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12-Switches Inverter Fed Brushless Dc Motor Variable Speed Drive System

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ABSTRACT:

Brushless dc motor has been used in industrial applications due to its low inertia, high power density, fast response, high reliability and maintenance-free. BLDC is usually supplied by hard-switching PWM inverter, which has low efficiency because the power losses across the switching devices are high. To reduce the losses, soft switching inverters have been introduced. Unfortunately, there are many disadvantages such as large dc link voltage ripple, complex control scheme, high device voltage stress etc.. This paper introduces a soft switching 12 switch inverter which generates notches of the dc bus voltage becomes to zero during chopping switches commutation to guarantee all switches working in zero voltage transition (ZVT). The result of this study is very effective for industrial applications.

INDEX TERMS:
Brushless dc motor (BLDC), Resonant dc link, soft switching, 12-switches inverter.

I.INTRODUCTION:

BRUSHLESS dc motor has been used in industrial applications because of low inertia, fast-response, high reliability and maintenance-free etc.. BLDC usually supplied by hard-switching PWM inverter, normally has low efficiency because the power losses across the switching devices are high. To reduce the losses, soft switching inverters have been introduced. Soft switching operation of power inverters has much attention in recent decades. In medium power applications, resonant dc link concept offered a practical and reliable way to reduce commutation losses and to remove individual snubbers. Thus it allows high operating frequencies and improved efficiency. The inverter is very simple to get the zero voltage switching (ZVS) condition of six main inverter switches just by adding single auxiliary switch.

However the inverter has the disadvantage of high voltage ripple of the dc link, high voltage stress of the switches, discrete pulse modulation (DPM) other than PWM control. To reduce the disadvantage of high voltage stress of the switches, actively clamped resonant dc link inverter was designed. The control scheme of inverter is very complex and the output contains sub harmonics which in some cases, cannot be accepted. To generate notches of the dc link at controllable instants, many quasi parallel resonant schemes were introduced. As a dwell is generally required after each notch, severe interferences occur, in multiphase inverters, leads to reducing the modulation quality. So, a new dc-rail parallel resonant one zero voltage transition (ZVT) voltage source inverter is designed, and overcomes many disadvantages mentioned above. Hence it requires two ZVT per PWM cycle, it would make unacceptable output and limits the switching frequency of the inverter.

The conventional three phase full wave inverter has the disadvantage of current ripple during commutation, so that the torque ripple of BLDC is high. Different authors proposed different methods to reduce torque ripple, but these methods have less effectiveness in practical applications because of motor parameter sensitivity and unacceptable performance over wide speed range.This paper introduces a new resonant dc link inverter for BLDC. The representation of the soft-switching inverter is shown in Fig. 1. This system contains an uncontrolled rectifier, a 12-switches inverter, a resonant circuit and control circuit. The resonant circuit comprises of three auxiliary switches (IGBT SL and switching thyristors Sa, Sb), a resonant inductor and a resonant capacitor. Each auxiliary switch work under either ZVS or ZCS condition. The inverter can generate voltage notches of dc link at controllable instants and width, such that main inverter switches (S1 – S12) of the inverter can get into ZVS condition. The conventional quasi resonant process is made into two half procedure for PWM operation.

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It has the advantage of low voltage ripple of the dc link, simple control scheme and low voltage stress of the switches. To reduce torque ripple, 12-switches inverter is designed. The inverter consists of three single phase inverters, and the three motor windings were connected to the three single phase inverters. The 12-switches inverter has other advantage for motor drives along with BLDC, but also for other ac motors likeinduction motor, synchronous motor. Normally the inverter requires many switching devices, for the given torque and and speed, the voltage stress across the switches can be reduced to half, and thus the total price of the switching devices would not be increased. Hence the price of switching device has reduced significantly, mainly for low power and medium power applications and the cost of switches has low proportion to the drive system. The control circuit contains commutation logic circuit of the BLDC, speed controller, auxiliary switches control circuit and gate signal drive.

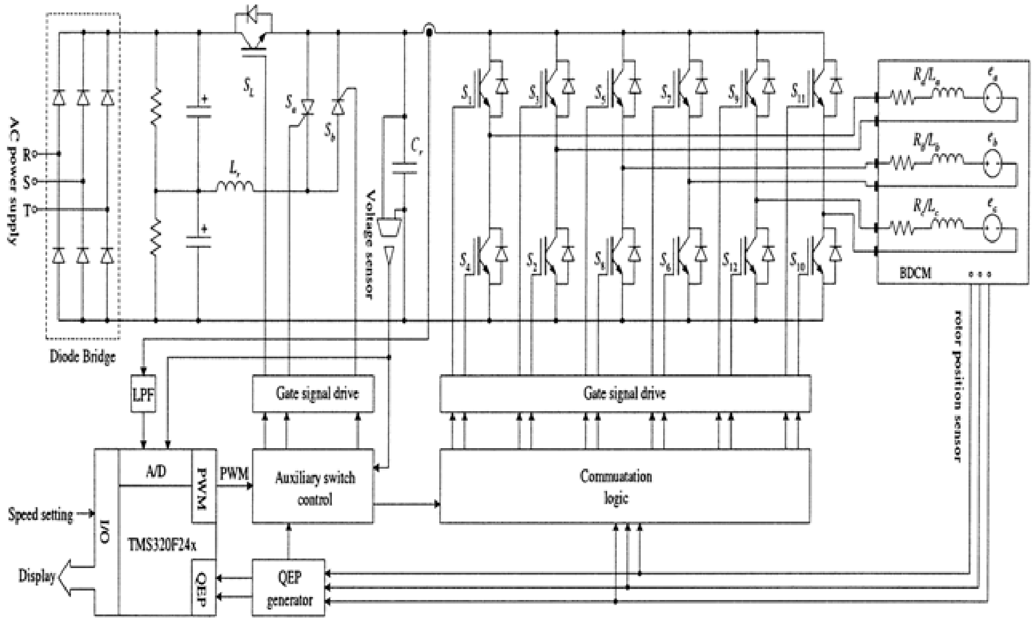

Fig. 1. Topology of soft-switching inverter for BLDC drive system

II. RESONANT CIRCUIT:

The resonant circuit contains of three auxiliary switches, a resonant inductor and a resonant capacitor. The auxiliary switches were controlled at certain instant to provide the resonance between inductor and capacitor. Hence the dc link voltage reaches to zero temporarily (voltage notch) and thus the main switches of the inverter get into ZVS condition.

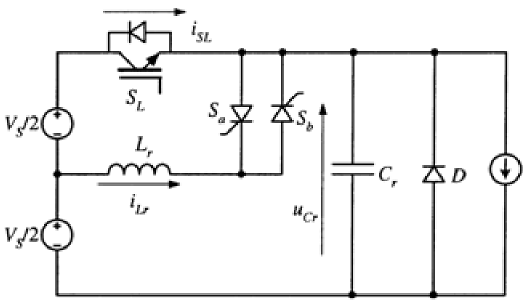

Fig.2. Equivalent circuit

A.OPERATION PRINCIPLE OF THE RESONANT CIRCUIT:

As the resonant procedure was very short, thus the load current was assumed constant. The equivalent circuit is shown in Fig. 2. The respective waveforms of gate signals of auxiliary switches, inductor current (iLr), resonant capacitor voltage (vCr) and current of switch SL (iSL) are shown in Fig. 3.

The dc link voltage reduces to zero and then starts raising up to dc supply voltage again which is called as one zero voltage transition process or one dc link voltage notch, shortened as ZVT. The operation of ZVT was divided into six modes.

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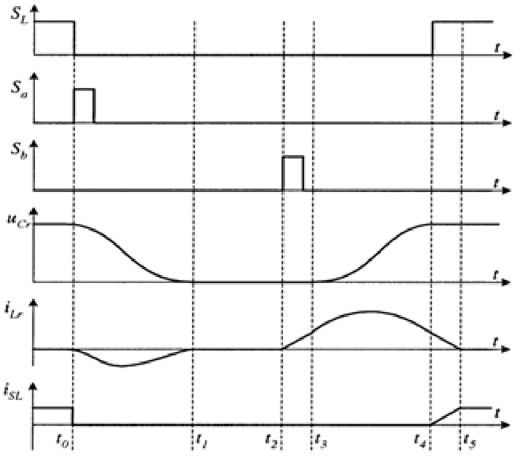
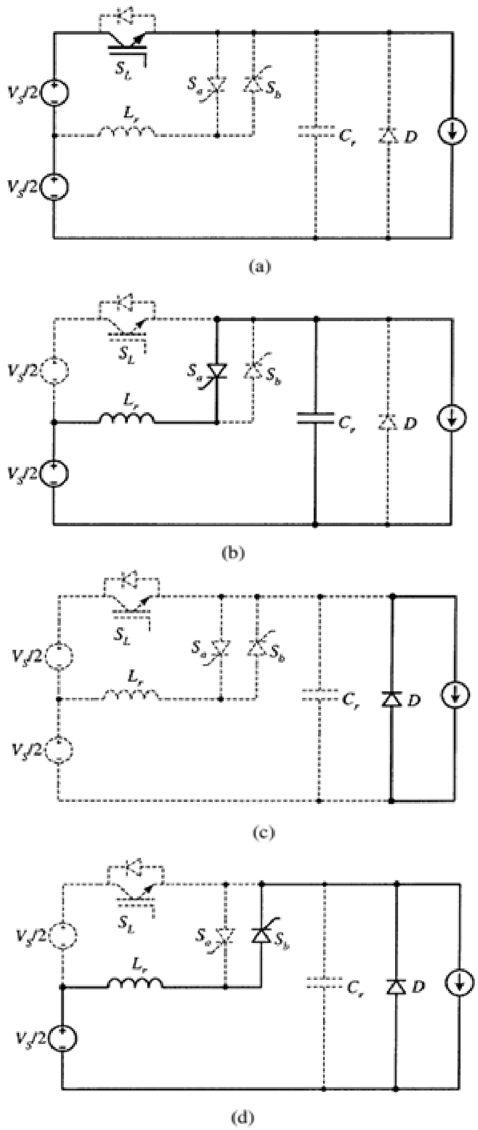


Fig.3. Waveforms of simplified circuit



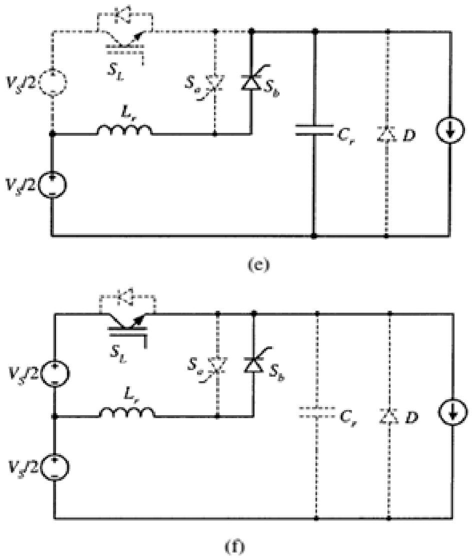


Fig.4.Operation mode of the zero voltage transition. (a) Mode 0, (b) Mode 1, (c) Mode 2, (d) Mode 3, (e) Mode 4, (f) Mode 5.

MODE 0 [shown in Fig. 4(a)] 0 < t < t0. The operation is similar to conventional inverter. Current flows from dc supply through SL to the load. The voltage across Cr (VCr) is equal to the supply voltage (Vs). The auxiliary switches Sa and Sb are in off state.

MODE 1 [shown in Fig. 4(b)] t0 < t < t1. When the inverter is in the instant for phase current commutation or PWM signal is dropped from “1” to “0,” thyristor Sa is triggered (ZCS turn on due to Lr) and IGBT SL is turned off (ZVS turn off due to Cr) at the same interval. Capacitor Cr resonates with inductor Lr, the voltage across capacitor Cr is reduced. Redefining the initial time we has the equation

$$\begin{cases} V_{Cr}(t) + R_{Lr} i_{Lr}(t) + L_r \frac{di_{Lr}(t)}{dt} = \frac{V_S}{2} \\ I_0 - i_{Lr}(t) + C_r \frac{dV_{Cr}(t)}{dt} = 0 \end{cases} \quad (1)$$

Where R_{Lr} is the resistance of inductor L_r, I_0 is load current, V_s is the dc supply voltage, taking initial conditions $V_{cr}(0) = V_S$, $i_{Lr}(0) = 0$, solving (1), we get

$$\begin{cases} V_{Cr}(t) = \left(\frac{V_S}{2} - R_{Lr} I_0\right) + \left(\frac{V_S}{2} - R_{Lr} I_0\right) e^{-\frac{t}{\tau}} \cos(\omega t) + \frac{1}{L_r C_r \omega} \\ X e^{-\frac{t}{\tau}} \left(\frac{1}{4} R_{Lr} C_r V_C - L_r I_0 + \frac{1}{2} R_{Lr}^2 C_r I_0\right) \sin(\omega t) \\ i_{Lr}(t) = I_0 - I_0 e^{-\frac{t}{\tau}} \cos(\omega t) - \frac{V_S + R_{Lr} I_0}{2 L_r \omega} e^{-\frac{t}{\tau}} \sin(\omega t) \end{cases}$$

(2)

Where

$$T = \frac{2L_r}{RL_r}, \quad \omega = \sqrt{\frac{1}{L_r C_r} - \frac{1}{\tau^2}}.$$

As resonant frequency is very high (that is several hundred KHz), $\omega_{Lr} >> R_{Lr}$, therefore resonant inductor resistance R_{Lr} will be neglected. Then (2) can be modified as

$$\begin{cases} V_{Cr}(t) = \frac{V_S}{2} + K\cos(\omega_r t + \propto) \\ i_{Lr}(t) = I_0 - K\sqrt{\frac{C_r}{L_r}}\sin(\omega_r t + \alpha) \end{cases} \quad (3)$$

Where

$$K = \sqrt{\frac{V_S^2}{4} + \frac{I_0^2 L_r}{C_r}}, \quad \omega_r = \sqrt{\frac{1}{L_r C_r}}, \quad \propto = tg^{-1}\left(\frac{2I_0}{V_S}\sqrt{\frac{L_r}{C_r}}\right).$$

Let $V_{cr}(t) = 0$, we get

$$\Delta T_1 = t_1 - t_0 = \frac{\pi - 2\alpha}{\omega_r} \quad (4)$$

$I_{Lr}(t_1)$ is zero at the same time. Then thyristor S_a is self turned-off.

MODE 2 [shown in Fig. 4(c)] t1 < t < t2. No auxiliary switch is fired and voltage of the dc link (Vc) is zero. Under ZVS condition the main switches of the inverter can be either turned on or turned off during the interval. The load current flows through the freewheeling diode D.

MODE 3 [shown in Fig. 4(d)] t2 < t < t3. As the main switches were turned on or turned off, so thyristor Sb is fired (ZCS turn on due to Lr) and iLr starts to raise up linearly in the auxiliary branch. The current in the freewheeling diode D starts to fall linearly. The load current is diverted from the freewheeling diode D to the resonant branch. But Vc is still zero. We have

$$\Delta T_2 = t_3 - t_2 = \frac{2I_0 L_r}{V_S} \quad (5)$$

At t_3, i_{Lr} equal to the load current Io and the current through the diode D becomes to zero. Thus the freewheeling diode D turn off under zero current condition.

MODE 4 [shown in Fig. 4(e)] t3 < t < t4. iLr is increasing continuously from Io and Vc is increased from zero when the freewheeling diode D is turned off. By redefining the initial time, we obtain the same equation as (1). Since the initial conditions is Vc(0) = 0, iLr(0) = I0, neglecting the inductor resistance, by solving the equation, we have

$$\begin{cases} V_{Cr}(t) = \frac{V_S}{2}[1 - \cos(\omega_r t)] \\ i_{Lr}(t) = I_0 + \frac{V_S}{2}\sqrt{\frac{C_r}{L_r}}\sin(\omega_r t) \end{cases} \quad (6)$$

When

$$\Delta T = t_4 - t_3 = \frac{\pi}{\omega_r} \quad (7)$$

V_{cr} = Vs, IGBT S_L is fired (due to ZVS turn on), $i_{Lr} = I_0$ again. The peak inductor current is derived from (6), that is

$$i_{Lr-m} = I_0 + \frac{V_S}{2}\sqrt{\frac{C_r}{L_r}} \quad (8)$$

MODE 5 [shown in Fig. 4(f)] t4 < t < t5. When dc link voltage equals to the supply voltage, then auxiliary switch SL is turn on (ZVS turned on due to Cr). ILr is decreasing linearly from I0 to zero at interval t5 and thyristor Sb is self turned off.ZThen mode 0 will repeat again. The operating principle of the other procedure is similar to the conventional inverter.

III. OPERATION PRINCIPLE OF THE 12-SWITCHES INVERTER

A.Commutation Process With Conventional Inverter

Assumption the rotor reluctance of BLDC is constant independent rotor position θr and the fundamental components of the flux linkages contributed by the permanent magnet are considered. Then the mathematical model of the BLDC can be written as [10]

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \rho \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (9)$$

Where R is the phase resistance, L is the phase inductance, M is the mutual inductance, v is the phase voltage, i is the phase current, e is the phase back EMF, and ρ is the derivative operator (d / dt).

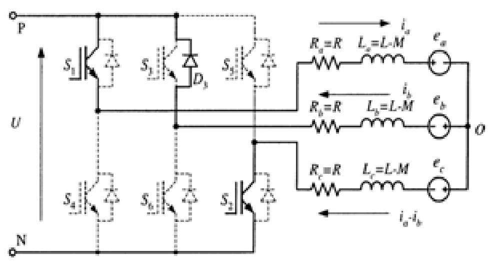


Fig. 5. Equivalent circuit during commutation

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$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}$$

$$\text{X} \quad \rho \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (10)$$

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \qquad (11)$$

So the equivalent circuit of the BLDC drive system during commutation can be simplified as Fig. 5. Neglecting the voltage drop across the diodes and switches, the governed current voltage equations can be obtained [11]

$$\begin{cases} V = i_a R_a + L_a \dfrac{di_a}{dt} + e_a + e_c + L_c \dfrac{d(i_a - i_b)}{dt} + (i_a - i_b) R_c \\ i_a R_a + L_a \dfrac{di_a}{dt} + e_a + e_b + L_b \dfrac{di_b}{dt} + i_b R_b = 0 \end{cases} \qquad (12)$$

Where $R_a = R_b = R_c = R$, $L_a = L_b = L_c = L - M$, $e_a = e_b = e_c = e$. For approximate solution, assume that circuit has reached the steady state condition before commutation; we have the equation as conventional dc motor.

$$V = 2IR + 2e \qquad (13)$$

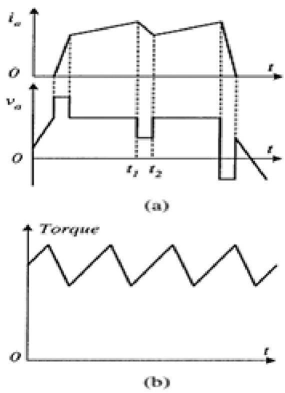


Fig.6. Waveforms of phase current, phase voltage and torque with conventional inverter, (a) Phase A current and voltage. (b) Torque

Thus we can draw the waveforms of current and voltage of phase A in Fig. 6(a) and torque in Fig. 6(b). From the waveforms we can observe that the current ripples of phase A is the cause for commutation, the phase voltage is decreased between t1 and t2. Maintaining the uncommutated phase voltage to be constant, the current ripples can be eliminated, and the torque ripples can be decreased. For this purpose, half wave inverter can be used, that is conventional half wave inverter, Miller inverter, C- dump inverter and Buck – fronted inverter.

The drawback is the efficiency of the motor is low with these inverters for there is only one winding conducting at the same time. So the 12 – switches inverter is introduced.

B.Commutation Process With 12-Switches Inverter:

The topology of the inverter is shown in Fig. 7. It comprises of three single-phase inverters and the three armatures of the motor connected to them respectively. Thus the phase current can be controlled independently and not affected by other commutation procedure.

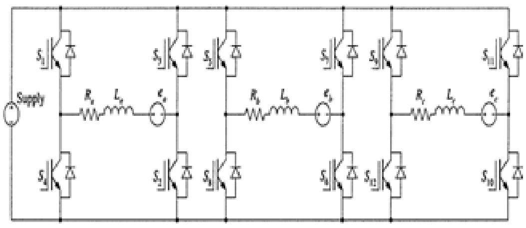


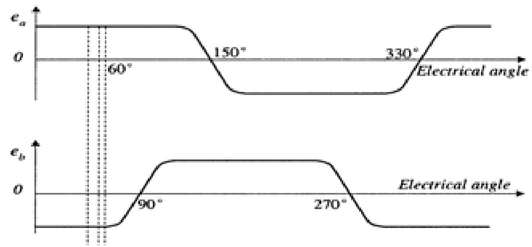
Fig.7. Topology of 12-switches inverter

With the 12-switches inverter, two independently governed current and voltage equations of the phase B, C can be obtained (current of phase A is not affected by commutation)

$$\begin{cases} V = R_b i_b + L_b \dfrac{di_b}{dt} + e_b \\ -V = R_c i_c + L_c \dfrac{di_c}{dt} + e_c. \end{cases} \qquad (14)$$

For trapezoidal BLDC, the waveform of the back EMF is shown in Fig. 8(a). If the commutation occurs at time t_1, with initial conditions $i_{b0+} = -I$, $i_{c0+} = 0$, $e_b \approx e_c = -(U - IR)$, solving the equation, we have

$$\begin{cases} i_b = \dfrac{2V}{R} - I + \dfrac{2V}{R} e^{-\frac{R}{L-M}t} \\ i_c = I\left(1 - e^{-\frac{R}{L-M}t}\right) \end{cases} \qquad (15)$$



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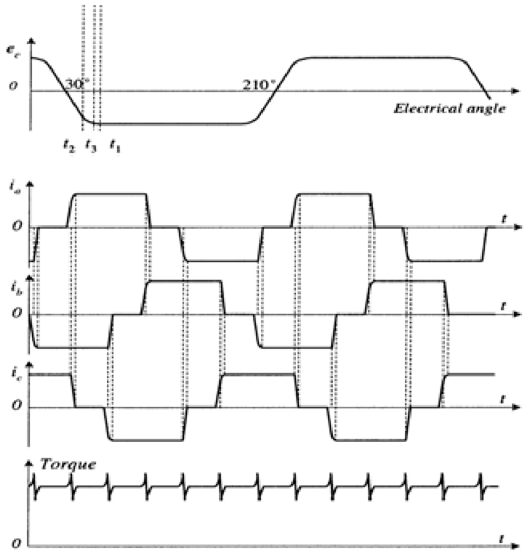

Fig.8. Waveforms of back EMF, phase current and torque with 12-switches inverter, (a) Back EMF of trapezoidal BLDC. (b) Phase current and torque.

ib can reduce to zero very fastly, but the ic raises very slowly. In order to minimise the commutation procedure, S11, S12 are turned on at t2, S7, S8 are turned off at t3, then ic can be increased quickly. As the back EMF Vs time (or electrical degree) is a continuous function, there exists an instant t2 that ic can reach the steady state value at t1. Such that the phase current is smoother, and the motor torque was reduced [as shown in Fig. 8(b)].The 12-switches inverter not only reduces the torque ripple significantly, but also includes the advantage of the conventional three phase half wave inverter and full wave inverter, but has other advantage as follows.

•For the given supply voltage, the current flows through one winding only other than two windings in conventional inverters, so it can offer twice phase current and torque. The supply only needs to get over back EMF of one phase, so that the speed of the motor is also doubled.
•For the given motor speed, it only requires half supply voltage, such that the voltage stress of switching device is reduced to half. It is very easier to select required device and the price of two low voltage stress devices is lesser than that of one voltage stress device.
•The insulation class requirement can also be reduced.
•The inverter is also applicable to other motors like synchronous motor, induction motor and no dead beat time is required.
•The phase current can also be controlled and is more flexible.

IV. SIMULATION RESULTS:

The simulation results of phase current, phase voltage, speed and torque of conventional three-phase full wave inverter and 12-switches inverter are shown in Fig. 9. The waveforms in Fig. 9(a) are with conventional three-phase full wave inverter, and supply voltage is 500 V; waveforms in 9 (b) are with 12-switches inverter, and supply voltage is 250 V. From the simulation results we can see that average torques in the two inverters are almost the same, the first order of the torque harmonics is much less in 12-switches inverter as compared to conventional inverter. So the torque ripples with 12-switches inverter reduced significantly. The magnitude of phase current and torque with the two inverters is similar, the speed is also similar, but the supply voltage of conventional inverter is twice as that of 12-switches inverter.

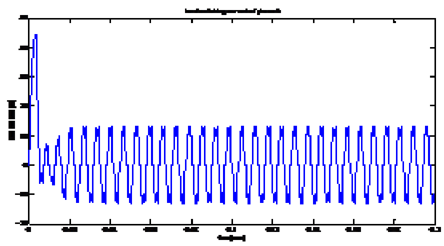

Fig. 9. Hard switching current of phase A

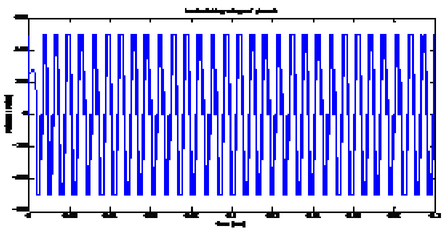

Fig.10. Hard-switching voltage of phase A

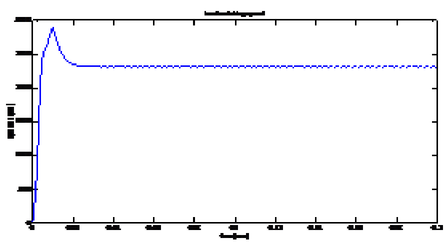

Fig.11. Hard-switching speed

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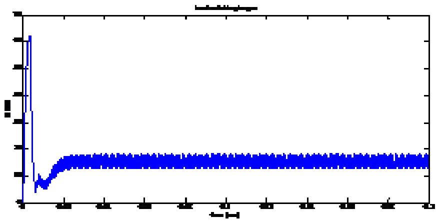

Fig.12. Hard-switching Torque

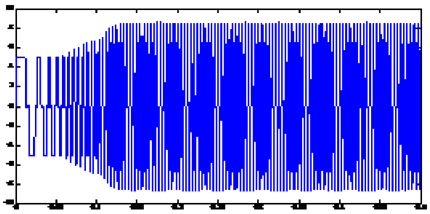

Fig.13. Soft-switching current of Phase A

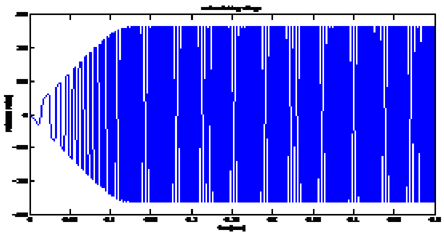

Fig.14. Soft-switching voltage of phase A

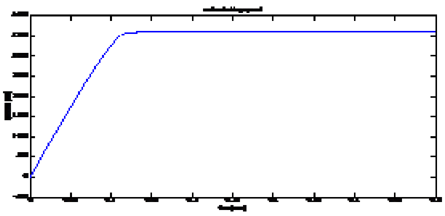

Fig.15. Soft-switching Torque

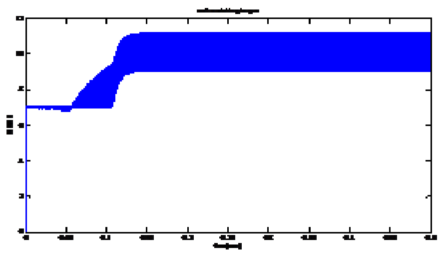

Fig.16. Soft-switching speed

V. CONCLUSION:

A novel soft switching inverter for BLDC variable speed drive system is introduced. Operation principles, analysis and simulation results are

1.All switches work under soft-switching condition, so the power losses are less. Only one dc link voltage notch is necessary for every PWM cycle. Simple auxiliary switches control scheme.

2.Torque ripple of motor is reduced significantly. For the given voltage of supply, torque and speed of the motor are doubled.

3.For the given speed of the motor, the voltage stress of the switching device is reduced to half, the inverter is also applicable to induction motor.

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