Feasibility of Four-Switch Three-phase Brushless DC Motor Control Scheme Based on Quasi Z-Source Network

Lirong Shen[1,2*] Kun Xia[2,3]
[1] Shanghai University of Medicine and Health Sciences, Shanghai, China
[2]School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai, China
[3]National Engineering Laboratory of Energy-saving Motor & Control Technique, Hefei, Anhui, China
E-mail:360035344@qq.com

***Abstract*—This paper proposes a novel four-switch three-phase brushless dc motor control scheme based on quasi Z-source network (QZFSTP), which improves the utility ratio of DC voltage, extends the range of speed and increases the output torque. The additionally partial circuits of quasi Z-source network and the bridge arm of four-switch inverter constitute the quasi Z-source converter. During the operation of motor, shoot-through states are inserted. Then the input voltage of inverter increases and the performance of motor can be markedly improved. The operating principle of four-switch three-phase (FSTP) brushless dc motor are analyzed, and the new topology and its controlling method are illustrated in detail. The experimental result indicated that the novel circuit structure could solve above problems effectively.**

Keywords—Brushless dc motor; Quasi Z-source networ; experimental result

I. INTRODUCTION

Brushless dc motor is widely applied in various fields, because of its high power density, large output torque and quickly dynamic response, etc. Four-switch three-phase brushless dc motor is developed based on the driving circuit that is composed of conventional six-switch inverter. It has the advantages of low-driven cost and less switching loss. Therefore, it is of great significance to research on performance enhancements of four-switch three-phase brushless dc motor.

According to the deficiency of FSTP brushless dc motor, many scholars at home or abroad put forward a series of improved strategy. In full dc-link voltage period, the distortion of phase current will happen for existence of C phase back-EMF. Consequently, the current control based voltage vector is adopted in paper [1-2]. It can make the C phase current converge to zero through inserting adjusting vectors. The strategy is easy to implement and has merits of fixed frequency, high stability and rapid dynamic response. In paper [3], the double closed-loop control that contains speed and current hysteresis loop are established. The back-EMF of silent phase is compensated by detecting and controlling the phase current independently. Then the distortion of phase current is restrained effectively. To further reduce controlling costs, a novel control scheme of four-switch three-phase brushless dc motor without current sensor is presented in paper [4-5]. The commutation time of motor can be determined through the zero-crossing detection for terminal voltage. Meanwhile, the phase error is significantly decreased for no need of delaying 30 or 90 electrical angles. The paper [6] introduces a novel topology of five-switch three-phase brushless dc motor to extend the range of speed and improve the load capacity when supply voltage is low or battery. It combines four-switch three-phase inverter with the boost circuit to increase the input voltage of inverter by three-effective-vector current control. Furthermore, it features the compact structure and simple arithmetic.

A novel topology for FSTP brushless dc motor is presented in the paper. The quasi Z-source converter boosts the input voltage of brushless dc motor to enhance its dynamic performance.

II. OPERATINGN PRINCIPLE OF FSTP BRUSHLESS DC MOTOR

The conventional topology of FSTP brushless dc motor is shown in Fig.1, and the dc bus voltage is U_{dc}. The phase current of stator windings are driven by rectangular wave in order to reduce the torque ripple. As a result, table 1 lists the conducting sequence of some components. Taking mode II and III as an example, its working process is analyzed. Depending on table I, the power switch Q_1 and Q_4 are on at this moment, A and B phase current are conducting and C phase current is regarded as be silent. Hence, the power applied to motor is U_{dc}. Since, there is the commutation region before the motor enter the next working mode. In the beginning of mode III, Q_4 is switched off and Q_1 is held on. The B phase current does not vanish immediately due to the existing of winding inductance, and decreases progressively via the freewheel diode. Meanwhile, the C phase current increases gradually the steady value. The motor is fed by half of U_{dc} after the commutation interval.

Based on the above analysis, it is found that the asymmetrical voltages is one of drawbacks of FSTP brushless dc motor, which restricts the change rate of phase currents and the speed of motor.

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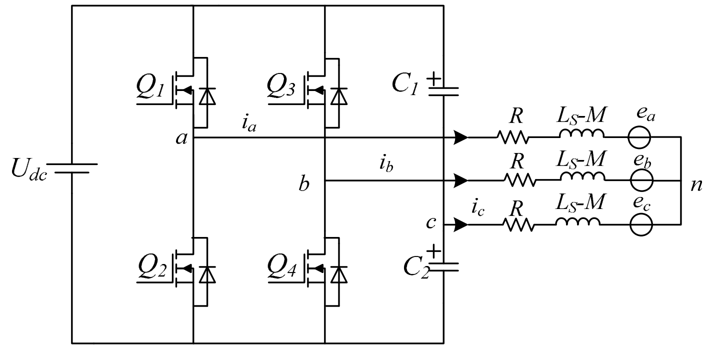


Fig.1. Circuit topology of FSTP brushless dc motor driver

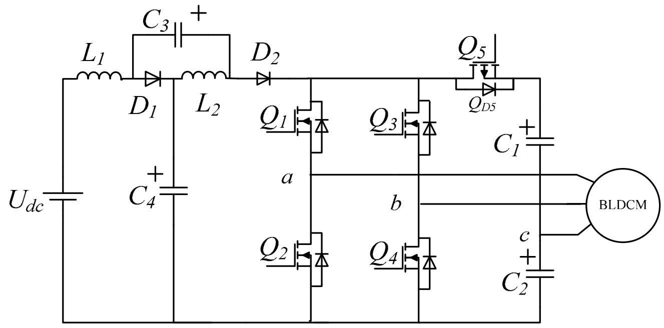


Fig.2. Circuit topology of QZFSTP brushless dc motor driver

On the other hand, due to C phase of motor is connected to the mid of two capacitors in series, three phase currents affected by C phase back-EMF are unexpected and distorted in mode II and V.

TABLE I.
STATUS OF DEVICES IN SIX MODES OF FSTP MOTOR

Mode	Hall	Active phase	Silent phases	Conducting device
I	001	C/B	A	Q_1
II	101	A/B	C	Q_1,Q_4
III	100	A/C	B	Q_1
IV	110	B/C	A	Q_3
V	010	B/A	C	Q_3 ,Q_2
VI	011	C/A	B	Q_2

III. THE CONTROL STRATEGY OF NEW TOPOLOGY

According to Fig.2, it is the circuit topology of QZFSTP brushless dc motor driver. The partial circuit of quasi Z-source converter is added before the input of FSTP inverter. Moreover, the power switch Q_5 is applied between the bridge arm of phase A and phase B.

The current control scheme based voltage vector is adopted, and the working time of voltage vector is determined through the speed and current double closed loop. From table I, $V(q_1q_2q_3q_4q_5)$ is defined as the voltage vector , Which q_x is the state of switch Q_x , the switch Q_x is on if q_x is '1', and off versus '0', $x\in\{1,2,3,4,5\}$. And V(10001), V(00101), V(10001), V(10011), V(00011), V(00101), V(01101) , V(01001), V(01000), V(11000), V(00010), V(00110) and zero vector V(00000) are involved.

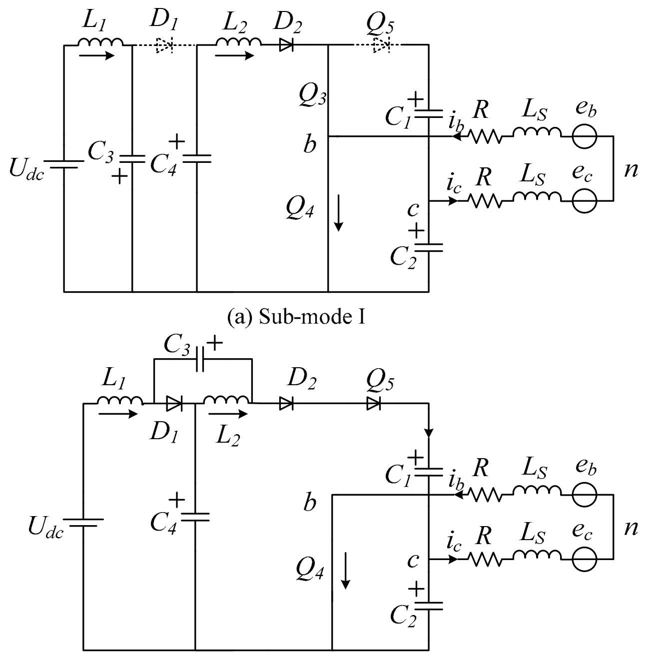
In response to the above analysis of deficiencies of FSTP brushless dc motor, the principles overcoming them for new circuit are studied in detail as follows.

A. Boosting DC Voltage of FSTP Inverter

Only half of DC bus voltage participates in work on account of the particularity of FSTP inverter. Nevertheless, brushless dc motor operates under lower than the rated voltage. For this case, the quasi Z-source network works in boosting status in mode I and VI. Then DC voltage of FSTP inverter increases and the normal operation of motor would not be disturbed. Taking mode I for instance, the running principles of motor are analyzed.

As shown in Fig. 3(a), it is equivalent circuit when the upper and lower devices of phase leg are gated simultaneously. At the moment, the power U_{dc} and capacitor C_3 recharge inductance L_1, and L_1 stores energy. Also, the capacitor C_4 recharges inductance L_2, and L_2 stores energy. The brushless DC motor is fed by the power of capacitor C_2. The reverse bias voltage across diode D_1 blocks itself from working. The reason why Q_5 is switched off is preventing the capacitor C_1 and C_2 from being short circuited.

The equivalent circuit when the switch Q_4 is on is shown in Fig. 3 (b). In this case, the inductances release energy. The power U_{dc} and inductance L_1 recharge capacitor C_4, also the inductance L_2 recharges capacitor C_3. Hence, the voltage of inverter side rises to the sum of U_{dc}, C_3 and L_2. For the sake of reducing switching power loss, the switch Q_5 should keep off. Therefore, there are three voltage vectors participating in work, and they are V(00000), V(00001) and V(00110) in mode I. Same explanations can be found in mode VI.



(a) Sub-mode I

(b) Sub-mode II

Fig.3. The principle of boosting voltage in mode I

B. Minimizing the Distortion of Phase Currents Caused by C Phase Back-EMF

In mode II and IV, there exists current distribution in C phase windings due to the C phase back-EMF is not zero. Based on KCL, there is relationship among A, B, C phase currents. Therefore, the distortion of phase currents would happen if the switch Q_1 and Q_4 are gated by the same control signal.

In order to solve the above problem, two switches of one bridge arm should be controlled independently by detecting the value of C phase current value. Taking mode II as an example, the control method on minimizing the distortion of phase currents is analyzed theoretically. The typical mathematical model of FSTP brushless DC motor is as:

$$\begin{cases} U_{ag}=sU_{dc}=Ri_a+(L_S-M)\dfrac{di_a}{dt}+e_a+U_{ng} \\ U_{bg}=(1-s)U_{dc}=Ri_b+(L_S-M)\dfrac{di_b}{dt}+e_b+U_{ng} \\ U_{cg}=Ri_c+(L_S-M)\dfrac{di_c}{dt}+e_c+U_{ng} \end{cases} \quad (1)$$

$$e=e_a+e_b+e_c \quad (2)$$

Where i_x is x phase current, R is the phase resistance, L_s is the self-inductance, M is the mutual inductance, e_x is the back-EMF voltage of x phase, U_{xg} is the voltage between x phase and ground, U_{ng} is the voltage between n point and ground, s=1 refers to the switch is on and s=0 refers to the switch is off.

From (1) and (2), the voltage between n point and ground is given by

$$U_{ng}=\frac{1}{3}[U_{dc}+(U_{cg}-e)] \quad (3)$$

According the above equation, we found out that U_{ng} is determined by U_{dc}, U_{cg} and e, and is irrelevant to the status of switches. Then, the value of C phase current could not be regulated, two cases of which can be described as:

$$\begin{cases} (U_{cg}-e)=\dfrac{1}{6}U_{dc}\Rightarrow U_{ng}=\dfrac{1}{2}U_{dc}\Rightarrow i_c=0 \\ (U_{cg}-e)\neq\dfrac{1}{6}U_{dc}\Rightarrow U_{ng}\neq\dfrac{1}{2}U_{dc}\Rightarrow i_c\neq 0 \end{cases} \quad (4)$$

Therefore, the switch Q_1 and Q_4 should be controlled independently. A new equation is obtained by:

$$\begin{cases} U_{ag}=s_1U_{dc}=Ri_a+(L_S-M)\dfrac{di_a}{dt}+e_a+U_{ng} \\ U_{bg}=(1-s_4)U_{dc}=Ri_b+(L_S-M)\dfrac{di_b}{dt}+e_b+U_{ng} \\ U_{cg}=Ri_c+(L_S-M)\dfrac{di_c}{dt}+e_c+U_{ng} \end{cases} \quad (5)$$

That, s_1=1 refers to Q_1 is on, s_1=0 refers to Q_1 is off and the same to s_4.

By simplifying the equation (5), the voltage between n point and ground can be described as:

$$U_{ng}=\frac{1}{3}[U_{dc}+(U_{cg}-e)]+(s_1-s_4)U_{dc} \quad (6)$$

From (6), it is found out that the value of U_{ng} can be adjusted by s_1 and s_4. According to, there are three circumstances. They are given by:

$$\begin{cases} (U_{cg}-e)=\dfrac{1}{6}U_{dc}(i_c=0) \\ s_1=s_4 \end{cases} \Rightarrow U_{ng}=\frac{1}{2}U_{dc}\Rightarrow i_c=0 \quad (7)$$

$$\begin{cases} (U_{cg}-e)>\dfrac{1}{6}U_{dc}(i_c<0) \\ s_1=0,s_4=1 \end{cases} \Rightarrow U_{ng}\downarrow\Rightarrow i_c\uparrow \quad (8)$$

$$\begin{cases} (U_{cg}-e)<\dfrac{1}{6}U_{dc}(i_c>0) \\ s_1=1,s_4=0 \end{cases} \Rightarrow U_{ng}\uparrow\Rightarrow i_c\downarrow \quad (9)$$

From equation (7), (8), (9), the C phase current can be regulated close to zero. If i_c is less than zero, Q_1 would be switched off to make i_c larger. Similarly, Q_4 should be switched off to make i_c smaller if i_c is larger than zero. But, in fact, it is impossible that i_c reaches zero accurately. I_{th} is defined as a small value close to zero. So, the controlling vectors are confirmed based on the value of C phase current in mode II. If $|i_c|<I_{th}$, the working vectors will be V(00001) and V(10011). If $i_c>I_{th}$, they will be V(00001), V(10001) and V(10011). If $i_c<-I_{th}$, they will be V(00001), V(00011) and V(10011). Same explanations can be found in mode V.

IV. Experiment Results and Analysis

The four-switch three-phase brushless DC motor control scheme has been implemented, in which the hardware circuit is built, and the chip STM32 is adopted. Referring to Fig.3, it is the system experimental platform, where BLDC motor, magnetic powder brake, controlling and driving board, DC stabilized power supply, digital oscilloscope are included. The nominal parameters of the brushless dc motor are as follows: 24V (rated voltage), 31W (rated power), 2000r/min (rated speed), 2 (number of poles), 0.5Ω (stator resistance), 0.5mH (stator inductance).And the parameters of quasi Z-source network are C_1=C_2=4700μF, C_3=C_4=1000μF and L_1=L_2=45mH.

As shown in Fig. 5, 6, the channel 1 of oscilloscope is waveform of mode and channel 2 is the C phase current. The traditional current control method based on voltage vector is used when U_{dc} is 12V in Fig. 5(a). The C phase current is distorted seriously because of the existing of C phase back-EMF in mode II and V. Nevertheless, the C phase current is almost close to zero in full-voltage mode when the switches are controlled separately in Fig. 5(b). Moreover, Fig. 6 shows the comparison of A phase current before and after the improvement, we found that the waveform of A phase current becomes more ideal when the new approach works.

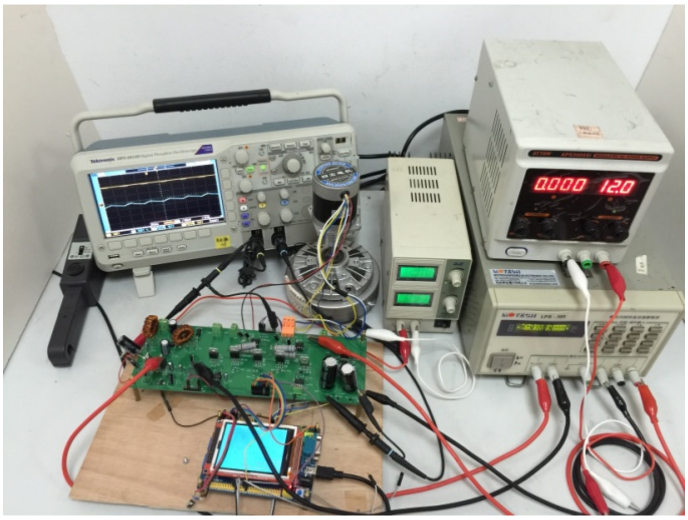
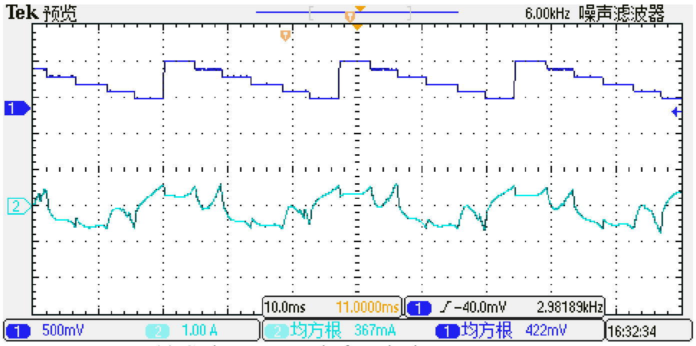
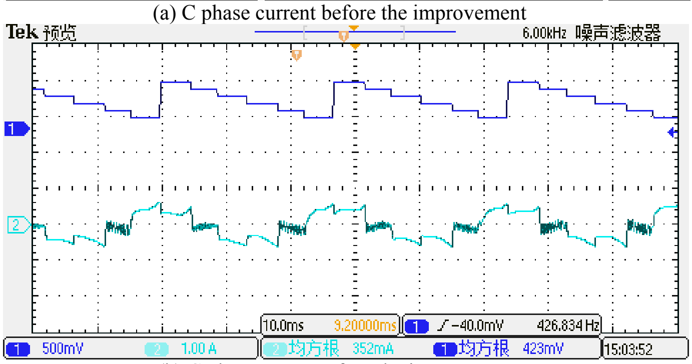


Fig.4. The system experimental platform

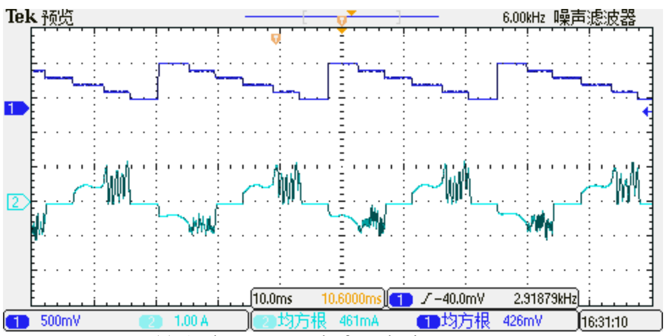


(a) C phase current before the improvement

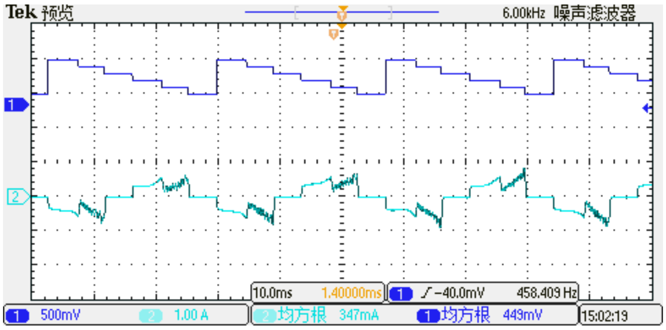


(b) C phase current after the improvement

Fig.5. The comparison of C phase current before and after the improvement



(a) A phase current before the improvement



(b) A phase current after the improvement

Fig.6. The comparison of A phase current before and after the improvement

As shown in Fig.7, the channel 1 of oscilloscope is waveform of DC bus voltage and channel 2 is the voltage of inverter for new topology when the short-through duty cycle is 25%. Theoretically, the average output voltage of quasi Z-source is:

$$\overline{V_o} = \frac{1}{1-2D} V_{in} \tag{10}$$

Where V_{in} is the input voltage, and D is the short-through duty. So, the output voltage of inverter should be 24V. But in fact, it fluctuates from 17.5V to19V due to that the short-through state can be inserted in only two modes. From Fig.8, the capacitor C_2 is charged in mode I and VI and is discharged in mode II, III, IV and V. And the A phase current increases and is not influenced by the raising of input voltage of inverter in Fig.9. As shown in Fig. 10(a), the speed of conventional FSTP BLDC motor is 1000r/min (500mv) when U_{dc} is 12V. Under the same condition, the speed of QZFSTP BLDC motor reaches 1800r/min (760mv). It is obviously that the QZFSTP BLDC motor control system is better.

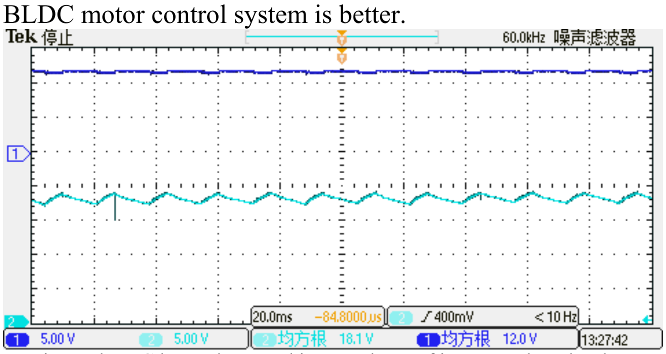


Fig.7. The DC bus voltage and input voltage of inverter when the shoot-through status is inserted

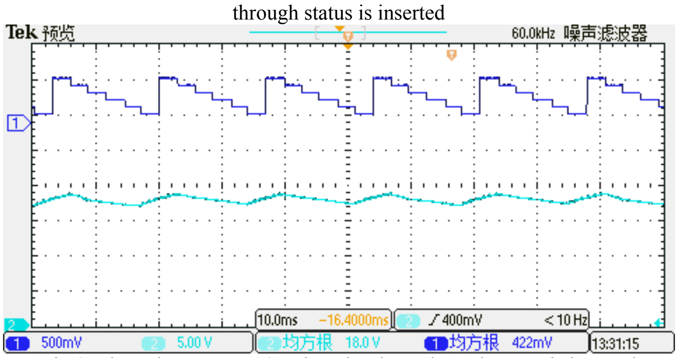


Fig.8. The voltage across C_2 when the shoot-through status is inserted

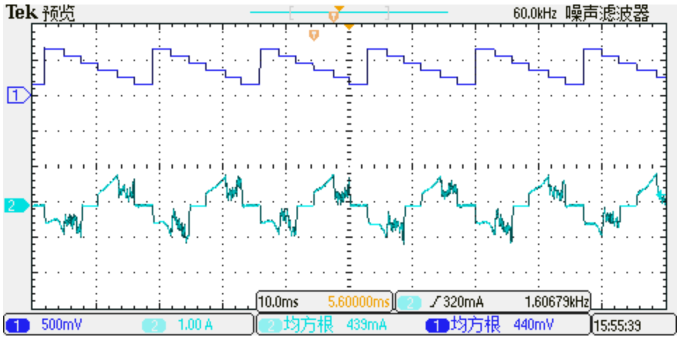
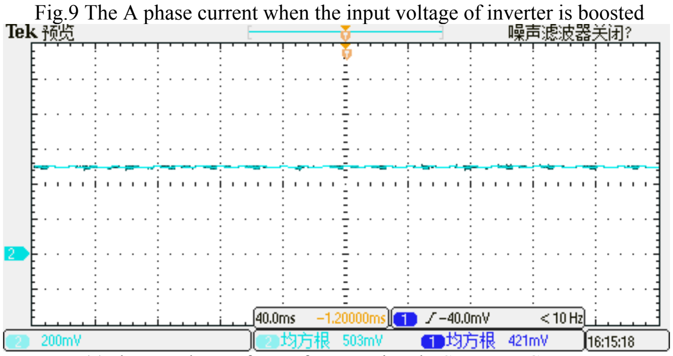
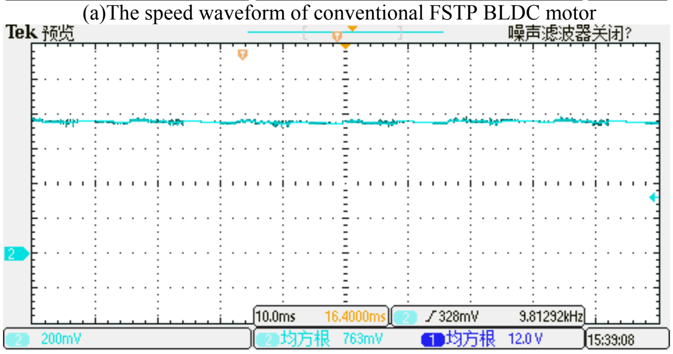


Fig.9 The A phase current when the input voltage of inverter is boosted



(a)The speed waveform of conventional FSTP BLDC motor



(b) The speed waveform of QZFSTP BLDC motor

Fig.10 The comparison of speed for FSTP and QZFSTP BLDC motor (U_{dc}=12V)

V. Conclusion

A novel four-switch three-phase brushless dc motor control scheme based on quasi Z-source network is presented in the paper, which combines FSTP BLDC motor and quasi Z-source network. The experimental facilities are constructed and its results suggest:

- In mode II and IV, the distortion of phase current caused by C phase back-EMF is minimized by gating two switches independently.
- The input voltage of FSTP inverter is boosted to enlarge the range of speed and enhance the ability with load when quasi Z-source converter works.
- The new topology circuit is easy to implement, has rapid response and its control method is simple.

On the other hand, the cost is increased due to adding more devices, which results in reducing the reliability and increasing the complexity of system. Nevertheless, the performance of FSTP BLDC motor is improved actually, it has some application prospects.

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