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180-Degree Commutation System of Permanent Magnet Brushless DC Motor Drive Based on Speed and Current Control

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***Abstract*—To drive Brushless dc motor, each coil of conventional 120-degree commutation rotates only 120-degree with current to generate torque, and wait for next excitation in the other 60 degree without torque generated. However, each coil of 180-degree commutation works for the entire electrical period, which is expected to deliver more power. Analysis, modeling and simulation of 180-degree commutation have not been addressed in previous publications. In this paper, 180-degree commutation theory is analyzed. A 180-degree square-waveform inverter method is designed. A novel 180-degree commutation system is proposed with initial condition, speed and current control. Simulation results prove that the proposed 180-degree system works properly with greater maximum torque than conventional 120-degree system.**

Keywords-brushless dc motor; 180-degree commutation system; 180-degree inverter; hysterisis current control

I. INTRODUCTION

Three phase Y connected Brushless dc motors (BLDCM) are widely used in industrial applications because of numerous performance advantages, such as high efficiency, high torque to inertia ratio and so on. The BLDCM with trapezoidal back-emf waveform is conventionally driven by 120-degree commutation, and various control methods have been summarized in [1]. However, in each conduction interval, only two windings are excited and the other winding keeps floating until the next conduction interval. During each conduction interval, there is always one floating winding that has no current flowing inside the phase, which results in that no torque created by this floating winding.

In this case, the need exists for a BLDCM-drive system to increase the power delivered from inverter side to the BLDCM side for a given dc voltage supply. Rather than conventional 120-degree commutation, the 180-degree commutation can be realized as a three-phase-drive model, which means that all of the three phases are conducted with current to generate torque in each of the conduction intervals. Theoretically, 180-degree commutation system is expected to generate greater maximum torque comparing to the conventional 120-degree.

To achieve more power delivery from inverter to BLDCM side, a three-phase drive of square-waveform inverter method is designed for the proposed 180-degree commutation system. The proposed current sequences require only one transistor is switched "on" or "off" in each modulation, which can effectively minimize the switching loss and the chance of short circuit. To get more accurate reference phase current, hysteresis current control is carried out to force phase current within the hysteresis band. Speed and initial condition control are also considered in the proposed system.

Base on Matlab/Simulink environment, the simulation results present that the proposed 180-degree commutation system work properly with good performance characteristics. Under the same frame of simulation setup, comparing to conventional 120-degree commutation, the 180-degree commutation system produces greater maximum torque with the same given power supply.

II. COMPARATIVE STUDY BETWEEN 120 AND 180 DEGREE COMMUTATION

A. Theory Comparation

In the case of 120-degree commutation, the current flow of three phases is shown in figure 1(a). Phase A and B are conducted in this conduction interval, however the phase C is unconnected with neither high nor low side of the inverter. Each modulation is of 60 degree, which is 1/6 of electrical period. Each winding is conducted "on" for 120 degree. In contrast, 180-degree commutation is conducted "on" of 180 degree of each phase. Three-phase current flow of 180-degree commutation is shown in figure 1 (b). Take the conduction interval as an example, transistor T1, T4 and T5 are "on". Current flows from phase A to phase B and phase C to phase B respectively.

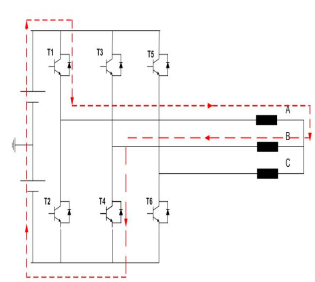

Figure 1(a): current in conduction interval of 120-degree commutation

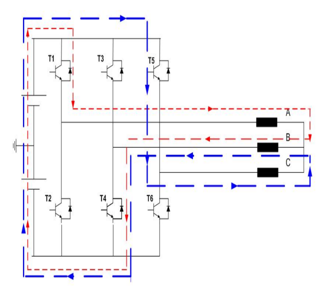

Figure 1 (b): current in conduction interval of 180-degree commutation

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B. *Switching Frequencies*

Switching frequencies of 120-degree and 180-degree commutation has been summarized in table 1. Three phase terminal polarities are clearly presented to provide future implementation reference on BLDCM drive.

	120-degree commutation		180-degree commutation	
Intervals (degree)	Transistor "on"	Polarities A B C	Transistor "on"	Polarities A B C
0 to 60	T1, T6	+ 0 -	T1,T6,T5	+ - +
60 to 120	T3, T6	0 + -	T1,T6,T2	+ - -
120 to 180	T3, T2	- + 0	T1,T3,T2	+ + -
180 to 240	T5, T2	- 0 +	T4,T3,T2	- + -
240 to 300	T5, T4	0 - +	T4,T3,T5	- + +
300 to 360	T1, T4	+ - 0	T4,T6,T5	- - +

Table 1: 120-degree and 180-degree switching frequency

C. *Inverter Gate Signals*

To drive BLDCM, a two-level six switches inverter is commonly used. Gate signal is to control the switches "on" or "off" for each transistor. 120-degree commutation and 180-degree commutation gate signals are shown in figure 2 (a) and (b), respectively. As can be seen from figure 2, each transistor of 180-degree is conducted for 180 degree without a waiting time of 60 degree rather than conventional 120-degree commutation. Three phases of A, B and C are driven with current all the electrical period with current for 180-degree commutation.

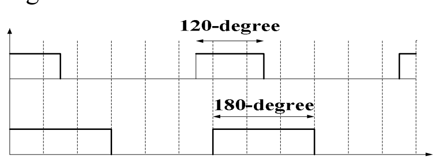

Figure 2:120-degree and 180-degree commutation gate signals

D. *Hall Sensor Signals*

Three phase hall sensors are used to detect rotor position information. No matter whether phase terminal polarity is positive, zero or negative, hall sensor output signals are the same for both 120-degree and 180-degree commutation. Three-phase hall sensor signals are shown in figure 3 as follows:

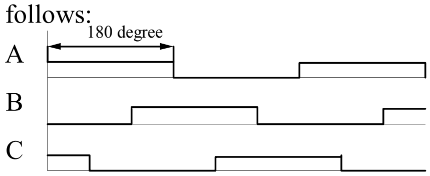

Figure 3: Hall sensor signals for 120 and 180-degree commutation

E. *Line-Line and Line-Neutral Voltage*

For Y connected BLDCM, three phases A, B and C are connected in the neutral point N. Line to line voltage is defined as the voltage between two phases, and line to neutral voltage refers to the voltage between phase and neutral point N. It is well known that the line to line voltage can be measured from inverter output voltage. Line to neutral voltage is considered as phase voltage, which can be detected by BLDCM sensor. The line-line voltage and line-neutral voltage of 120 degree and 180 degree commutation are shown below in figure 4 (a) and (b).

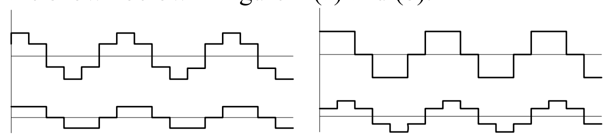

Figure 4: (a) 120-degree line-line and line-neutral voltage (b) 180-degree line-line and line-neutral voltage

III. THE PROPOSED 180-DEGREE COMMUTATION SYSTEM

A. *BLDCM Model*

To carry out the mathematical model of the BLDCM, voltage equations of each phase of A, B and C are expressed in equation 1, which is obtained based on the dynamic equivalent circuit of BLDCM [2]. The values of mutual inductance M between each two phases are assumed to be the same. L is the stator inductance in each phase and R is the stator resistance, where three-phase R and L are respectively assumed to be the same. V_a , V_b and V_c are phase voltage signals of phase A, B, C. E_a , E_b , E_c are back-emf signals. It is well known that PMSM has the type of sinusoidal back-emf. In contrast, BLDCM is in the type of trapezoidal back-emf. Base on [3], to take the place of sinusoidal signal of back-emf in the model, a piecewise linear signal with period of 2π is adopted, which is $trape(\theta)$. The BLDCM model [4] is set up as shown in figure 5.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \qquad (1)$$

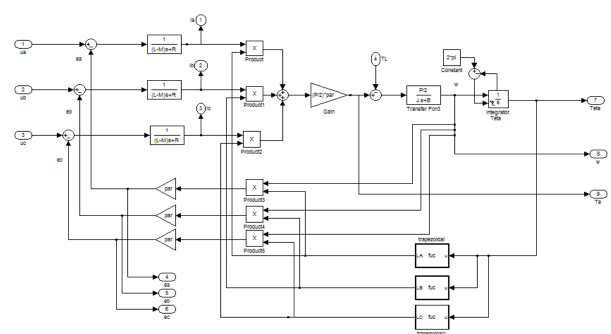

Figure 5: BLDC model

B. *Current Controller for 180-degree Commutation*

For 3-phase Y connected BLDC motor, 180-degree system is a three phase driven model. Three phase current are nonzero in each conduction interval. The generated reference current is shown in table 2. As what is mentioned in introduction section, the proposed current sequences require only one transistor is switched "on" or "off" in each modulation, which can minimize the switching loss and chance of short circuit.

θ	I_{ar}	I_{br}	I_{cr}
$0 \le \theta < \frac{\pi}{3}$	$\frac{I_s}{2}$	$-I_s$	$\frac{I_s}{2}$
$\frac{\pi}{3} \le \theta < \frac{2\pi}{3}$	I_s	$-\frac{I_s}{2}$	$-\frac{I_s}{2}$
$\frac{2\pi}{3} \le \theta < \pi$	$\frac{I_s}{2}$	$\frac{I_s}{2}$	$-I_s$

θ	I_{ar}	I_{br}	I_{cr}
$\pi \le \theta < \frac{4\pi}{3}$	$-\frac{I_s}{2}$	I_s	$-\frac{I_s}{2}$
$\frac{4\pi}{3} \le \theta < \frac{5\pi}{3}$	$-I_s$	$\frac{I_s}{2}$	$\frac{I_s}{2}$
$\frac{5\pi}{3} \le \theta \le 2\pi$	$-\frac{I_s}{2}$	$-\frac{I_s}{2}$	I_s

Table 2: a,b,c 3-phase reference current

The simulation block diagram of the 180-degree current controller is shown in figure 6(a). Conventional PI control is used inside of the speed control block, which is built up as shown in figure 6(b).

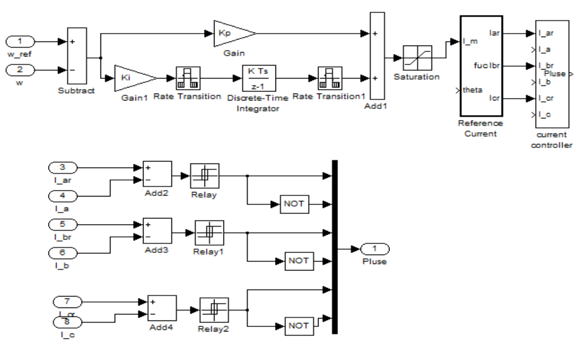

Figure 6: (a) current controller
(b)speed controller, respectively

C. 180-degree Commutation System Setup

For the characteristics of BLDCM, back-emf is directly proportional to the motor speed, and the torque production is almost directly proportional to phase current [5]. Because of these factors, the following drive scheme is commonly used in speed and current control, which is shown in figure 7. This control scheme for 180-degree commutation system has never been taken into account in pervious literatures. The implementation of this 180-degree commutation is challenging due to more complicated operation of reference current generated and the stability of speed control.

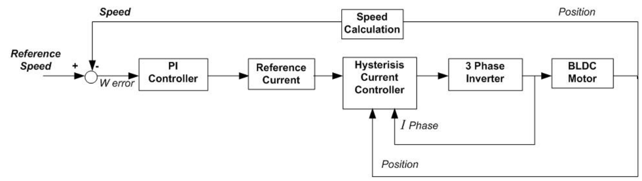

Figure 7: Speed and Current Control Loop for 180-degree commutation

The simulation block of 180-degree commutation system is set up as shown in figure 8. The actual speed information is obtained from the feedback position information. By comparing the difference between the actual speed and the reference speed, speed error is calculated. PI controller is implemented to generate the reference current according to the logic of the proposed 180-degree commutation current controller. In the Hysteresis current regulator, the power transistors are switched on or off depend on whether the current is larger or less than the generated 180-degree commutation current. This scheme works properly with excellent performance results for 180-degree commutation system, which is proved in the next section.

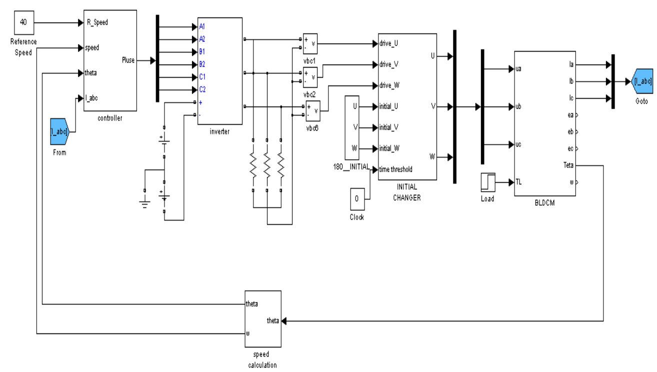

Figure 8: 180-degree commutation simulation block diagram

IV. SIMULATION STUDY

A. Performance of Proposed 180-degree commutation system

The 180-degree inverter output voltage waveform is theoretically shown in figure 9 (a) [6]. In the operation of simulation, 180-degree inverter output voltage, which is shown in figure 9 (b), is matched to the theoretical one. For phase current of winding A as an example, it is can be seen that, as what is expected, phase current is proved to be non-zero for 180-degree commutation system.

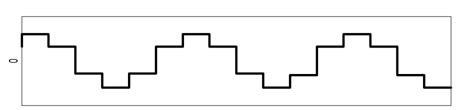

Figure 9 (a) theoretical inverter output

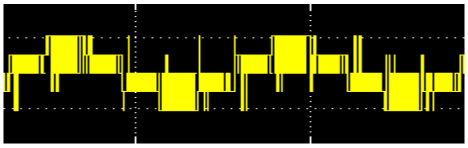

Figure 9 (b): simulation inverter output voltage

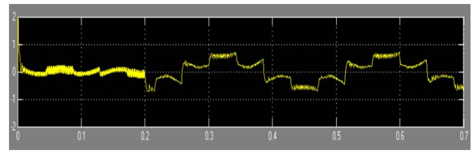

Figure 9 (c): Phase A current

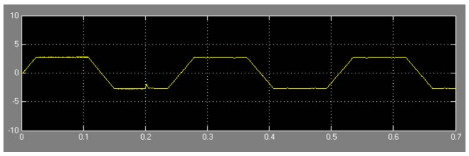

Figure 9 (d): Phase A back-emf voltage

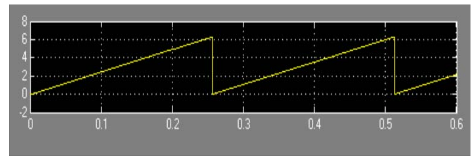

Figure 9 (e) position information

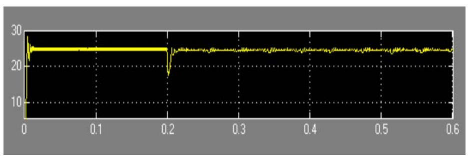

Figure 9 (f) speed information

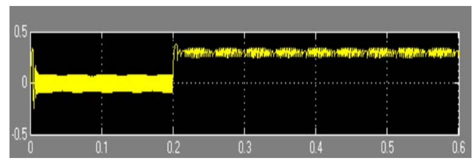

Figure 9 (g) torque waveform

Figure 9 : Performance results on 180-degree commutation system: (a) theoretical inverter output; (b): simulation inverter output voltage; (c): Phase A current; (d): Phase A back-emf voltage; (e) position information; (f) speed information; (g) torque waveform, respectively

BLDCM Motor parameters: $R = 0.552\Omega$, L=0.0215h, M=0.002h, P=6, J=0.0001, B=0.001, flux linkage magnitude =0.11Wb.To get the dynamic results as well, T-load=0.3 Nm is put at the time of 0.2s. According to the simulation results shown in figure 9, the proposed 180-degree commutation system works properly with excellent performance characteristics. Base on speed and current control, phase current is obtained as what is expected for the 180-degree commutation drive.

B. Numerical Comparesion Results on Torque

To find the maximum load torque, keep increasing the TL until the speed decreases to zero. This maximum torque is realized as short-circuit torque of BLDCM in industry as well. The simulation maximum load torque, in each given power supply voltage of inverter, has been summarized in table 3. Under the same frame of simulation setup, it is fairly to present and analyse the comparative results between 120-degree and 180-degree commutation systems. As what is theoretically expected, the numerical results prove that greater short-circuit torque can be generated by the proposed 180-degree commutation system.

	10V	12V	14V	16V	18V
120-degree Torque	0.178Nm	0.212Nm	0.251Nm	0.291Nm	0.332Nm
180-degree Torque	0.295Nm	0.352Nm	0.412Nm	0.475Nm	0.531Nm

V. CONCLUSION

In this paper, the theory of 180-degree commutation is fully addressed rather than conventional 120-degree. The comparative study between the 120-degree and 180-degree commutation is taken into account for analysis of difference and improvement for BLDCM drive. A developed 180-degree current controller is designed for the speed and current control loop of system. The proposed 180-degree commutation system works properly with excellent dynamic results in computer simulation. The analysis, modelling and simulation work provide good reference for future research on 180-degree commutation. Numerical results prove that greater maximum torque is generated than the conventional 120-degree commutation system.

VI. REFERENCES

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