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Improved Four-Switch BLDCM Direct Current Control

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Abstract: The main purpose of this study is to describe a low cost four-switch brushless dc motor (BLDCM) drive. An improved direct current controlled scheme is designed and implemented to produce the desired dynamic and static current and speed characteristics. Eight voltage vectors are summarized, which are selected to control BLDCM in SVPWM pattern. This method avoids the undesired current distortion which is caused by uncontrollable phase. The operational principle of the four-switch BLDC motor drive and the developed control scheme are theoretically analyzed and the performance is demonstrated by both simulation and experimental results.

Keywords: Brushless dc motor, direct current control, four-switch inverter, voltage space vector

INTRODUCTION

As BLDCMs have such good features as simple construction, high reliability, light electromagnetic pollution, and high power density, they are used extensively in servo systems and low-power drive systems (Lee *et al*., 2008; Kim *et al*., 2006).

Usually, the conventional structure of the three-phase voltage-source inverter comprises three legs, six power switches, and a complementary pair for each phase. However, the Four-Switch Three-Phase Inverter (FSTPI) employs only four switches, a pair of complementary switches as shown in Fig. 1. But the uncontrollable phase current causes unsymmetrical voltage vector in four-switch three-phase inverter and its waveform is much of distortion from rectangular. The direct current control based on hysteresis avoids this problem, and it senses currents of phases b and c individually by two current sensors and then switches them separately. Therefore, the desired rectangular current waveform is directly obtained (Lee *et al*., 2003). A new speed control method using the acceleration feed forward compensation is proposed to improve the speed response characteristic for a four-switch three-phase BLDC motor (Lee *et al*., 2004). The disturbance torque estimation method is adopted to improve the robustness of the method. It is verified to be economical and efficient in some occasions with light load, such as robot arm. An adaptive inference system controller is proposed (Niasar *et al*., 2006). This newly developed design does not require an accurate model of the motor and has a fairly simple structure. Simulation results show better transient and steady-state responses compared with the Proportional-Integral (PI) controller in the wide speed range. Some work has also been done on a sensorless four-switch BLDC motor drive (Lin *et al*., 2008; Niasar *et al*., 2007a). Such as, an asymmetric PWM scheme is proposed (Lin *et al*., 2008) for a four-switch three-phase BLDC motor drive to make six commutations and produce four floating phases to detect back electromotive force (back-EMF). The position information of the rotor can be acquired based on the crossing points of the voltage of controllable phases. Virtual Hall sensor signals are made by detecting the zero crossing points of the stator terminal voltages, and there is no need to build a 30º phase shift (Niasar *et al*., 2007b), which is prevalent in most of the sensorless algorithms.

In this study, an improved direct current control method control technique is proposed to avoid the current distortion caused by uncontrollable phase. The theoretical operating principle of the four-switch converter for the three-phase BLDC motor drive and the proposed control scheme are explained. The validity of the proposed system is verified by simulation results and a experimental system based on dsPIC6010A is built to provide the experimental results.

MATHEMATICAL MODEL OF BLDCM

The FSTPI topology consists of 4 power switches that provide two of the inverter output phases. The third phase is fed by the dc link from the center of a split-capacitor bank, as shown in Fig. 1. The mathematical model of four-switch BLDCM is shown in (1) and (2) (De Rossiter Corrêa *et al*., 2006; Niasar *et al*., 2006).

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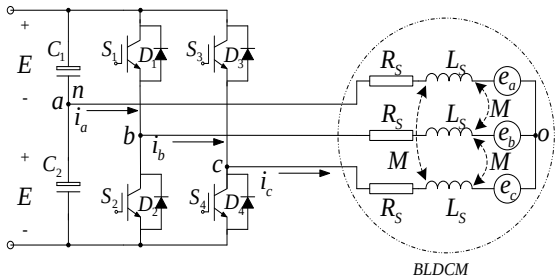

Fig. 1: Power Circuit of 4-switch 3-phase inverter

The typical mathematical model of a three-phase BLDC motor is as:

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{ao} \\ e_{bo} \\ e_{co} \end{bmatrix} \quad (1)$$

$$\begin{cases} v_a = v_{an} + v_{no} = v_{no} \\ v_b = v_{bn} + v_{no} \\ v_c = v_{bn} + v_{no} \end{cases} \quad (2)$$

where,

v_{ao}, v_{ao}, v_{ao} = Phase voltages
R = Stator resistance
M = Mutual inductance of stator winding
L_s = Elf-inductance of stator winding and $L = L_s - M$
i_a, i_b and i_c = Phase currents
e_{ao}, e_{bo}, e_{co} = Phase back-EMFs
p = Differential operator d/dt

FSTPI TOPOLOGY AND SPACE VECTOR ANALYSIS

Generating a 120 electrical degree current conduction is inherently difficult with the conventional four-switch topology, because a BLDCM with non-sinusoidal back-EMF (i.e., trapezoidal) requires a quasi-square wave current profile to generate constant output torque compared to that of a permanent magnet synchronous motor with sinusoidal back-EMF requiring sinewave current (Fu and Lin, 2006; Fu *et al*., 2006; Lin *et al*., 2006). These currents which have 120 electrical degrees conduction period are synchronized with the flat portion of the corresponding phase back-EMFs, therefore a smooth electromagnetic torque can be obtained. As a result, at every instant of time only two phases conduct and the other phase is supposed to be inactive. Although four voltage vectors in conventional four-switch inverter system are sufficient enough to control the three-phase ac motors using

Table 1: The controlling voltage space vector and switch combination

	V_{bn}	V_{cn}	$S_1S_2S_3S_4$ (1:on;0:off)
V_0	-E	-E	0101
V_1	0	-E	0001
V_2	+E	-E	1001
V_3	+E	0	1000
V_7	+E	+E	1010
V_4	0	+E	0010
V_5	-E	+E	0110
V_6	-E	0	0100

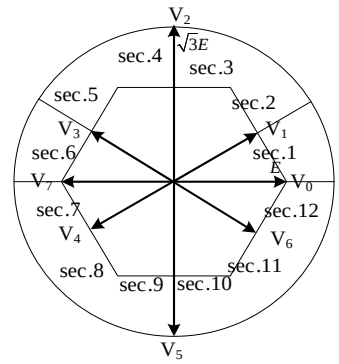

Fig. 2: Voltage space vector chart

PWM techniques, additional voltage vectors are required for BLDC motor with two phase conduction mode in order to control the midpoint current of the split capacitors at a desired value (Abolfazl *et al*., 2006, 2008; Su and McKeever, 2004). Since the conventional method cannot provide a two-phase conduction method completely, a new control scheme with new switching patterns should be developed such that only two of the three motor phases conduct.

To obtain the switch modes of operation in four-switch BLDC motor drive, a novel voltage vector selection look-up table is designed as shown in Table 1. Based on the Table 1, implementation of the voltage space vectors is depicted in Fig. 2.

Based on the voltage space vectors in Fig. 2, the current regulation is actually performed by using hysteresis current control. The purpose of regulation is to shape quasi-square waveform with acceptable switching (ripple) band. The detailed switching sequences are described in Table 2. In Table 2, if the reference current is bigger than the actual current, within the hysteresis bandwidth, the current error τ is defined as "1," otherwise it is "-1".

Normally, six-possible voltage space vectors of four-switch topology are supposed to be used in Table 2 as shown in Fig. 3(a)-(f) similar to the six-switch version, however two of the voltage vectors V_2 and V_5 as shown in Fig. 3 create problems in the current control. When they are directly used in the voltage vector selection table (Table 2), back-EMF of the uncontrolled phase (phase–*a*) generates undesired current therefore distortions occur in each phase current. As a result, undesired electromagnetic torque is inevitable. Therefore, when the rotor position is in the sec.1, 2, 4, 5, 7, 8, 0 and 11, special switching pattern

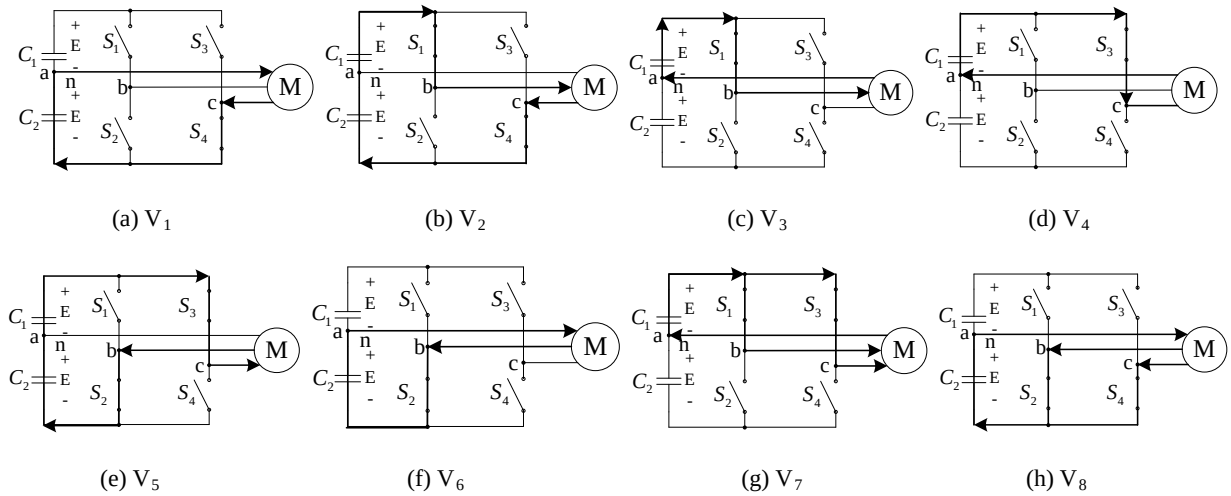

Fig. 3: Proposed four-switch voltage vector topology for BLDCM

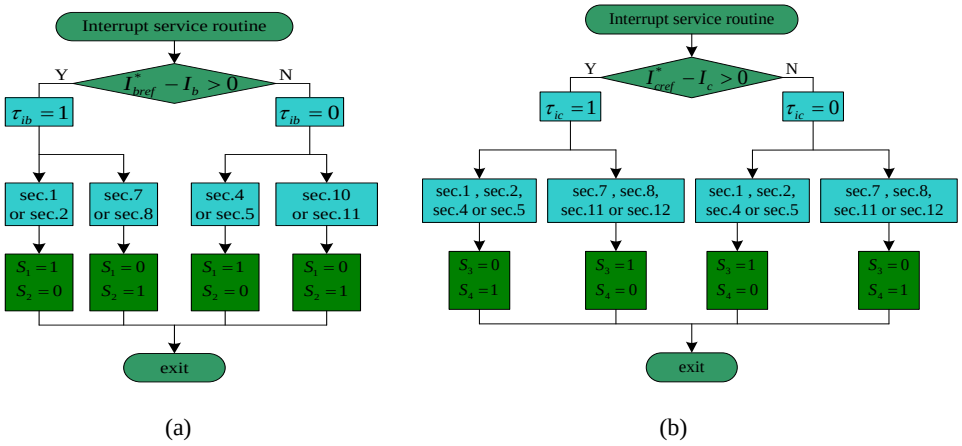

Fig. 4: Individual phase-b and-c current control, Ib and Ic, in sec. 1, 2, 4, 5, 7, 8, 10 and 11

Table 2: Four-Switch Voltage Space Vector Selection for BLDCM Drive

	θ											
τ	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
1	~~1001~~	~~1001~~	1000	1000	0010	0010	~~0110~~	~~0110~~	0100	0100	0001	0001
-1	~~0100~~	~~0001~~	0001	~~1001~~	~~1001~~	1000	1000	0010	0010	~~0110~~	~~0110~~	0100

Table 3: Voltage vector selection in sectors II and V for four-switch BLDCM drive (CCW)

τ_{ib}	τ_{ic}	sec.1	sec.2	sec.4	Sec.5	sec.7	sec.8	sec.10	sec.11
1	1	1001	1001			0110	0110		
	-1	1010	1010			0101	0101		
-1	1			1001	1001			0110	0110
	-1			1010	1010			0101	0101

should be adapted, as shown in Table 3 (CCW). At sec.1, 2, 4, 5, 7, 8, 10 and 11, phase-*b* and -*c* current are independently controlled by the hysteresis current controllers. Additional two voltage vectors V_0 and V_7 which are unused in conventional four-switch PWM scheme are included in the voltage selection look-up table to obtain smooth quasi-square current in two-phase conduction four-switch BLDC motor drive.

Additional two voltage vectors V_0 and V_7 which are unused in conventional four-switch PWM scheme are included in the voltage selection look-up table to obtain quasi-square current in two-phase conduction four-switch BLDC motor drive. The reason is there will be always current trying to flow in phase-*a* due to its back-EMF and the absence of switches controlling its current.

As a result, there will be a distorted current in phase-*a* as well as in phase-*b* and -*c*. Therefore, voltage space vectors of phase-*b* and -*c* conduction can be difficult to implement for BLDC motor drive unless some modifications are applied to overcome the back-EMF effect of the phase-*a* in these conditions. Selecting

Table 4: Parameter of BLDC motor

Rated voltage	V	310V	Stator induction	L	5.22 mH
Rated torque	Te	3Nm	Rotational inertia	J	0.08 kg·m^2
Rated speed	n	1500	Number of pole pairs	Pn	2
Stator resistance	Rs	1.5Ω			

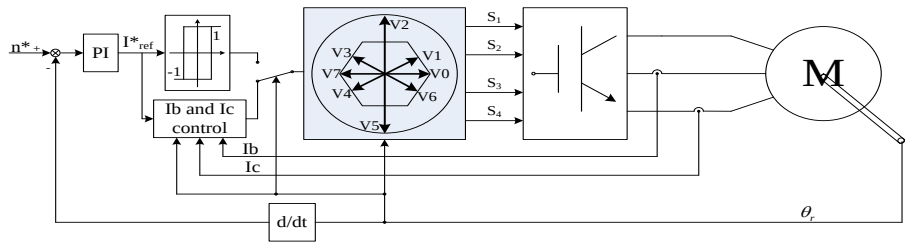

Fig. 5: Control system structure of four-switch BLDCM

the right switching pattern to control the current on phase-*b* and -*c* independently will reduce the distorted currents on those phases and result in a smoother overall current and electromagnetic torque. Solution to the above phenomenon is explained in detail below:

For BLDC motor with two-phase conduction, one of phase current should be zero as shown in Table 2. This can be achieved in sec. 3, 6, 9 and 12 whereas in sec. 1, 2, 4, 5, 7, 8, 10 and 11 phase-*a* current I_a is uncontrollable due to the split capacitors. In sec.1, 2, 4, 5, 7, 8, 10 and 11, voltage vectors V_2 and V_5 cannot be directly used, instead phase current I_b and I_c should be individually controlled by properly selecting the S_1, S_2, S_3, and S_4 switches, such as if the rotor position resides in sec. 2 and the rotor rotates in CCW direction then to increase the phase-*b* current I_b S_1 should be "1" and S_2 is "0" and vice versa to decrease the I_b. To increase the phase-*c* current I_c S_3 should be "0" and S_4 should be "1" and vice versa to decrease the I_c. Reference current value for those phase current should be the desired total reference current $I_{bref} = I_{cref} = I_{ref}$. This special current control phenomenon can be explained with the aid of the program flow chart in Fig. 4. Consequently, in sec.1, 2, 4, 5, 7, 8, 10 and 11 only phase-*b* and -*c* current are controlled independently and therefore the I_a is tried to be kept at zero value. This will eliminate the distorted current problem on each phase in two-phase conduction four-switch BLDC motor drive.

The direction of the rotor is important to define the specific switching pattern. If the rotor direction is CW, then the above claims are reversed, such as in sec. 2 to increase the phase-*b* current I_b S_1 is "0" and S_2 is "1" and vice versa for decrementing the I_b. The same is true for the phase-*c* current I_c.

SIMULATION AND EXPERIMENTAL RESULTS

The control system adopts the double-loop structure. The inner current loop maintains the rectangular current waveforms, limits the maximum current, avoids undesired distortions current that is generated by back-EMF of the uncontrolled phase

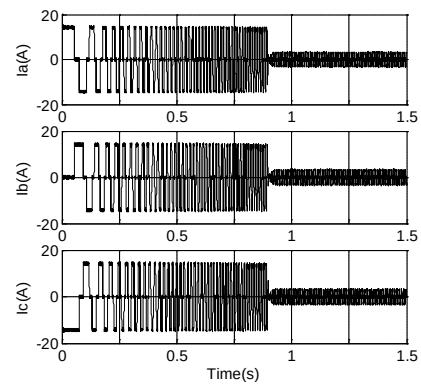

Fig. 6: Current curve under reference rated speed and rated torque

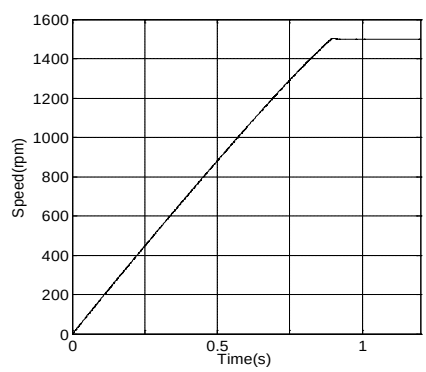

Fig. 7: Speed curve under reference rated speed and rated torque

(phase-*a*) and ensures the stability of the system. The outer speed loop is designed to improve the static and dynamic characteristics of the system. The structure of the system is shown in Fig. 5 and the parameters of BLDCM are shown in Table 4.

To verify the correctness and feasibility of the proposed strategy for the four-switch three phase BLDCM drive, a complete simulation system has been built by Matlab/Simulink (max(dv/dt = 2000)). The simulation content as follows:

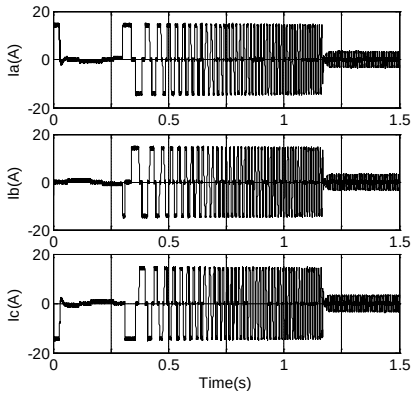

Fig. 8: Current curve under different reference speed and rated torque

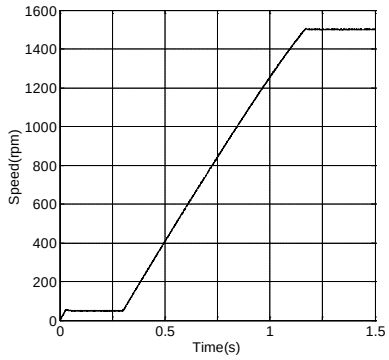

Fig. 9: Speed curve under different reference speed and rated torque

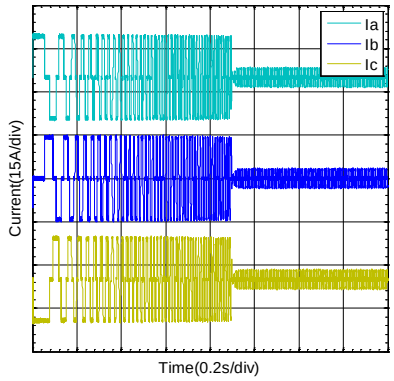

Fig. 10: Current curve under rated speed and rated torque

Firstly, the motor starts up with a speed reference of rated speed and rated load. The results are shown in Fig. 6 to 7. From Fig. 6, it can be seen that the current of phase a, phase b and c are close to ideal quasi-square waveform and the undesired distortions current, which is generated by back-EMF of the uncontrolled phase (phase-*a*) , is rejected in static and dynamic operation. From Fig. 6, it can be seen that speed curve show only slight overshot, and the transient process is also short.

Secondly, the motor starts up with a speed reference of 50 rpm and a load of 1Nm. At 0.6s, the

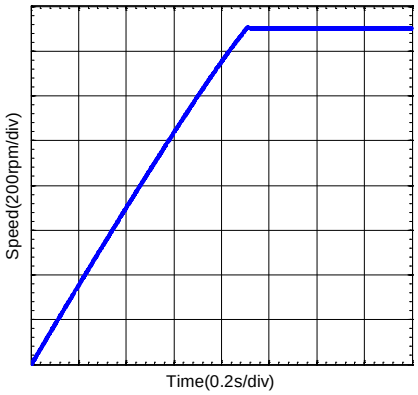

Fig. 11: Speed curve under reference rated speed and rated torque

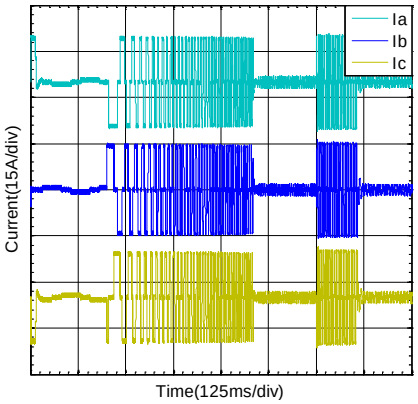

Fig. 12: Current curve under different reference speed and rated torque

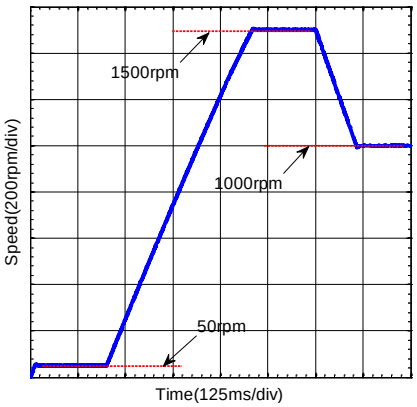

Fig. 13: Speed curve under different reference speed and rated torque

speed reference and load step to the rated ones. The results are shown in Fig. 8 to 9. From Fig. 8, it can be seen that the current of phase a, phase b and c are close to ideal quasi-square waveform in low speed and high speed scope. The problem of undesired distortions current generated by back-EMF of the uncontrolled phase (phase-*a*) is solved in low speed and high speed scope.

The whole system is implemented by the dsPIC6010A, the structure of experimental system and BLDCM parameters are respectively shown in Fig. 5 and table 4 (max(dv/dt = 2000)). The experimental content as follows:

Firstly, the motor starts up with rated speed and rated load. The experimental results are shown in Fig. 10 to 11.

Secondly, the response characteristics under the changed speed and the rated load are shown, in Fig. 12 to 13.

From Fig. 10 to 13, it can be seen that whether working at low speed and middle speed or at rated speed, the motor performs satisfactorily. Phase currents maintain rectangular waveforms, speed curve is stable with slight overshot and short transient process.

CONCLUSION

In this study, the four-switch converter topology is studied to provide a possibility for the realization of low cost and high performance three-phase BLDCM drive system. From the analysis, a novel direct current control topology for four-switch BLDCM drive has been proposed. The algorithm provides a novel voltage space vector and proper selection table of voltage vector for satisfaction system performance. The algorithm is easy to implement on the microcontroller. Finally, qualified performance was verified by simulation and experimental results under different working conditions.

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