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New Resonant AC Link Snubber-Assisted Three-Phase Soft-Switching PWM Inverter and Its Comparative Characteristics Evaluations

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ABSTRACT

This paper presents a novel prototype of three-phase voltage source type zero voltage soft-switching inverter with the auxiliary resonant snubbers suitable for high-power applications with IGBT power module packages in order to reduce their switching power losses as well as electromagnetic conductive and radiative noises. A proposed single inductor-assisted resonant AC link snubber circuit topology as one of some auxiliary resonant commutation snubbers developed previously to achieve the zero voltage soft-switching (ZVS) for the three-phase voltage source type sinewave PWM inverter operating under the instantaneous space voltage vector modulation is originally demonstrated as compared with the other types of resonant AC link snubber circuit topologies. In addition to this, its operation principle and unique features are described in this paper. Furthermore, the practical basic operating performances of the new conceptual instantaneous space voltage vector modulation resonant AC link snubber-assisted three-phase voltage source type soft-switching PWM inverter using IGBT power module packages are evaluated and discussed on the basis of switching voltage and current waveforms, output line to line voltage quality, power loss analysis, actual power conversion efficiency and electromagnetic conductive and radiative noises from an experimental point of view, comparing with those of conventional three-phase voltage source hard-switching PWM inverter using IGBT power modules.

Keywords: Three-phase voltage source inverter, A single inductor type resonant AC link snubber, Zero voltage soft-switching, Specific instantaneous space voltage vector modulation, Actual efficiency evaluation, Electromagnetic conductive and radiative noises

1. Introduction

In general, high frequency switching carrier-based sinewave pulse width modulation (PWM) strategies of the MOS gate controlled power semiconductor devices and power modules as MOS-FETs, IGBTs and IEGTs in the three-phase PWM inverter and three-phase PWM rectifier are more indispensable for high performance implementations. However, this sort of inverter and rectifier causes some significant problems to be overcome in actual power conditioning applications such as much more increases of the switching power losses and electromagnetic noises, leak current generation related to a high *dv/dt* stress and electrical insulation breakdown of the reactor and transformer in addition to the stator winding of AC machines due to a high *di/dt* stress as well as the

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voltage and current rating reduction of the available power semiconductor devices and power modules In order to overcome these practical problems effectively, three-phase soft-switching sinewave PWM power conversion processing circuit and system technologies with a high frequency carrier are able to give effective solutions for high frequency carrier-based sinewave PWM scheme power conversion conditioning and processing systems including three-phase sinewave PWM inverters and PWM rectifiers from a practical point of view[1][2] In recent years, three-phase soft-switching PWM power conversions conditioning and processing circuits and systems technologies have attracted special interest for implementing the downsizing in physical volumetric size, lowered electromagnetic conductive and radiative noises, improved high performances in the voltage waveform quality and quick responses and high actual efficiency in order to achieve high frequency switching-based sinewave pulse modulated power conditioners such as new energy interactive and dispersed power supply plants, electric vehicle and hybrid electric vehicle equipment as well as UPS in telecommunication energy plants

To achieve the zero voltage soft-switching (ZVS) commutation for the main active power switches of the three-phase sinewave PWM inverters and sinewave PWM rectifiers, the auxiliary resonant commutation snubber circuits are effectively introduced and implemented for the voltage source power conditioners The auxiliary resonant snubber circuit topologies mentioned above are divided into four, auxiliary resonant DC link snubber schemes, auxiliary resonant commutation bridge leg link snubber schemes, auxiliary resonant AC link snubber schemes and auxiliary resonant switch arm link snubber schemes A variety of resonant commutation snubber schemes developed so far have a few advantages and disadvantages Therefore, it is hard to choose the most suitable and acceptable resonant commutation snubber circuit depending on load current and pulse width modulation requirements In this paper, the auxiliary resonant AC link snubber (ARACL) scheme is treated suitable and acceptable for high power and energy applications[3]

In this paper, a novel prototype of the ARACL-assisted three-phase soft-switching PWM inverter (ARACL-PWM inverter) using IGBT-IPM or IGBT power module packages in which the auxiliary resonant commutation snubber circuit is connected in parallel with its three-phase balanced AC load is considered to achieve the ZVS-PWM operation for high power applications. The operation principle of the quasi-resonant commutation of a novel type of ARACL circuit is described, along with its unique features The time sharing output pulse pattern using instantaneous space voltage vector modulation-based PWM suitable for three-phase ARACL-PWM inverter is proposed here in. The performance evaluations as actual efficiency and electromagnetic noise evaluations of this ARACL-PWM inverter are basically evaluated and discussed as compared with those of three-phase hard-switching PWM inverter (HSW-PWM inverter) from an experimental point of view The effectiveness of this three-phase ARACL-PWM inverter is verified on the basis of simulations and experimental results.

2. A Novel Resonant AC Link Snubber-Assisted ZVS- PWM Inverter

2.1 Single Inductor Type Resonant AC Link Snubber

The circuit configurations of the ARACL circuit topologies are roughly divided into three types, delta-configured ARACL scheme, star-configured ARACL scheme and single resonant inductor type ARACL scheme[3-5] Of these, the single inductor type ARACL circuit has some advantageous points as compared with delta-configured ARACL scheme and star-configured ARACL scheme Those include,

(a) Simple circuit configuration by using IGBT power module packages
(b) Only one quasi-resonant inductor configuration
(c) Easy current control implementation of quasi-resonant inductor

Considering these advantages, the single inductor type ARACL-PWM inverter which can operate under a principle of specific instantaneous space voltage vector modulation sinewave processing is treated in this paper.

Figure 1 shows the three-phase ARACL-PWM inverter circuit configuration using IGBT power module packages

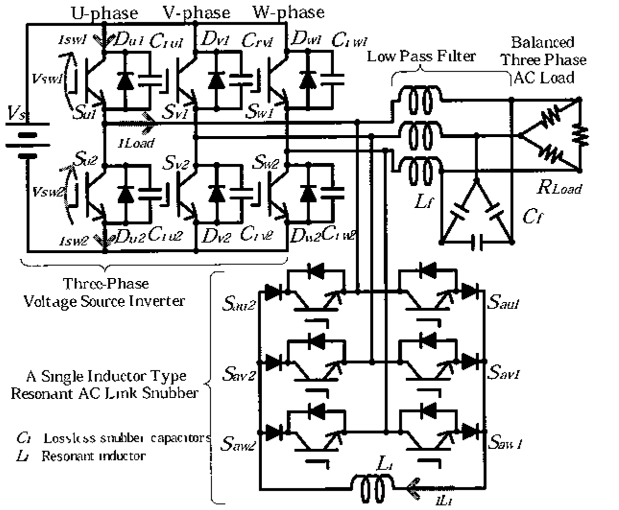


Fig 1 Single inductor type resonant AC link snubber-assisted three-phase voltage source inverter

or IGBT-IPM This three-phase ARACL- PWM inverter topology consists of the single inductor type ARACL circuit with reverse broking diode connected to the 6 in 1 power module packages, and the single resonant inductor, and each lossless capacitive snubbers connected in parallel with each main power switch in the bridge arms of this three-phase inverter To charge and discharge these lossless capacitive snubbers in the bridge arms when the main power switches in the bridge arms are turned on and off in accordance with depending on the PWM signals, zero voltage soft- switching commutation at turn off and zero voltage and zero current soft-switching commutation at turn on can completely achieve for the main power switches in the bridge arms

2.2 Lossless Capacitive Snubber-Assisted Commutation

To achieve ZVS for the main power switches in the bridge arms of the three-phase PWM inverter, the lossless capacitive snubbers in the bridge arms connected in parallel with the main power switches in the bridge arms have to charge to the DC source voltage V_s and discharge toward the zero voltage. Figure 2 shows the operation behavior of the soft commutation transition on the basis of the lossless capacitive snubbers to be charged and discharged completely In the steady state, assume that the switch current is flowing through the main power switch S_{w1}, when the main power switch S_{w1} in the bridge arm is

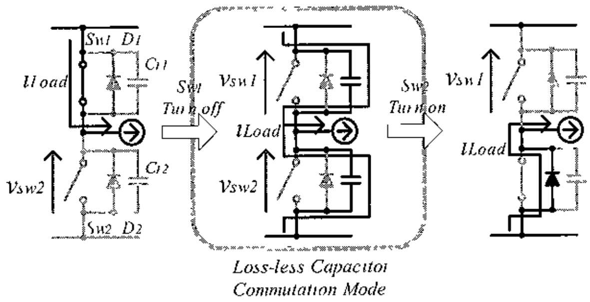


Fig 2 Lossless capacitive snubber commutation mode

turned off, the load current is commutated to the lossless capacitive snubber C_{r1} and C_{r2} This capacitor C_{r1} is charged from the zero voltage to the DC source voltage V_s On the other hand, the capacitor C_{r2} is completely discharged from the DC supply source voltage V_s to the zero voltage. When the voltage across the capacitor C_{r2} reaches the zero voltage, the diode D_2 in antiparallel with the main power switch S_{w1} is forward biased, and the switch current is commutated from C_{r2} to D_2 This switching mode transition can be achieved by only connecting the lossless capacitive snubber to the main power switches of the inverter bridge arms, therefore, this commutation mode is exactly called lossless capacitive snubber commutation mode.

On the other hand, Figure 3 shows the switching mode transition in case that lossless capacitive snubber commutation mode cannot achieve actually In case that the switch current is following through the diode D_2, when main power switch S_{w2} in the inverter bridge arm is turned off, even if the main power switch S_{w2} is turned off. The switch current continues flowing through the diode D_2, therefore, the lossless capacitive snubbers are not charged and discharged, and the voltages across lossless capacitive snubbers are maintained to a certain constant value. Under these conditions, when the main power switch S_{w1} of the inverter bridge arms is turned on, the lossless capacitive snubber C_{r1} is shorted by the conduction of S_{w1}, therefore, hard-switching mode occurs In order to prevent such a hard-switching mode, the auxiliary resonant commutation snubber circuit must be operated for the purpose that the switch current through the main power switch to be turned off commutation through the IGBT side instead of the diode side Figure 4 depicts the voltage and current operation waveforms of the single inductor type ARACL

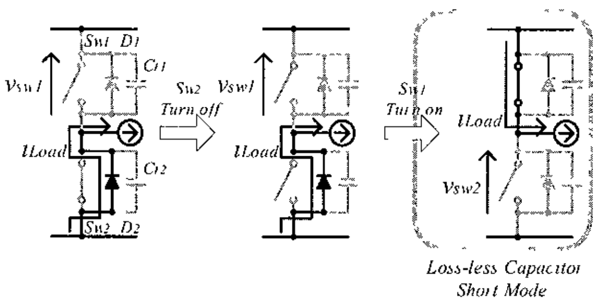


Fig 3 Lossless capacitive snubber short mode

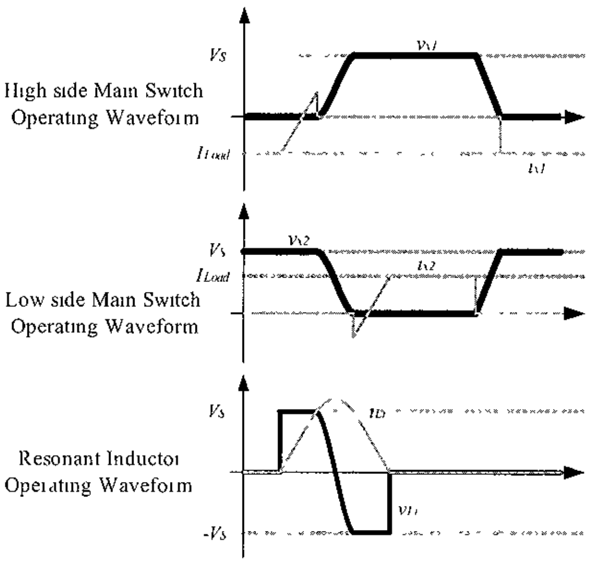


Fig 4 Operation waveform of auxiliary resonant AC link snubber

circuit. The circuit operation principle of ARACL circuit is described on reference [6] and [7] Considering this figure, in case that the switch current flows through the IGBT side of the main power switch, it is needless to operate the ARACL circuit and lossless capacitive snubber commutation mode can be achieved, and zero voltage switching at turn off can be performed for the main power switch in the bridge arms of this inverter On the other hand, in case that the switch current flows through the antiparallel diode of the main power switch, it is understood that it is necessary to operate the ARACL circuit treated here In this case, to operate the ARACL circuit, zero voltage switching at the turn off can be achieved for the main power switch in the bridge arms of this inverter.

3. Instantaneous Space Voltage Vector Modulation and Time Sharing Output Pulse Pattern

To modulate the three-phase ARACL-PWM inverter, it is needed to give the voltage across the output terminal of each bridge phase to the resonant inductor of the ARACL circuit In addition to this, the switching state that all high-side or low-side power switches are turned on and single-phase switching are not available Therefore, the specialized time sharing output pulse pattern using the instantaneous space voltage vector modulation is necessary to achieve the soft- switching for the three-phase ARACL-PWM inverter

Figure 5 indicates the instantaneous space voltage vector and command output voltage vector. For example, in case that the command output voltage vector v_c^* exists in the Sector 1, the length of the α-axis direction of the command output vector is expressed by v_α^*, and the length of β-axis direction of the command output voltage vector is expressed by v_β^* And more, the command output vector of direction of $\mathbf{V}_1$ is represented with v_a and the command output vector of direction of $\mathbf{V}_3$ is represented by v_b v_α^* and v_β^* are indicated by the following equations,

$$v_\alpha^* = mV_s \cos(\omega_o t) \tag{1}$$

$$v_\beta^* = mV_s \sin(\omega_o t) \tag{2}$$

where, m is the modulation ratio of three-phase ARACL-PWM inverter and V_s means the input DC source

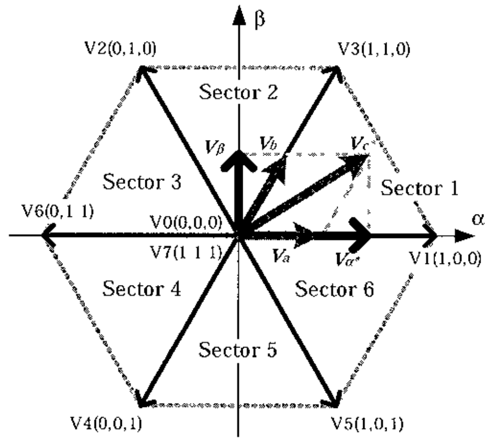


Fig 5 Instantaneous space voltage vector and command output voltage vector

voltage v_a and v_b are represented by the followıng equatıons,

$$v_a = v_\alpha^* - \frac{v_\beta^*}{\sqrt{3}} \quad (3)$$

$$v_b = \frac{2v_\beta^*}{\sqrt{3}} \quad (4)$$

Usıng the v_a and v_b, the pulse wıdth of the v_a and v_b ıs specıfied by the followıng equatıons

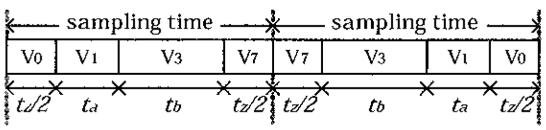
$$t_a = m\sqrt{\frac{3}{2}}\frac{|v_a|}{V_s}Ts \quad (5)$$

$$t_b = m\sqrt{\frac{3}{2}}\frac{|v_b|}{V_s}Ts \quad (6)$$

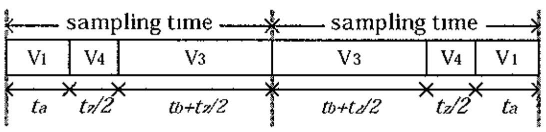
And the pulse width allocatıons of the zero voltage vector are denoted by t_a, t_b and T_s.

$$t_z = T_s - (t_a + t_b) \quad (7)$$

Introducıng these equatıons, the tıme-sharıng output pulse pattern of the conventıonal three-phase HSW-PWM ınverter ın Sector 1 ıs dısplayed ın Fıg 6 (a) On the other hand, zero voltage vectors ($\mathbf{V}_0$ and $\mathbf{V}_7$) are not avaılable ın prıncıple for the output pulse pattern of the three-phase ARACL-PWM inverter and single-phase commutatıon such that the output pulse moves from $\mathbf{V}_1$ to $\mathbf{V}_3$ is not adopted Therefore, the output pulse pattern ıllustrated ın Fıg 6 (b) ıs proposed for the three-phase ARACL-PWM ınverter Usıng thıs output pulse pattern suıtable for



(a) Output pulse pattern for HSW-PWM ınverter



(b) Output pulse pattern for resonant AC lınk snubber-assısted ZVS-PWM ınverteı

Fıg 6 Comparatıve tıme sharıng output pulse pattern

three-phase ARACL-PWM ınverter, the output voltage vector can be achıeved durıng one samplıng tıme as equal as the output pulse pattern of the conventıonal three-phase HSW-PWM ınverter.

4. Experimental Results and Discussions

4.1 Experimental Setup

Table 1 ındıcates the desıgn specıficatıons and cırcuıt parameters of the three-phase ARACL-PWM ınverter and three-phase HSW-PWM ınverter. Each capacıtance of lossless capacıtıve snubbers and the ınductance of sıngle resonant ınductor of ARACL cırcuıt are respectıvely estımated from the dead tıme of ınverter swıtchıng perıod ıncludıng the commutatıon operatıon tıme of the ARACL cırcuıt.

Table 1 Experımental setup specıficatıons

Inverter specıficatıons

Parameters	Value
DC Source Voltage (V_s)	200 0 [V]
Samplıng Frequency (f_s)	12.0 [kHz]
Fılter Inductance (L_f)	675.0 [μH]
Fılter Capacıtance (C_f)	40 [μF]
Modulatıon Ratıo (m)	0 7
Output Frequency (f_o)	60 0 [Hz]
Maın poweı swıtchıng Devices (S_{u1}, S_{u2}, S_{v1}, S_{v2}, S_{w1}, S_{w2})	MITSUBISHI CM100DU-12F

Soft-swıtchıng specıficatıons

Lossless Capacıtıve Snubber (C_{ru1}, C_{ru2}, C_{rv1}, C_{rv2}, C_{rw1}, C_{rw2})	0 033 [μF]
Resonant Inductance (L_r)	5.0 [μH]
Auxılıary Swıtchıng Devıces (S_{au1}, S_{au2}, S_{av1}, S_{av2}, S_{aw1}, S_{aw2})	MITSUBISHI CT60AM-18F
Auxılıary Blockıng Dıodes (D_{au1}, D_{au2}, D_{av1}, D_{av2}, D_{aw1}, D_{aw2})	TOSHIBA 30JL2C41

Hard-swıtchıng specıficatıons

Dead Tıme	1 28 [μs]
Hıgh frequency-Passıng Snubber Capacıtance	0 132 [μF]

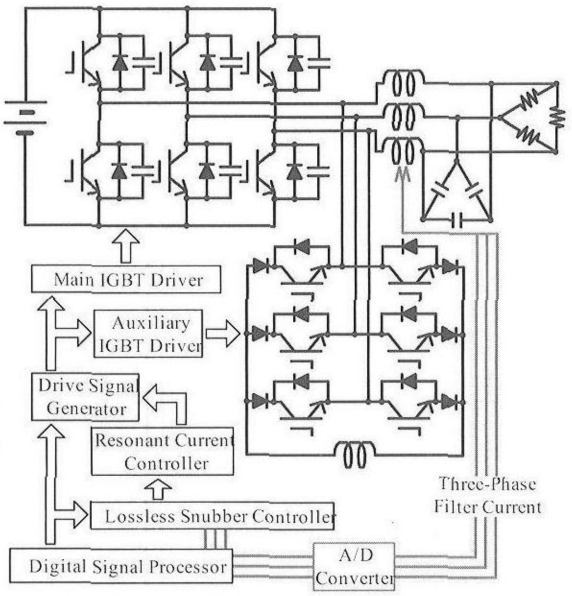


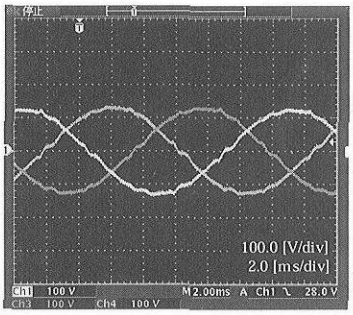
Fig. 7. Control system diagram of ARACL-PWM inverter.

On the other hand, three-phase HSW-PWM inverter is evaluated by only connecting the high-pass capacitor across the DC bus line. The high-pass capacitor was connected in parallel with the DC bus line to remove the high frequency components of the DC bus line voltage. The high-pass capacitors are also available to protect the IGBT modules from the switching surge voltage.

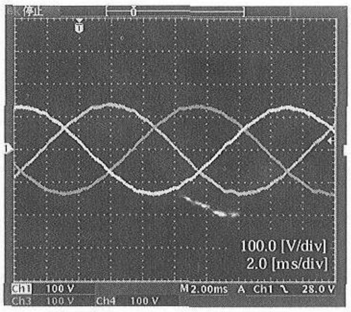
Figure 7 shows the control system diagram of three-phase PWM inverter using a proposed ARACL circuit. The signals of sinusoidal pulse modulation for three-phase HSW-PWM inverter are produced by DSP-based software implementation, and soft-switching control signals are produced by the resonant current controller to determine the value of resonant inductor current by detecting the load current and direction, lossless snubber commutation controller to determine whether lossless capacitive snubber commutation mode can be achieved or not. The HSW-PWM inverter is configured with removing the ARACL circuit and lossless snubber capacitors from ARACL-PWM inverter. Therefore, three-phase HSW-PWM inverter can be easily compared with ZVS-PWM inverter.

4.2 Output Voltage Waveforms and Actual Efficiency

Figure 8 depicts comparative output line- to-line voltage waveforms in case of the three-phase ARACL-PWM and



(a) Resonant AC link inverter



(b) Hard-switching inverter.

Fig. 8. Output line-to-line voltage waveforms.

HSW-PWM inverters. This output line-to-line voltage waveforms are generated under an open loop control scheme without any output voltage controllers. The output voltage waveforms of three-phase ARACL-PWM inverter are generated by using the specialized time-sharing output pulse pattern that is proposed in chapter 3. Observing the output voltage waveforms of three-phase ARACL-PWM inverter, these operating waveforms are not distorted as compared with those of HSW-PWM inverter. Therefore, it is considered that specialized time-sharing output pulse pattern suitable for three-phase ARACL-PWM inverter that is proposed in chapter 3 is more effective in actual.

Figure 9 shows the comparative actual power conversion efficiency characteristics for three-phase ARACL-PWM and HSW-PWM inverters. Under 2 kW power rating, the actual power conversion efficiency of three-phase HSW-PWM inverter is better for 0.8 % only than that of three-phase ARACL-PWM inverter. On the other hand, in the power ranges over 2kW, the actual power conversion efficiency of the three-phase ARACL-PWM inverter is better for 0.5 % than that of three-phase HSW-PWM inverter. From these measured results, this three-phase ARACL-PWM inverter is more suitable and acceptable for high power applications.

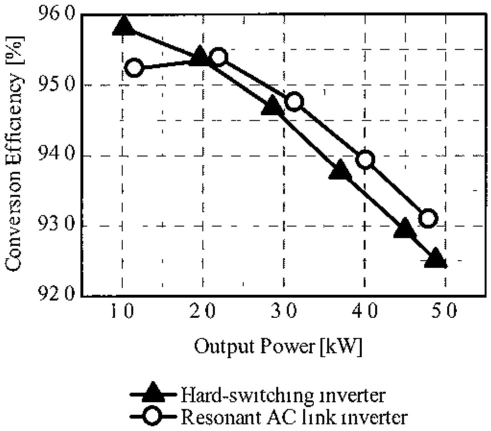
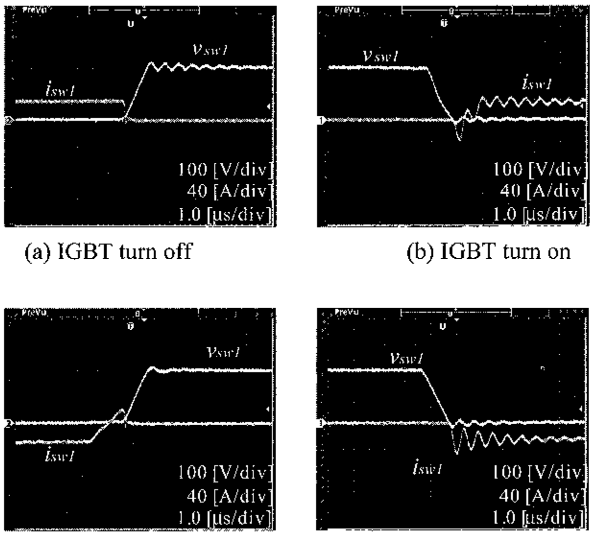


Fig 9 Output power vs actual power conversion efficiency characteristics

4.3 Switching Waveforms and Power Loss Analysis

To analyze the power loss of the newly-proposed three-phase ARACL-PWM inverter, the switching voltage and current waveforms are measured by using the digital oscilloscope These measured results for the proposed three-phase ARACL-PWM inverter are illustrated in Fig 10 The IGBT switching waveform at turn off is illustrated in Fig 10 (a) and the diode switching waveform at turn on is shown in Fig.10 (d). It is noted that the lossless capacitive snubber commutation mode can be achieved completely. Observing these switching voltage and current waveforms, the switching power losses are little more than zero in case of using the proposed ARACL circuit except for the power loss based on tail current peculiar to IGBT itself

The power losses are analyzed by using the computer simulation including these measured switching power loss characteristic data and conduction voltage characteristic data of IGBT and effective resistance characteristic data of the resonant inductor These analytical results are represented in Fig 11 Observing these analyzed results, it is understood that the major power losses to be generated in the proposed three-phase ARACL-PWM inverter are mainly occupied by the conduction power losses of the main power switch IGBTs in the bridge arms and reverse blocking diodes and the auxiliary power switch IGBTs of the ARACL circuit In addition to this, it is verified that the switching power losses of main power switches of the



(a) IGBT turn off (b) IGBT turn on

(c) Diode turn off (d) Diode turn on

Fig 10 Switching voltage and current waveforms of three-phase auxiliary resonant AC link inverter using IGBT power modules

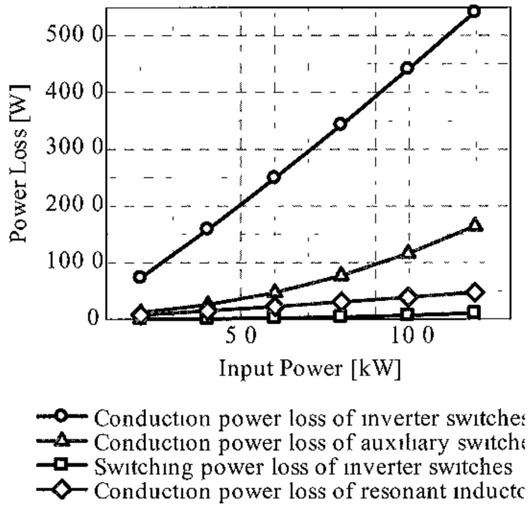


Fig 11 Power loss analysis of three-phase auxiliary resonant AC link inverter using IGBT power modules

inverter are extremely small Therefore, using the power semiconductor devices which has the characteristics of low saturation voltage such as Carrier Stored Trench Gate Bipolar Transistors (CSTBTs) are more effective to improve the actual power conversion efficiency of ARACL-PWM inverter.

4.4 Electromagnetic Conductive and Radiative Noises

The electromagnetic conductive common mode and radiative noises measurement systems are shown in Fig.12. The common mode noise are measured by using the line impedance stabilization network which made by Kyoritsu Electric Corporation in Japan and spectrum analyzer produced by Tektronix. And electromagnetic radiative noise can be measured by using the 3.5 cm electric field probe made by Electro Metrics. Both conductive and radiative electromagnetic noises are to be measured without any noise filters in the input side of this inverter. The measured frequency bands on the conductive and radiative noises are between 100 kHz to 30 MHz.

Figure 13 indicates the comparative measurement results of the conductive common mode noise in case of the three-phase ARACL-PWM and HSW-PWM inverters. The conductive noise level of three-phase ARACL-PWM inverter is almost equal as compared with those of three-phase HSW-PWM inverter in the frequency bands under 500 kHz. On the other hand, in the frequency bands between 500 kHz to 3MHz, the common mode noise level of the proposed three-phase ARACL-PWM inverter is better about 10 dB than that of three-phase HSW-PWM inverter although the peak value about 2 MHz is observed in case of three-phase ARACL-PWM inverter. In addition to these, in the frequency bands over 4 MHz, the common mode noise level of the three-phase ARACL-PWM inverter is better for 15 dB by a maximum value than that of three-phase HSW-PWM inverter. The cause that the peak values observing by the three-phase ARACL-PWM inverter are is the voltage-ringing phenomenon due to the parasitic inductances of IGBT modules and wiring at the main power switches in the inverter bridge arms which shown in Fig 10. Considering this measured results, the ARACL-PWM inverter can reduce the conductive common mode noise.

Figure 14 shows the comparative measured results of the radiative noises in case of the three-phase HSW-PWM and ARACL-PWM inverters. The radiative noise level of the three-phase ARACL-PWM inverter shows the high peak value at the 6.5 MHz, but the peak value is smaller than that of three-phase HSW-PWM inverter. Judging from this result, the radiative noise level is improved in the all measured frequency band from 100 kHz to 30 MHz by applying three-phase ARACL-PWM inverter. It is sufficiently considered that the appearance of the peak value in 6.5 MHz is the parasitic resonance phenomenon

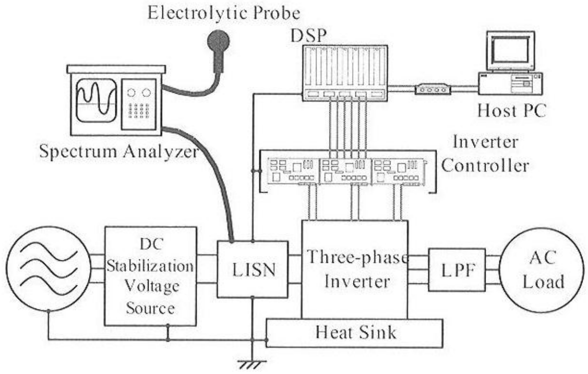


Fig. 12. Noise measurement setup.

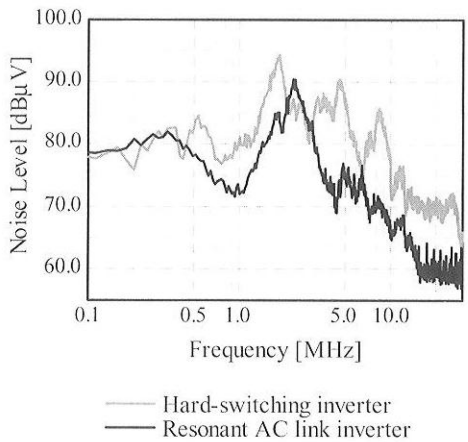


Fig. 13. Comparative conductive noise characteristics.

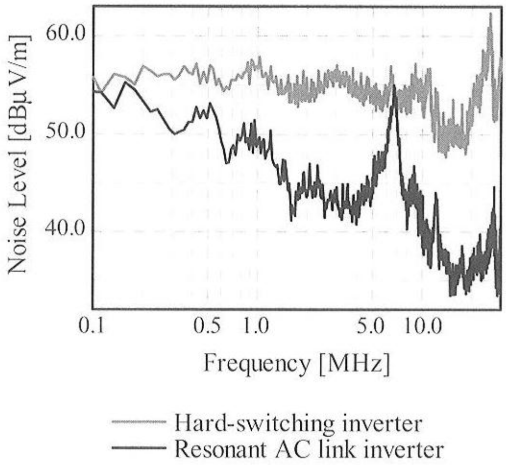


Fig. 14. Comparative radiative noise characteristics.

between the resonant inductance and output capacitance of the reverse blocking diodes, because the effective resistance of the resonant inductor that the ferrite core composed of Zn-Mn material is used in experiment which is smaller at the high frequency band over 500 kHz than that of another core material such as amorphous core of the iron material core or 6 5 % ferrosilicon core Considering these results, it is understood that the radiative electromagnetic noise of proposed ARACL-PWM inverter can be reduced than that of HSW-PWM inverter

Judging from the measurement results of the conductive electromagnetic noise and radiative electromagnetic noise, it is considered that the ARACL-PWM inverter is more effective to improve the electromagnetic environment.

5. Conclusions

This paper has presented the new topological single inductor type resonant AC link snubber-assisted soft-switching PWM inverter to achieve the high power conversion efficiency and lowered electromagnetic noise as compared with the conventional three-phase voltage source hard-switching PWM inverter At first, the circuit configuration of the single inductor type resonant AC link snubber circuit was presented, and the lossless capacitive snubber commutation mode to achieve the zero voltage soft-switching at the inverter main power switches only connecting the lossless capacitive snubber in parallel with main power switches in bridge arms were explained in detail The time-sharing output pulse pattern using the instantaneous space voltage vector modulation suitable for resonant AC link snubber-assisted soft-switching PWM inverter are proposed as a method of the sinewave PWM strategy

The actual power conversion efficiency resonant AC link snubber-assisted soft-switching PWM inverter as compared with conventional hard-switching PWM inverter was measured As a result, the power conversion efficiency of resonant AC link snubber-assisted soft-switching PWM inverter was better about 0 5 % for 5 kW than that of hard-switching PWM inverter Therefore, it was considered that power conversion efficiency was improved by applying the proposed the resonant AC link snubber circuit The power losses of resonant AC link snubber-assisted soft-switching PWM inverter were analyzed It was suggested that the actual power conversion efficiency was improved by reducing the conduction losses of main inverter switching IGBTs and reverse blocking diodes of resonant AC link snubber circuit

And more, the electromagnetic conductive noise and radiative noise of the resonant AC link snubber-assisted soft-switching PWM inverter were evaluated as compared with those of hard-switching inverter. Judging from these results, it was described that the conductive and radiative electromagnetic noises can be reduced by applying the resonant AC link snubber-assisted soft-switching PWM inverter as compared with those of hard-switching PWM inverter

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