme. It lasts 180 electrical degrees before changing the polarity of one phase, which is shown in Fig. 2. It should be remarked that the phase commutations occur at the multiple-60 electrical degrees.

III. PROPOSED SENSORLESS DRIVES

A. Twelve-Step 150° Sensorless Drive Scheme

It is known that the torque constant of the six-step 180° drive is always larger than that of 120° drive, so that the former can achieve higher speed under the same supplied voltage condition. We can combine the 120° and 180° drives to develop a twelve-step 150° sensorless drive scheme, which has the advantage of the 120° drive scheme to detect the back EMF and the advantage of the 180° drive scheme to improve the torque constant.

Between the electrical angles of $(30 + 60k)$ and $(60 + 60k)$ degrees, where k is a natural number, the motor rotates in the six-step 120° drive mode so that the zero-crossing points can be

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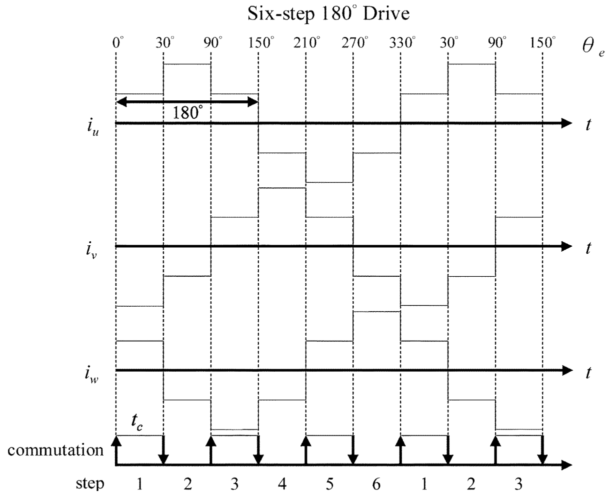


Fig. 2. Traditional six-step 180° drive scheme.

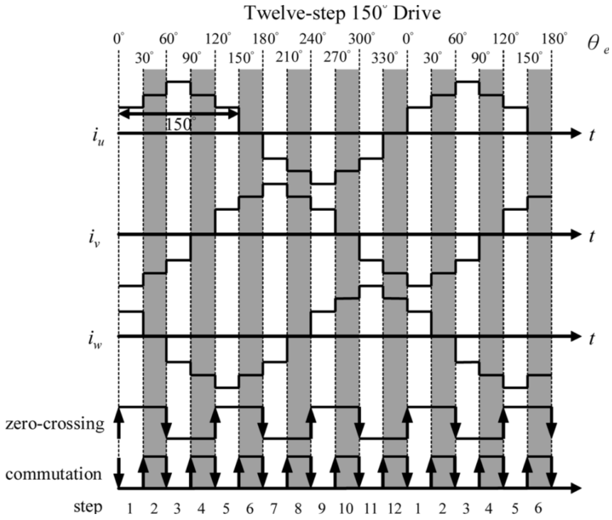


Fig. 3. Twelve-step 150° sensorless drive scheme.

detected, while the 180° drive mode applies between the electrical angles of $(0+60k)$ and $(30+60k)$ degrees. This is illustrated in Fig. 3. It is apparent that there are twelve steps and the frequency of the phase commutations is doubled. The odd steps are the 180° drive mode, while the even steps are the 120° drive mode. There are two phase commutations for each zero-crossing of the back EMF:

- one is at the same time of the happening of the zero-crossing (for the 180° drive mode);
- the other is Δt_c delay as that in (1) (for the 120° drive mode).

It should be remarked that it lasts 150 electrical degrees before changing the polarity of one phase.

B. Extension to Various Active Angular Periods

If we increase the conducting interval for some more $\Delta\theta$ in the even steps, then we can extend the twelve-step 150° sensorless drive scheme to the one with varied active angular period (see Fig. 4). The implementation is similar to that of the 150° one with the exception that the delay time Δt_c is no more that in (1). The two phase commutations for each zero-crossing of the back EMF are:

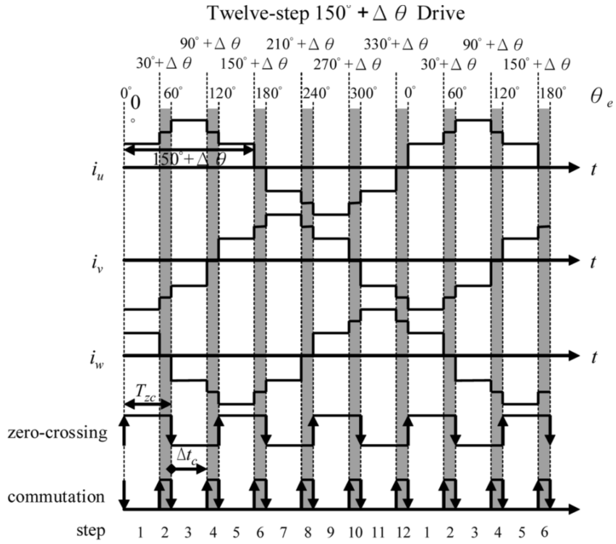


Fig. 4. Universal twelve-step sensorless drives.

- one is at the same time of the happening of the zero-crossing (for the 180° drive mode);
- the other is Δt_c delay (for the 120° drive mode), where

$$\Delta t_c(k) = \alpha T_{\mathrm{zc}}(k), \quad 0 \leqslant \alpha < 1. \tag{2}$$

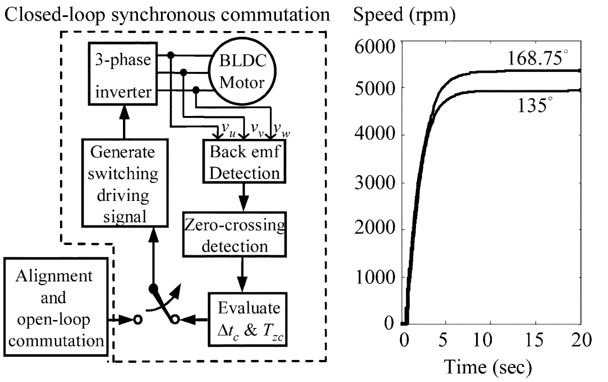
When $\alpha = 1/2$, it is the 150° drive scheme. For a $(150° + \Delta\theta)$ sensorless drive scheme, we have the following relation:

$$\Delta\theta = (2\alpha - 1)30°. \tag{3}$$

For instance, $\alpha = 0.25, 0.8125$ correspond to the 135° and 168.75° sensorless drives. Ideally, α can be selected to approach 1. However, this would make the detection of the zero-crossing of the back EMF impossible, so that the maximal α is about 0.8125 according to our experience. A special case is $\alpha = 0$, which turns out to be another six-step 120° sensorless drive that leads the traditional one with a phase of 30°.

IV. IMPLEMENTATION AND EXPERIMENTS

A BLDCM used as a spindle motor of a 50x CD-ROM is taken as an experimental target. In order to apply the sensorless commutation control for a BLDCM, a general and proper sensorless starting procedure is used to produce the sufficient large back EMF for detecting the zero-crossing, which is, in order, an alignment procedure, the open-loop commutation for start-up, and the closed-loop synchronous commutation mode [3], [4]. The six-step sensorless drive scheme in the last step in the earlier works is now replaced with the proposed twelve-step one. The motor will speed up in the open-loop commutation mode, and then be switched to the twelve-step sensorless drive scheme



(a) (b)

Fig. 5. Twelve-step sensorless drive scheme: (a) block diagram; (b) speed response histories.

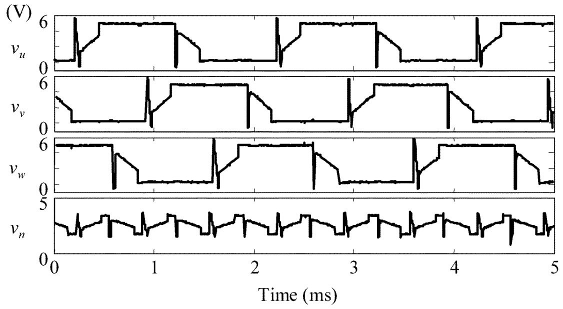


Fig. 6. Voltages of the twelve-step 135° drive.

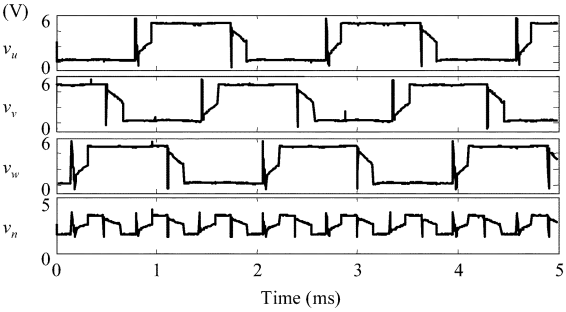


Fig. 7. Voltages of the twelve-step 150° drive.

when the speed of the motor is high enough to generate the sufficient large back EMF, about 0.5 V [3], [4]. A block diagram of this drive scheme is shown in Fig. 5(a). This paper does not consider the speed control, so that the motor will run as fast as possible until it reaches a steady state. This is shown by the speed response histories of 135° and 168.75° drives in Fig. 5(b).

The voltage waveforms of phases u, v, w, and n in the steady-state for some experiments are shown in Figs. 6–8. Comparing v_u of different drives, we find that the portion of 5 V increases, in percentage, with the active angular period. In fact, the portion for the 168.75° is the largest. This is consistent with the theory described above. All these figures also show that there exist the noises induced by the switching of power transistors.

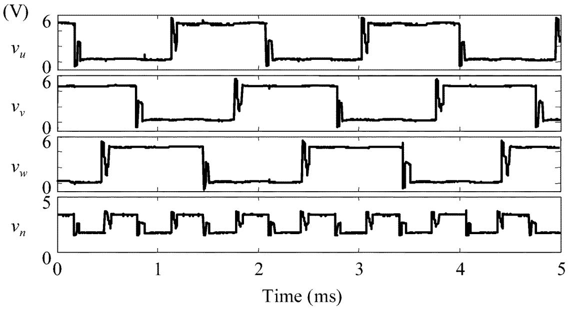


Fig. 8. Voltages of the twelve-step 168.75° drive.

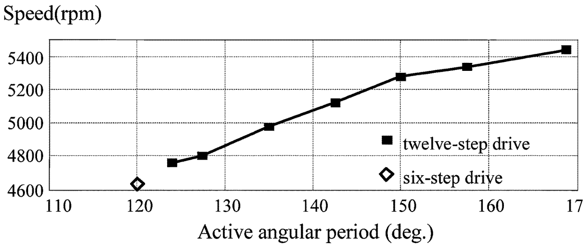


Fig. 9. Steady-state speeds of various active angular periods.

On the other hand, the free-running steady-state speeds of the motor for 124°, 127.5°, 135°, 142.5°, 150°, 157.5°, and 168.75° drives are, respectively, 4757, 4799, 4975, 5119, 5274, 5337, and 5440 rpm, and are depicted in Fig. 9. The speed increases rapidly to the 150° drive, and then slowly to the 168.75° drive.

V. CONCLUSION

The proposed drive scheme is implemented on a single FPGA-chip. Its application to the speed control can be realized by adding a PWM controller to the block of "generate switching drive signal" in Fig. 5(a), for which the reader is referred to [4].

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