

A Ringing Surge Clamper Type Active Auxiliary Edge-Resonant DC Link Snubber-Assisted Three-Phase Soft-Switching Inverter using IGBT-IPM for AC Servo Driver

Junji Yoshitsugu, Masanobu Yoshida, Eiji Hiraki, Kenji Inoue, Tarek Ahmed and Mutsuo Nakaoka

Abstract - This paper presents an active auxiliary edge-resonant DC link snubber with a ringing surge damper and a three-phase voltage source type zero voltage soft-switching inverter with the resonant snubber treated here for the AC servo motor driver applications. The operation of the active auxiliary edge-resonant DC link snubber circuit with PWM voltage is described, together with the practical design method to select its circuit parameters. The three-phase voltage source type soft-switching inverter with a single edge-resonant DC link snubber treated here is evaluated and discussed for the small-scale permanent magnet (PM) type-AC servo motor driver from an experimental point of view. In addition to these, the AC motor stator current and its motor speed response for the proposed three-phase soft-switching inverter employing Intelligent Power Module(IPM) based on IGBTs are compared with those of the conventional three-phase hard-switching inverter using IPM. The practical effectiveness of the three-phase soft-switching inverter-fed permanent magnet type AC motor speed tracking servo driver is proven on the basis of the common mode current in a novel type three-phase soft-switching inverter-fed AC motor side and the conductive noise on the mains terminal interface voltage as compared with those of the conventional three-phase hard-switching inverter-fed permanent magnet type AC servo motor driver for the speed tracking applications.

Keywords - edge-resonant dc link snubber with surge clipper, three-phase voltage source soft-switching inverter, IPM(Intelligent Power Module), permanent magnet type ac servo motor driver, common mode leak current reduction, lowered mains terminal interference voltage

1. Introduction

In recent years, tremendous developments have been made in the operating performances of the static power conversion circuits and systems using power MOSFETs, SITs, and IGBTs. The effective increase in the switching frequency of the three-phase voltage source inverters and three-phase voltage source power factor correction (PFC) rectifiers using a variety of pulse modulation schemes is actually indispensable for further improvements on their related controllability, acoustic noise, motor stator current ripple reduction, and their downsizing. However, in the conventional three-phase voltage source hard-switching sinewave PWM inverter using IGBTs for AC motor speed and positioning servo drivers used commonly, the increase of switching power losses in the power semiconductor devices and modules in addition to the increase in physical size of the heat sink and cooling fan equipment are presently one of the most significant issues from various application viewpoints. In addition, the voltage and current switching spike and ringing surges due to high dv/dt and

high di/dt -associated switching transients actually cause the conductive and radiative electromagnetic noises for the commonly-used inverter type AC servo driver.

Moreover, in the three-phase voltage source inverter or the three-phase active PFC converter with sinewave current shaping and unity power factor, which are used for the variable speed AC motor drive or the highly precise AC positioning and speed servo drive, the additional practical problems to be solved appear as the occurrence of the high dv/dt related high-frequency leak current which flows into the ground line through the distributed stray capacitor networks between the stator winding and the frame of the AC motor. That is what we call AC motor shaft current of the bearing current^[1, 2].

As an effective solution for these practical problems, the key technologies of three-phase soft-switching inverter and PFC rectifier with the active auxiliary edge-resonant snubber have attracted special interest in modern power electronics which can turn on and off all the power semiconductor devices in the semiconductor power converters under the principle of zero voltage, zero current, and zero voltage and zero current hybrid switching transitions.

At present, to minimize the switching losses of power semiconductor for high frequency pulse modulation, the edge-resonant snubber circuits for the inverter and the active PFC rectifier have been developed so far. In general, these are roughly divided into three topologies; edge-resonant

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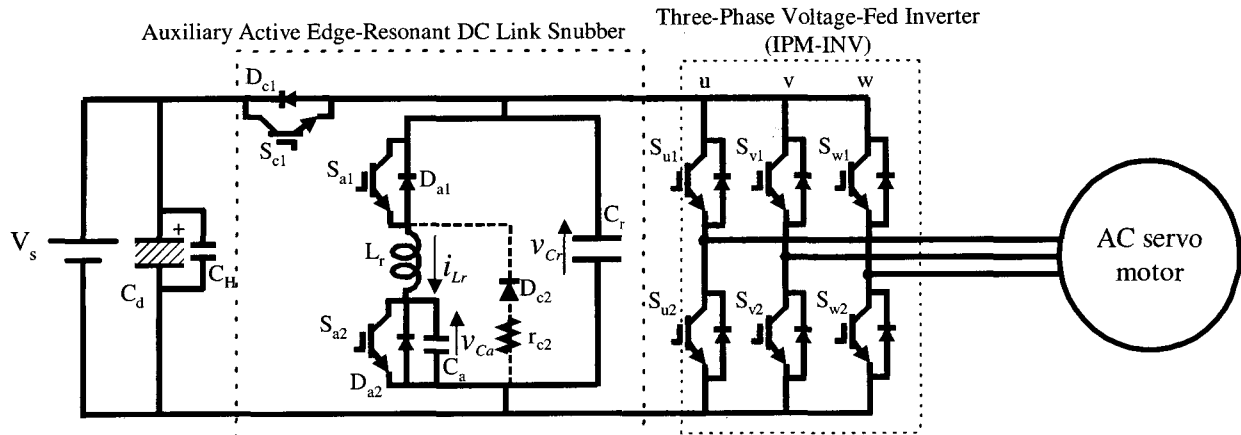


Fig. 1 Configuration of auxiliary active edge-resonant DC link snubber-assisted three-phase voltage-fed soft-switching inverter for AC servo motor drive.

DC link snubbers, edge-resonant AC link snubbers, and auxiliary edge-resonant arm or leg link snubbers for the three-phase voltage source type with the low pass filter inverter and three-phase active PFC rectifier with capacitor input filter^[3-10].

Under these technical backgrounds, this paper presents with a new circuit topology in a surge clipper type active auxiliary edge-resonant DC link snubber suitable for a three-phase voltage-fed soft-switching inverter IGBT-Intelligent Power Module (IPM) for the small-scale PM type AC servo driver application systems. In this active auxiliary edge-resonant DC link snubber circuit with an additional clipper diode and a damping resistance loop is included to suppress the parasitic parameter dependent peaky surge voltage ringing of the auxiliary active power switches. Firstly, the soft-switching commutation operation of the proposed active edge-resonant snubber circuit is presented for a steady-state operation. Secondly, the circuit parameter design procedure of the active auxiliary edge-resonant DC link snubber treated here is described and discussed from a simulation point of view. Thirdly, the circuit operation of the active auxiliary edge-resonant DC link snubber with a surge clamper is actually confirmed on the basis of the simulation and experimentation. Finally, the conductive noise and the common mode current of the three-phase voltage-fed zero voltage soft-switching inverter with a single edge-resonant snubber are evaluated and compared with those of the conventional three-phase voltage source hard-switching inverter for the PM type AC motor drive systems for the speed tracking applications.

2. Active Auxiliary Edge-Resonant DC Link Snubber with Surge Damper

2.1 Circuit Configuration and Basic Modelling

The schematic system configuration of the active auxil-

iary edge-resonant DC link snubber-assisted three-phase voltage source soft-switching inverter using IGBT type IPM is shown in Fig. 1. It is noted that this inverter which does not include the low pass filter in its AC motor load side. Since this application specific system is considered for the small-scale AC speed servo driver, the resonant inductor in the active auxiliary edge-resonant DC link snubber actually tends to be designed for its large value as compared with the resonant inductor inductance in the case of the high power AC speed servo driver design. As a result, the parasitic parameter-related surge voltage ringing of the active auxiliary power switch S_{a1} connected in series with the resonant inductor L_r becomes a critical problem in practice, which causes the ringing surge due to the parasitic capacitance of the auxiliary power switching block $Q_{a1}(S_{a1}/D_{a1})$. The authors introduce an additional diode-clamping circuit loop with D_{c2} and r_{c2} to make a solution this practical problem for a large design value on the resonant inductance.

The u-phase equivalent circuit in the bridge leg as shown in Fig. 2, is used to describe the operation of the active auxiliary edge-resonant DC link snubber circuit. This three-phase voltage source soft-switching inverter circuit for the small-scale AC motor drive is composed of the main active power switch S_{c1} for clamping the DC busline

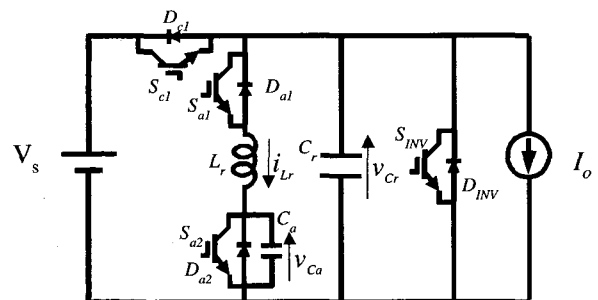


Fig. 2 Equivalent circuit of a single auxiliary active edge-resonant DC link snubber-assisted three-phase voltage-fed soft-switching inverter.

to the DC supply voltage V_s , the active auxiliary power switches S_{a1} and S_{a2} for producing the edge-resonant operation, the main edge-resonant capacitor C_r connected in parallel with the inverter main active power switch S_{INV} , the active auxiliary edge-resonant capacitor C_a connected in parallel with the active power switch S_{a2} , and the auxiliary edge-resonant inductor L_r . This active resonant snubber circuit topology is based on the lossless snubber operation under LC related edge-resonant mode for the switching patterns of S_{c1} , S_{a1} , and S_{a2} . Using this unique effect, the DC busline voltage across the equivalent main edge-resonant capacitor C_r corresponding to the inverter side lossless snubber capacitors is pulled down toward the zero voltage. Accordingly, ZVS/ZCS turn-on and ZVS turn-off commutations of the main active power switches in the inverter bridge arms or legs can be achieved completely.

2.2 Circuit Operation

The equivalent circuit of the active auxiliary edge-resonant DC link snubber-based three-phase voltage source inverter is illustrated in Fig. 2. The equivalent circuits for each sequence operation mode are respectively illustrated in Fig. 3. The gate pulse voltage signal switching patterns supplied to each power semiconductor device; IGBT as well as the voltage and current operating waveforms of the edge-resonant snubber circuit treated here are respectively illustrated in Fig. 4.

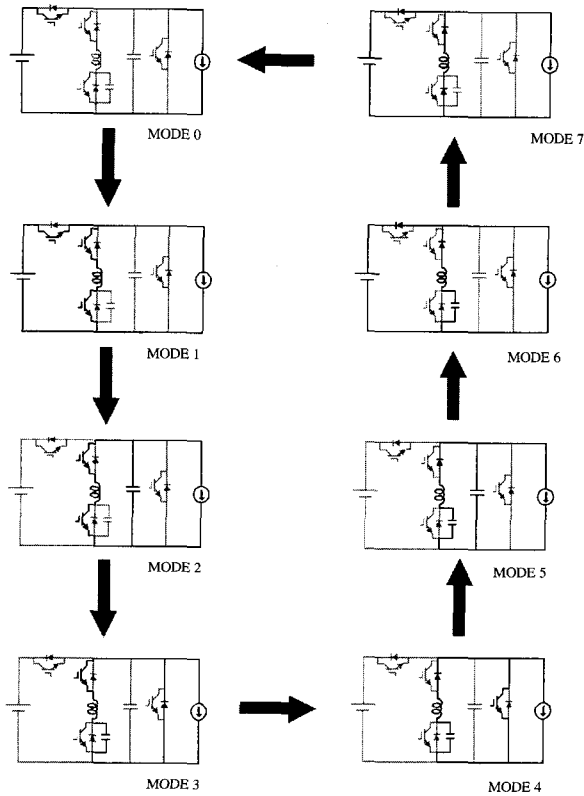


Fig. 3 Equivalent circuits of each operation mode.

<Mode 0 (Steady state mode)>:

Assuming that the voltage clamping active power switch S_{c1} in the DC busline and the auxiliary active power switch S_{a2} are now in the conduction state and the load current is kept flowing.

<Mode 1 (First edge-resonant initial current boost mode)>:

When the pulse pattern of the gate signal for the main active power switches in the three-phase voltage source type inverter is changed, S_{a1} is turned on under a principle of ZCS commutation. And then, the inductor current i_{Lr} is injected into the auxiliary resonant inductor L_r to pull the voltage across the main lossless snubbing capacitor down toward zero.

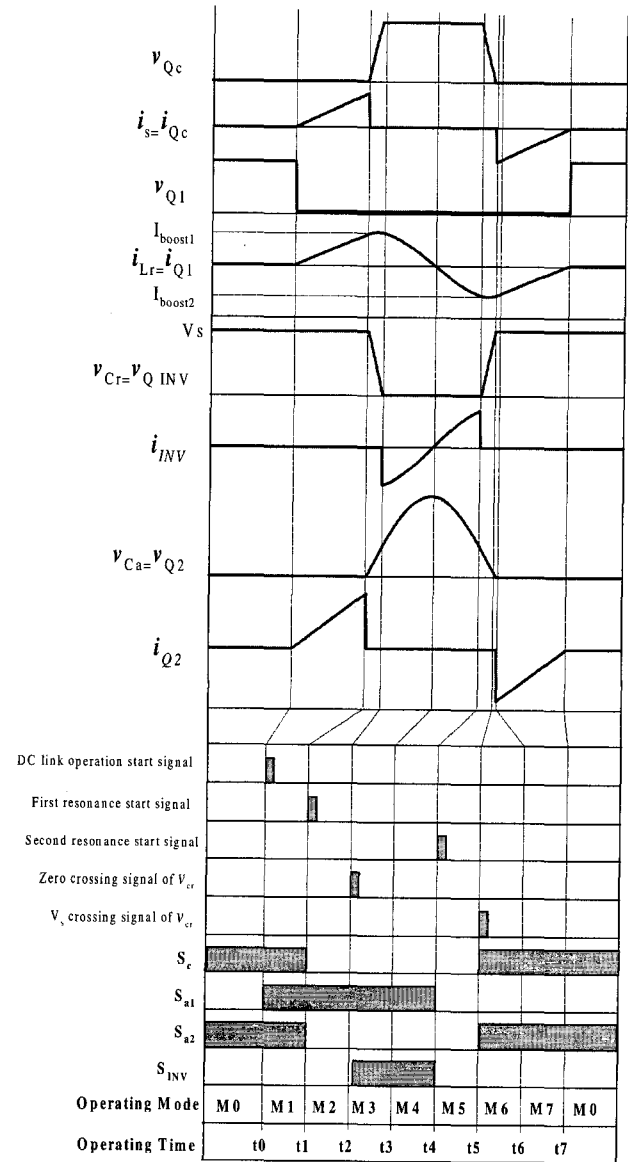


Fig. 4 Gate pulse signal switching pattern sequences of each power semiconductor device and operating waveforms of the auxiliary active edge-resonant DC link snubber circuit.

<Mode 2 (First edge-resonant mode)>:

When the resonant inductor i_{Lr} reaches the first resonant initial current I_{boost1} during a specified period, the auxiliary power switches S_{c1} and S_{a2} are both turned off under a condition of ZVS commutation. The edge-resonance operation determined by L_r , C_r and C_a starts immediately.

<Mode 3 (Zero voltage mode)>:

When the voltage across the main resonant capacitor v_{cr} is pulled down toward zero voltage, the anti-parallel diode D_{INV} connected to the representative main active power switch S_{INV} corresponding to the inverter bridge associated power switches begins conducting. And then, S_{INV} is turned on according to a ZVS/ZCS condition.

<Mode 4 (Second edge-resonant initial current boost mode)>:

The resonant inductor current i_{Lr} begins to increase toward the negative direction and is boosted enough to acquire a certain increase required for boosting the main capacitor (C_r) voltage to V_s . The S_{a1} is turned off with a ZVS/ZCS condition during this period.

<Mode 5 (Second edge-resonant mode)>:

When the resonant inductor current i_{Lr} reaches the second edge-resonant initial current I_{boost2} , the main power switch S_{INV} is turned off with ZVS, and the edge-resonance operation mode with L_r , C_r and C_a starts instantly.

<Mode 6 (Third edge-resonant mode)>:

When v_{cr} reaches V_s , the anti-parallel diode D_{c1} connected to the voltage clamping active power switch S_{c1} is conducted naturally. S_{c1} and S_{a2} are both turned on with ZVS/ZCS while D_{c1} is conducting.

<Mode 7 (Regeneration mode)>:

The edge-resonant inductor current i_{Lr} flows through D_{c1} . This residual inductor current is fed back to the DC supply voltage source V_s .

2.3 Resonant Circuit Design

The specifications to design the resonant circuit parameters of the shunt type active auxiliary edge-resonant DC link snubber are as follows.

(i) The voltage across the main edge-resonant capacitor must be pulled down toward zero voltage and again boosted toward the DC supply voltage source to complete the zero voltage soft switching.

(ii) The initial edge-resonant current I_{boost1} and I_{boost2} should be set to be as small as possible.

(iii) The di/dt value at a turn-on point must be as low as possible.

(iv) In the resonant circuit, the peak value of the edge-resonant current through the resonant inductor L_r must be as small as possible to reduce the power losses in the resonant snubber circuit and the peak voltage and current stresses for the power semiconductor switching devices during the edge-resonant mode period.

(v) The total operation period of the resonant DC link

snubber circuit should be as short as possible.

(vi) The dv/dt of the main edge-resonant capacitor C_r in the charging mode and in the discharging mode must be as low as possible.

(vii) The voltage v_{Cr} across the auxiliary edge-resonant capacitor must be as low as possible.

In these design specifications, the condition (i) is essential for the DC busline link resonant snubber circuit to achieve the soft-switching commutation. If the condition (i) is not met, the main active power switches in the three-phase inverter bridge legs u, v, w actually become a hard-switching commutation.

In experiment, the active auxiliary resonant snubber circuit (see Fig. 2) is designed for the following conditions: DC busline voltage is set to 280V, the maximum load current is specified as 3.0A from the allowable stator winding of the PM type AC motor, the internal resistance component of the resonant inductor is estimated as 0.2Ω in measurement, and the resonant frequency of this resonant snubber circuit is set to be 230kHz.

In the first step, the capacitance ratio A of the main resonant capacitor C_r to the active auxiliary resonant capacitor C_a is defined as $A = C_r/C_a$ and the resonant snubber circuit characteristics are examined in the case of varying the capacitance ratio A from 0.6 to 1.4 as shown in Fig. 5 under the condition of the temporarily-specified resonant characteristic impedance $Z = \sqrt{L_r/C_r} = 40 \Omega$. According to Fig. 5, when the capacitance ratio A is a small

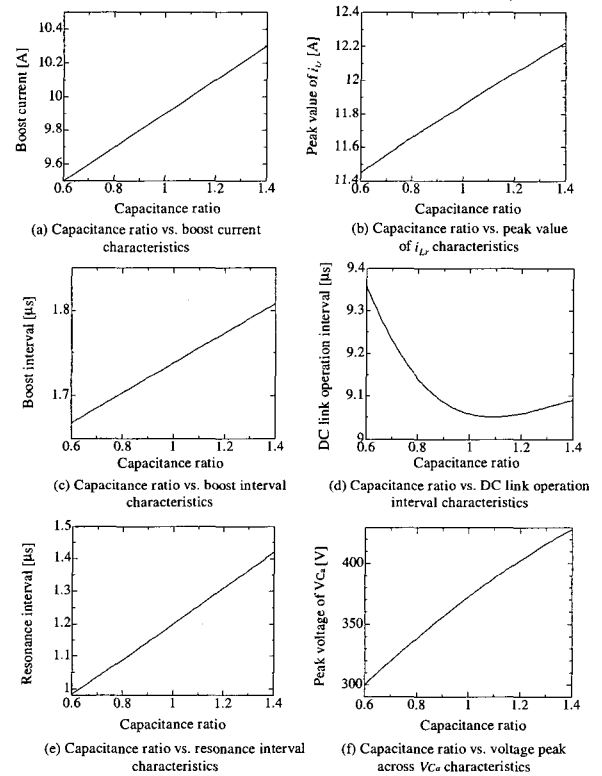


Fig. 5 Specific performances for capacitance ratio A in the active edge-resonant DC link snubber circuit.

value, the boosted inductor current and the peak value of the resonant inductor current injected into the resonant inductor are both small, but the soft commutation interval of the edge-resonant DC link snubber becomes relatively long.

On the other hand, when the capacitance ratio A defined previously is large, the auxiliary resonant DC link snubber operation time as the notched interval is relatively short but the boosted resonant current and the peak value of the resonant inductor current are both large. In terms of the capacitance ratio A versus the resonant DC link-operation commutation interval characteristics as indicated in Fig. 5(d), if the capacitance ratio A is less than 1, the smaller of A becomes, the larger of the edge-resonant DC link-operation interval becomes. On the other hand, if A is larger than 1, the edge-resonant DC link-operation interval changes little even if A becomes larger. As a result, the capacitance ratio A of the main resonant capacitor C_r and the auxiliary resonant capacitor C_a are firstly selected as a unity since the controllability of the PM type AC servo motor drive system worsens practically if the edge-resonant DC link-operation interval lengthens.

For the second step, the resonant characteristic impedance-related resonant snubber performances are verified by varying the resonant characteristic impedance $Z(=\sqrt{L_r/C_r})$ from 120Ω to 160Ω as indicated in Fig. 6. The boosted inductor current for the characteristic impedance is calculated first. Then, the peak value of the resonant inductor current, the boosted inductor current interval, the edge-resonant DC link-operation interval and the peak value of the auxiliary resonant capacitor voltage are estimated in accordance with the boosted inductor current. Observing Fig. 6, if the characteristic impedance Z is small,

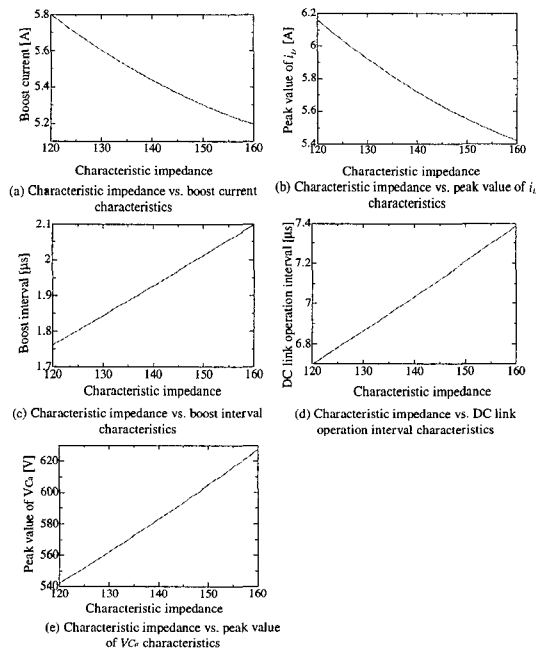


Fig. 6 Specific performance for characteristic impedance in the active edge-resonant DC link snubber circuit.

the edge-resonant DC link-operation interval becomes short and the peak voltage across the auxiliary resonant capacitor becomes low. But if the value of the boosted inductor current becomes large, the boosted inductor current interval becomes short, and the peak value of the resonant inductor becomes high. On the other hand, if the characteristic impedance Z is large, the boosted inductor current becomes small but the boosted inductor interval becomes long. In addition, the edge-resonant DC link-operation interval becomes long and the peak voltage across the auxiliary resonant capacitor becomes high. According to these graphical results, by limiting the boosted inductor current I_{boost} to a finite value less than $5.5A$ and regarding the edge-resonant DC link operation period including the increasing and decreasing resonant intervals, the characteristic impedance Z is specified as $Z=140\Omega$.

For the final step, under these design specifications, the edge-resonant snubber circuit parameters of the auxiliary resonant DC link snubber are designed for $L_r=100\mu H$ and $C_r=C_a=10nF$ by using selected parameters to be determined by the resonant capacitor ratio $A=1$, the resonant characteristic impedance $Z=\sqrt{L_r/C_r}=140\Omega$ and the specified resonant frequency $f_r=1/2\sqrt{L_r C_r}=230kHz$.

2.4 Simulation Results and Discussions

To confirm the validity of the circuit parameter design procedure in the auxiliary resonant DC link snubber, the simulation analysis of the active auxiliary edge-resonant DC link snubber circuit is actually performed for the equivalent circuit shown in Fig. 2 or Fig. 3. The typical operating voltage and current waveforms of the active auxiliary edge-resonant snubber are illustrated in Fig. 7.

Observing Fig. 7, the resonant inductor peak is limited to a value less than $5.5A$ and the edge-resonant DC link operation interval is set to a value less than $7\mu sec$. The voltage v_{cr} across the main resonant capacitor C_r is pulled down toward zero voltage and pulled up to the DC busline voltage V_s again. As a result, the notched mode soft-switching commutation of the auxiliary resonant DC link

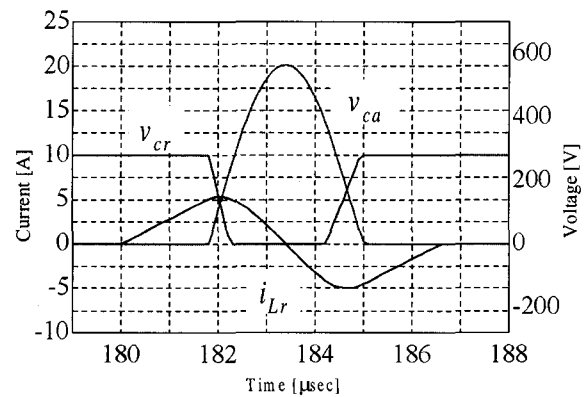


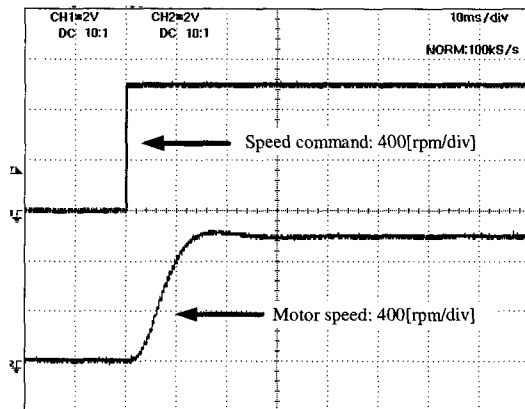
Fig. 7 Simulation results of the active auxiliary edge-resonant DC link snubber.

Table 1 indicates the design specifications and the circuit parameters of this experimental setup for the PM type AC speed servo motor driver. In experiment, Intelligent Power Module IPM (PM50RSA060) is used for the main power switches in the three-phase bridge legs.

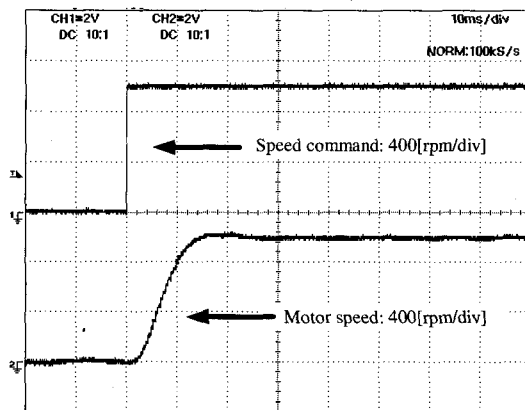
3.2 Experimental Results and Their Discussions

3.2.1 Edge-resonant DC link snubber

Fig. 9 represents the operating voltage and current waveforms of the active auxiliary edge-resonant snubber circuit for the three-phase voltage source soft-switching inverter using IGBT-IPM. Observing this figure, the voltage v_{Cr} across the main edge-resonant capacitor is pulled down toward the zero voltage and pulled up toward the DC bus-line voltage V_s , and all the main active power switches in the three-phase inverter bridge legs u, v and w can achieve zero voltage soft-switching (ZVS) during this notched switching mode period based on the edge resonance in the inverter DC busline side.



(a) Hard Switching



(b) Soft Switching

Fig. 11 Speed responses of AC speed servo motor.

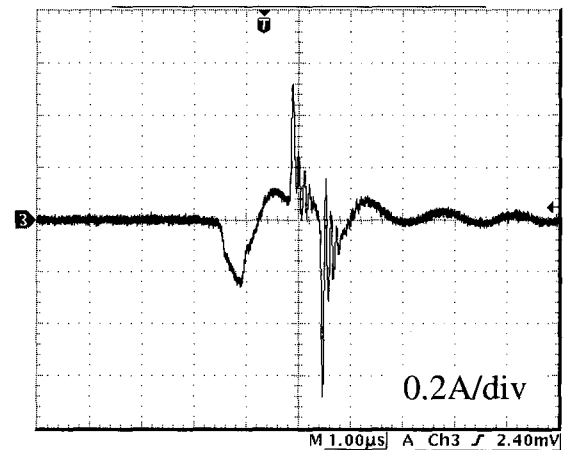
3.2.2 Three-phase voltage-fed inverter with a single edge-resonant DC link snubber

Fig. 10 shows the PM type AC motor stator current

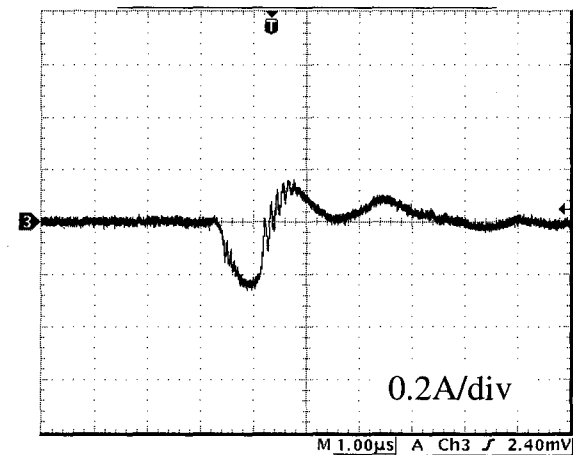
waveforms for no low pass filter in the output side of the soft-switching IPM inverter treated here. Under the three-phase voltage source soft-switching inverter without the low pass filter, the load current or AC motor stator current waveform is slightly distorted in comparison with that of the three-phase voltage-fed hard-switching PWM inverter because of the notched commutation period of the auxiliary resonant DC link snubber. On the other hand, the spike or ringing surge current appears in the case of the three-phase voltage-fed hard-switching inverter using IGBT-IPM has been effectively removed for the three-phase voltage-fed soft-switching inverter using IGBT-IPM.

Fig. 11 gives the speed response of the AC servo motor when the motor speed command is changed from zero rpm to 1000 rpm.

In terms of the small-scale PM type AC servo motor speed response, it is noted that almost the similar response performances can be achieved and implemented for this low noise three-phase voltage-fed soft-switching inverter using IPM.



(a) Hard Switching



(b) Soft Switching

Fig. 12 Common mode current.

The common mode current that flows through the three-phase AC power lines of the inverter output side in the case of hard-switching inverter and soft-switching inverter is comparatively represented in Fig. 12. The high-frequency common mode current flows through the PM type AC servo motor driven by the three-phase voltage-fed hard-switching IPM inverter, but it is substantially reduced for the three-phase voltage-fed soft-switching inverter.

The practical measurement method of the mains terminal interface voltage is demonstrated in Fig. 13. Figure 14 shows the measured conductive noise of the mains terminal interface voltage. The conductive noise is measured from 150kHz to 10MHz. According to Fig. 14, in the case of the three-phase voltage source soft-switching inverter, the noise level over 800kHz is actually considerably reduced in comparison with that of the conventional three-phase voltage-fed hard-switching IPM inverter.

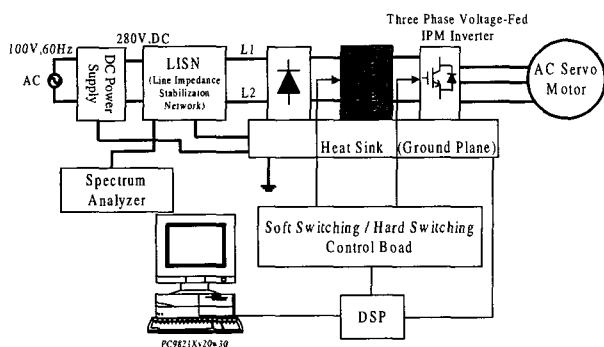


Fig. 13 A schematic system configuration of mains terminal interference voltage measurement.

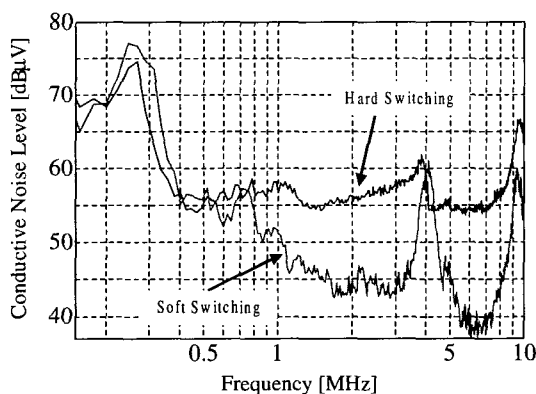


Fig. 14 Comparative conductive noises of mains interference voltage.

4. Conclusions

In this paper, a new circuit topology of the active auxiliary edge-resonant DC link snubber circuit with the voltage surge clamping and ringing damper diode loop was actually introduced as one of the active auxiliary edge-resonant DC link snubbers used effectively in the three-phase voltage source type soft-switching inverter using IGBT-IPM

for several hundred watts class small-scale AC speed servo motor driver systems. Its operation principle, the practical circuit parameter design method, and the experimental results of this resonant snubber circuit were described from a practical point of view, together with the operation in steady-state. The stable operation of the active auxiliary edge-resonant snubber-assisted three-phase voltage source soft-switching inverter using IGBT-IPM, which operates under an instantaneous space voltage modulation strategy, was confirmed and the design procedure of the active auxiliary edge-resonant DC link snubber was explained by the illustrative computer simulations on the basis of the resonant capacitance ratio A and resonant characteristic impedance Z parameters. The common mode current as the AC motor leak current and the conductive noise in the mains terminal interface voltage have been reduced under the three-phase voltage source soft-switching inverter-driven PM type AC speed servo driver. The possibilities of the PM type AC servo driver applications and the common mode current reduction by the three-phase voltage source soft-switching inverter using IGBT-IPM have been verified from an experimental point of view.

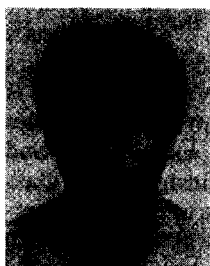
In the future, the feasible comparative studies on the three-phase voltage source soft-switching inverter with the other types of the active auxiliary edge-resonant DC link snubbers and the power loss analysis of the three-phase voltage-fed soft switching inverter with a single active auxiliary edge-resonant snubber treated here should be performed in experiment for the high power AC servo driver. The further evaluations of the three-phase voltage source soft-switching inverter with the spike clipper type edge-resonant DC link snubber must be evaluated by using the new Carrier Storage Trench Gate IGBTs (CSTBT) with lowered saturation voltage characteristics.

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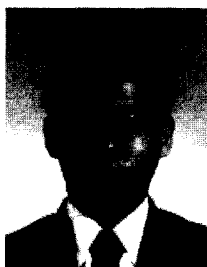
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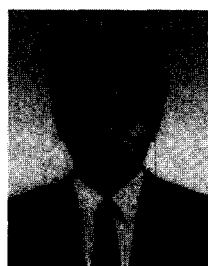
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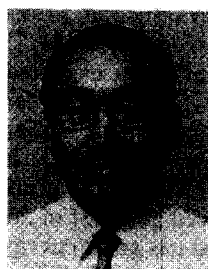
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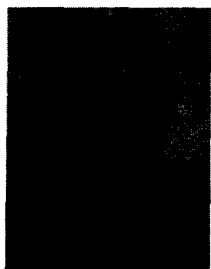
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