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Auxiliary Resonant Commutated Leg Snubber Linked 3-Level 3-Phase Voltage Source Soft-Switching Inverter

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ABSTRACT

This paper presents a performance analysis in steady-state of a novel type Auxiliary Resonant Commutation Snubber-linked 3-level 3-phase voltage source soft switching inverter suitable and acceptable for high-power applications in comparison with other three types of 3-level 3-phase voltage source soft switching inverters. This soft switching inverter operation which can operate under a condition of Zero Voltage Switching (ZVS) The practical steady-state performances of this inverter are illustrated and evaluated on the basis of the experimental results.

Keywords: 3-level 3-phase voltage source inverter, Auxiliary resonant commutated leg snubber, Soft switching, Power loss analysis

1. Introduction

In recent years, a variety of 3-phase voltage source inverter and active rectifier using IGBTs or IGCTs, which can operate under a principle of zero voltage or zero current soft commutation transition schemes have been actively studied in order to minimize the switching power losses of power semiconductor devices, their electrical dynamic and peak stresses, voltage and current surge-related EMI/RFI noises under high frequency switching[1][2].

The 3-phase voltage-fed inverters and rectifiers operating under zero voltage soft switching transition PWM modes are roughly divided into 3 types; resonant AC link and resonant DC link[3][4] Auxiliary Resonant Commutated leg Snubber (ARCS) link[5]-[7]

In actual, the 3-phase voltage source soft switching inverters and PFC rectifiers required for utility interactive power supplies and active power filter and statatic var compensators, which can efficiently operate under a principle of zero voltage soft switching (ZVS) method have been developed so far. However, there have been only a few papers[9]-[13] of soft switching power conversion circuits and control techniques for 3-level 3-phase voltage source soft switching inverter and rectifier which are more suitable and acceptable for high power high voltage energy processing systems.

In this paper, the power loss analysis and efficiency calculation simulator for ARCS 3-phase soft switching inverter using IGBTs is presented, which are based on experimental results of power device characteristics. In addition, 3-level 3-phase voltage source soft switching inverter with ARCS circuits are introduced and discussed in terms of the efficiency calculation simulator. And more,

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the ARCS circuit which is more suitable for high power applications is presented as compared with the other type of ARCS assisted 3-level 3-phase soft-switching inverter is picked up here-in. Furthermore, the performance of 3-level 3-phase voltage source soft switching inverter with ARCS circuits originally selected here are illustrated and evaluated on the basis of the experimental results.

2. Efficiency Calculation Simulator for ARCS 3-Phase Voltage Source Soft Switching Inverter

Fig. 1 illustrates one phase of ARCS assisted 3-phase soft switching inverter. The efficiency calculation simulator of this inverter need 4 data; the resonant inductor resistance component RLr (RLr=0.141[Ω]), *v-i* characteristics of IGBT and diode used in ARCS 3-phase voltage source soft-switching inverter (see Fig. 2), the turn off switching power loss characteristics of the IGBT and the diode (see Fig. 3), the output filter resistance (RLf=0.05[Ω]. From this simulator and operating the hardware system of ARCS 3-phase soft-switching inverter, the comparative output power vs. inverter efficiency performances between experiment and practical simulator are shown in Fig. 4. Observing these results, it is understood that the output power vs. efficiency performance has the same values between experimental and simulation setup.

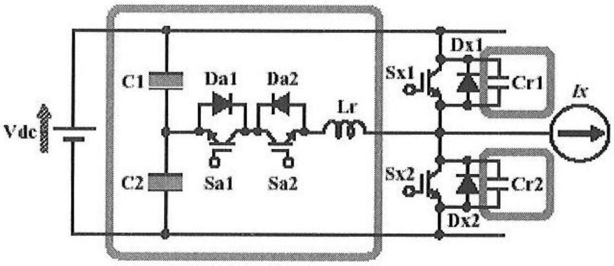
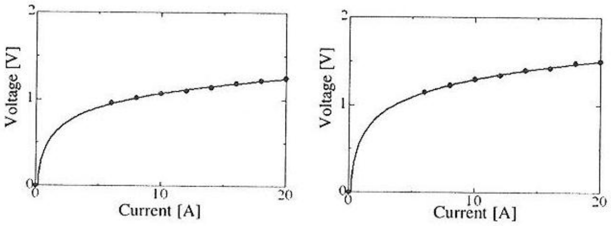


Fig. 1. 3-phase ARCS soft-switching inverter for one-phase part.



(a) IGBT (b) Diode

Fig. 2. v-i characteristics of IGBT and diode.

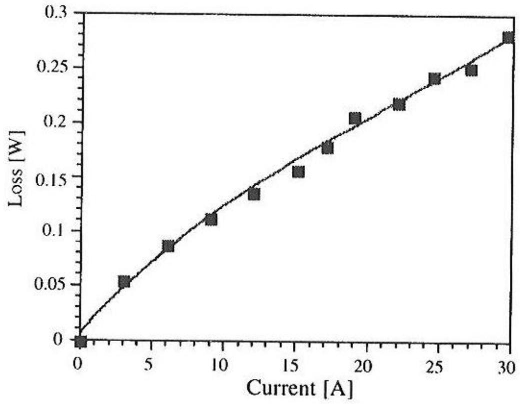


Fig. 3. Turn-off switching loss characteristics.

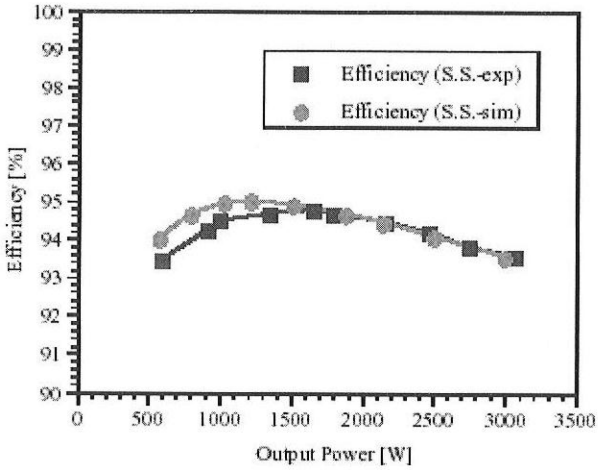


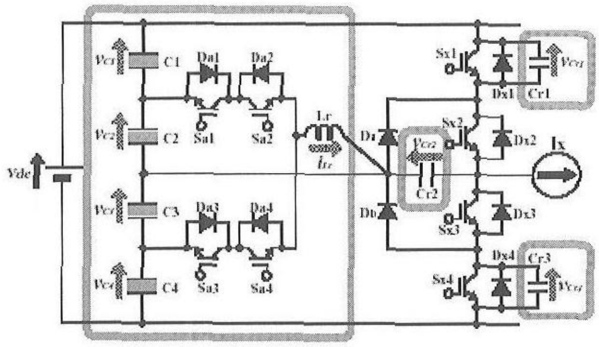
Fig. 4. Power efficiency performance.

3. 3-Level 3-Phase Voltage Source Soft Switching Inverter Topologies with ARCS Circuits

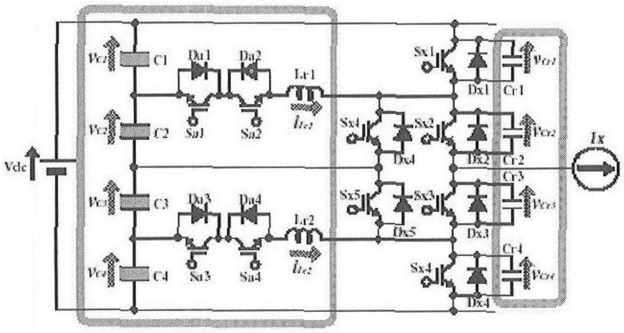
Fig. 5 shows one bridge leg phase equivalent circuit of 4 types Auxiliary Resonant Commutation leg Snubber linked 3-level 3-phase voltage-fed soft-switching inverter. Each operation of these four types ARCS circuit is briefly described as follows;

(Topology A)

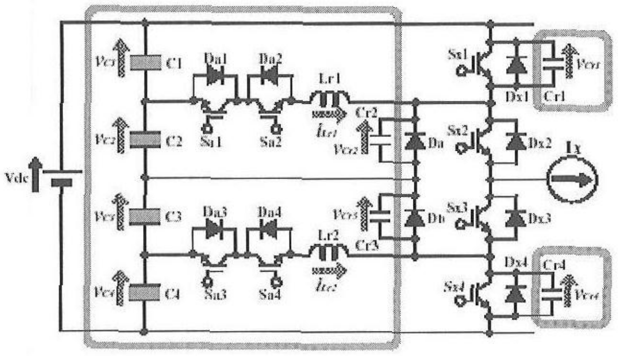
This ARCS circuit type consists of the minimum number of components as compared with the other types



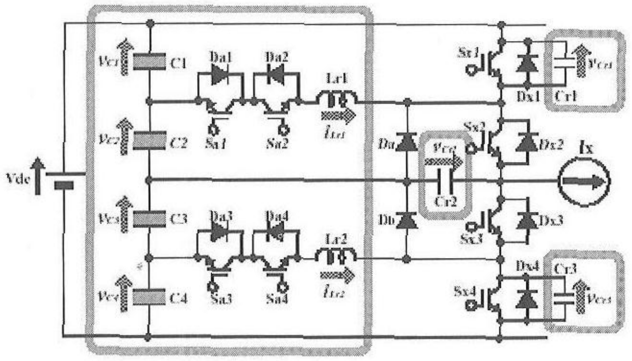
(a) Topology A



(b) Topology B



(c) Topology C



(d) Topology D

Fig. 5. Several 3-level 3-phase ARCS inverter for one-phase part.

of circuits (Topology B~Topology D). On the other hand, in steady state mode, the additional auxiliary power semiconductor devices (Sa1~Sa4) respectively require 3/4 of DC bus-line voltage in this type. Each voltage value of auxiliary power semiconductor devices in Topology B~Topology D is a half of DC bus-line voltage. As a result, This type of ARCS circuit topology is not more suitable for high voltage applications as compared with the other type of ARCS circuits.

(Topology B)

In this type of circuit topology, the voltage across auxiliary active power switches is sufficiently more reduced as compared with that of the Topology A. However, this circuit topology requires two additional power semiconductor switching devices as depicted in Fig. 5. So, it is clear that the configuration using this type of ARCS circuit is not more cost effective than the other types of ARCS circuits because of required additional two IGBTs as compared with those of each topology A, C and D. For this reason, the circuit of Topology B is not selected in this paper.

(Comparative Efficiency; Topology C and Topology D)

By using the efficiency calculation simulator, the efficiency in these 3 type soft switching inverters (Topology A, B, C and D) are shown in Table 1. It is proved that each efficiency of these ARCS circuits is almost the same value in spite of the differences of the circuits configurations. From the considerations in cost and efficiency, it could be understood that the efficiency of Topology C is better than those of the other topological types of 3-level 3-phase soft switching inverters.

Table 1. Comparative evaluations on efficiency of 3-level 3-phase voltage Source soft switching inverter.

Circuit Type	Efficiency [%]
Topology A	92.422
Topology B	92.894
Topology C	92.852
Topology D	92.858

4. Circuit Description and Operation

4.1 ARCS Circuit Description

Fig 6 shows one leg phase equivalent circuit of auxiliary resonant commutation-leg snubber (Topology D) linked 3-level 3-phase voltage source soft switching 3-level 3-phase voltage source inverter has basically three inverters using IGBT power modules. As shown in Fig 7, modes in steady-state operation (State A~State C) The relation between switching state and output phase voltage for 3-level 3-phase voltage source inverter is described in Table 2. To achieve complete ZVS operation, upper side ARCS circuit acts as the transition between State A and State B On the other hand, lower side ARCS circuit acts as the transition between State B and State C To illustrate the operating principle of the proposed 3-level 3-phase voltage source soft switching inverter, the commutation mechanism from the State A to the State B is discussed below. For simplicity, some assumptions are considered as follows;

(1) All the power semiconductor switching devices incorporated into the inverter are ideal.

(2) Load current equals to the positive Ix as indicated in Fig. 8 which is kept constant during a short commutation interval because the low pass filter is connected to the output parts of this inverter.

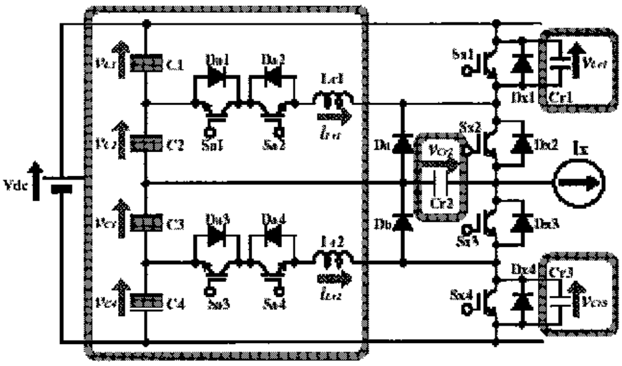


Fig 6 3-level 3-phase ARCS inverter for one-phase leg

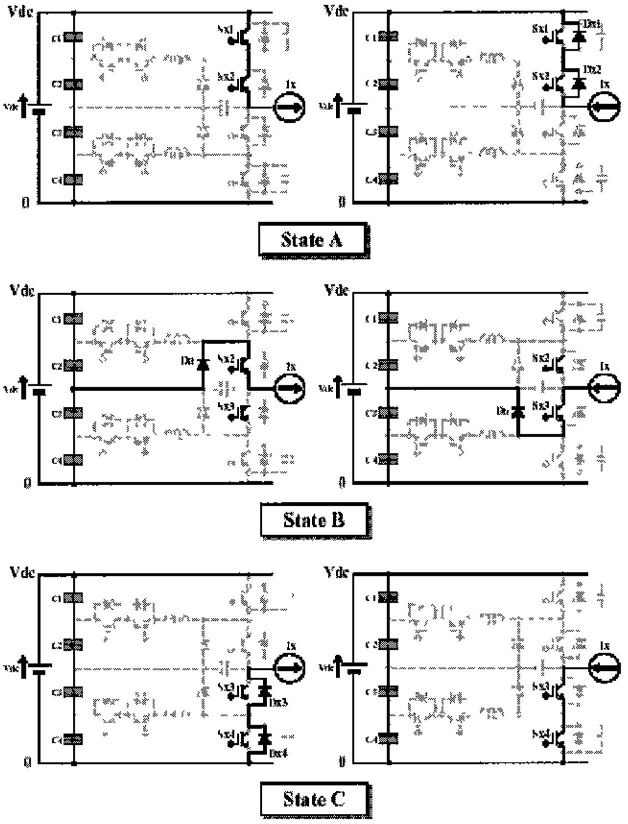


Fig 7 Circuit state of 3-level voltage source soft switching inverter

4.2 ARCS Circuit Operation

Fig. 9 represents the typical voltage and current waveforms of the main active power switches and the auxiliary active power switches of this soft-commutation circuit, ARCS circuit shown in Fig 6 As shown in Fig 9, there are 10 operation modes. The operating principle in periodic steady-state (in case of this explanation, from State B to State A) can be described as follows:

State B : mode 0 ($t < t_0$)

The positive load current is freewheeling through Da and Sx2, while Sx2 and Sx3 is on state and Sx1 and Sx4 is off state (State B)

State B : mode 1-1($t_0 - t_1$)

The auxiliary switch Sa2 is turned on under Zero Current Soft Switching (ZCS) condition. The current through Da begins to decrease linearly as the current through the resonant inductor increases linearly.

Table 2 Switching state of 3-level voltage source inverter

State	Switching Sequence States				Output States
	Sx1	Sx2	Sx3	Sx4	
A	ON	ON	OFF	OFF	Vdc
B	OFF	ON	ON	OFF	$\frac{1}{2}$Vdc
C	OFF	OFF	ON	ON	0

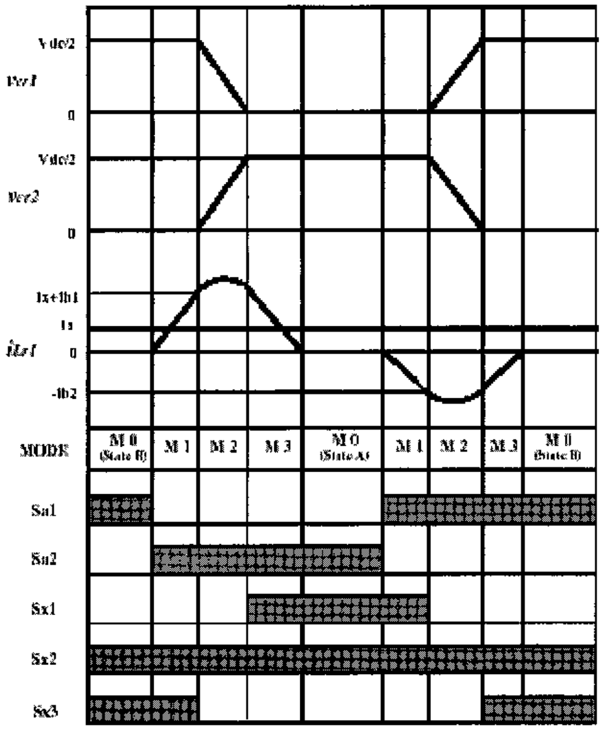


Fig 8 Gate pulse sequences and waveforms of ARCS circuit

State B : mode 1-2(t_1 - t_2)

At t_1, the current through Da reaches zero, when a resonant inductor current is equal to the load current Ix After this condition, the current in Sx3 begins to increase. The resonant inductor current becomes greater than the load current, and continues rising until the stored energy is high enough to charge and discharge the resonant capacitors (Boost current)

State B : mode 2(t_2 - t_3)

After turning off Sx3 with ZVS, the resonant losses capacitors Cr1 begins to discharge to zero while the resonant capacitor Cr2 begins to charge toward half of dc busline voltage This provides a resonance between the resonant inductor Lr1 and the resonant capacitors Cr1 and Cr2.

State B : mode 3-1(t_3 - t_4)

At t_3, Dx1 is conducted and resonant inductor current begins to decrease linearly. On the other hand, Sx1 can be turned on at ZVS/ZCS hybrid soft switching condition.

State B : mode 3-2(t_4 – t_5)

At t_4, the current through Dx1 is commutated to Sx1 and resonant inductor current decreases linearly

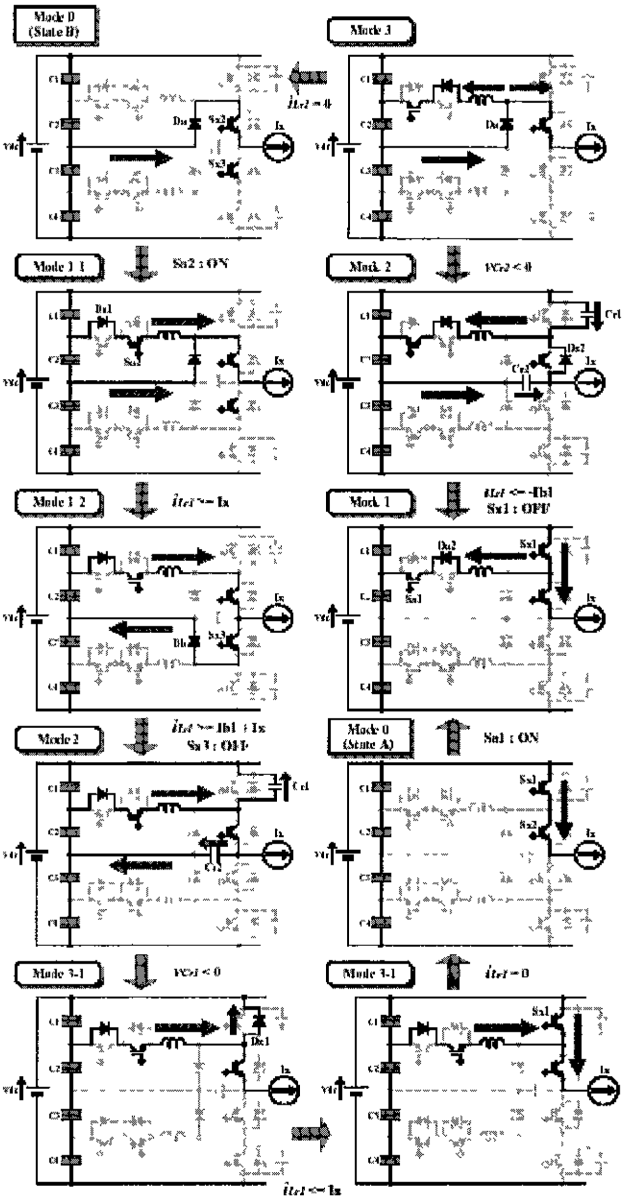


Fig 9 Equivalent circuits of ARCS circuit and operation mode

State A : mode 0(t_5 – t_6)

At t_5, the resonant inductor current becomes zero and Da1 is turned off. The load current is totally commutated to Sx1 and Sx2 (State A).

State A : mode 1(t_6 – t_7)

Sa1 is turned on with a ZCS condition. The resonant inductor current begins to increase toward minus direction linearly and continues to rise until the stored energy is high enough to charge and discharge the resonant capacitors.

State A : mode 2($t_7 - t_8$)

After turning off Sx1 with a ZVS, the resonant capacitor Cr1 begins to charge to a half of DC-link voltage while the other resonant capacitor Cr2 begins to discharge to zero.

State A : mode 3($t > t_8$)

At t_8, Da is conducted and the resonant inductor current begins to decrease toward minus direction linearly. When the resonant inductor current becomes zero, Da2 is turned off and be back to State B - mode 0

5. Experimental Results of 3-Level 3-Phase Voltage Source Soft Switching Inverter

5.1 Experimental Set up

In order to verify the operating performances of the selected 3-level 3-phase voltage source soft switching inverter, the topology depicted in Fig. 6 is tested under a balanced 3-phase inductive load on the basis of experimental setup. Fig. 10 illustrates the experimental set up of 3-level 3-phase voltage source soft switching inverter using IGBT modules. Table 3 indicates the design specifications and circuit parameters of the 3-level 3-phase soft switching inverter treated here. This new conceptual 3-level 3-phase voltage source soft switching inverter system includes DSP (TMS320C35) control implementation, voltage and current sensors and the divided DC voltage smoothing circuit. The active power switches S1, S2, S3 and S4 in the DC side circuit construction operate for stability of divided 4 smoothing capacitors.

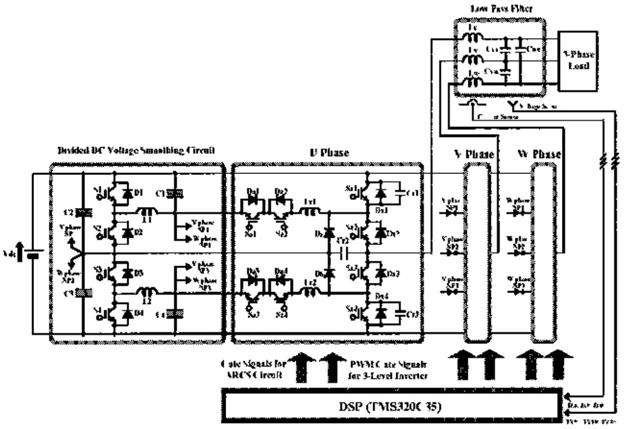


Fig. 10 Experimental setup of 3-level 3-phase voltage source soft-switching inverter

Table 3 Design specifications and circit parameters

Input DC Voltage	Vdc	280 [V]
Resonant Inducter	Lrx (x=1~2)	50.0 [μH]
Resonant Capacitor	Crx (x=1~3)	0.022 [μF]
DC Smoothing Capacitor	Cx (x=1~4)	8200[F]
Load Resistance	Ruv=Rvw=Rwu	4.0 [Ω]
Load Inducter	Luv=Lvw=Lwu	4.0 [mH]
Filter Capacitor	Cuv=Cvw=Cwu	65.0 [μF]
Filter Inducter	Lx (x=u,v,w)	500 [μH]
Sampling Frequency	fs	12.8 [kHz]
Output Frequency	fo	50.0 [Hz]
Swiching Frequency of S1~S4	fsdc	20.0 [kHz]

5.2 Experimental Results and Discussions

Fig. 11 displays the output voltage and current waveforms obtained from the experimental setup of the 3-level 3-phase voltage source soft switching inverter. The observed resonant inductor current, the current and the voltage across the main active power switch Su1 is shown in Fig. 12. Observing these experimental results, it is clear that the main objectives of the proposed 3-level 3-phase voltage source soft switching inverter system can be achieved in principle and in reality.

Fig. 13 shows the observed voltage and current waveforms at soft switching turn on and turn off for the 3-level 3-phase voltage source inverter main switch Su1 in the bridge arm, as compared with those of the hard switching experimental setup. In case of hard switching, the high dv/dt voltage and the high frequency current surge are observed because of parasitic circuit and device components in addition to the stray inductance of the wiring. On the other hand, significantly reduced dv/dt and di/dt values in soft switching inverter main switches means that EMI/RFI noises can be reduced greatly from Fig. 13.

Furthermore, it is clear that the switching power device power losses of the 3-level 3-phase voltage source soft switching inverter can be remarkably reduced from 117.0μJ to 49.8μJ because of soft switching operation achieved completely.

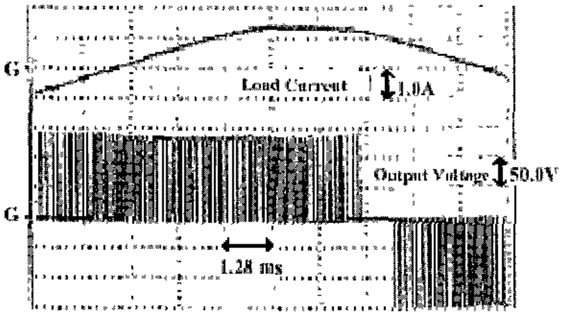


Fig 11 The output voltage and current waveforms of 3-level 3-phase voltage source soft switching inverter

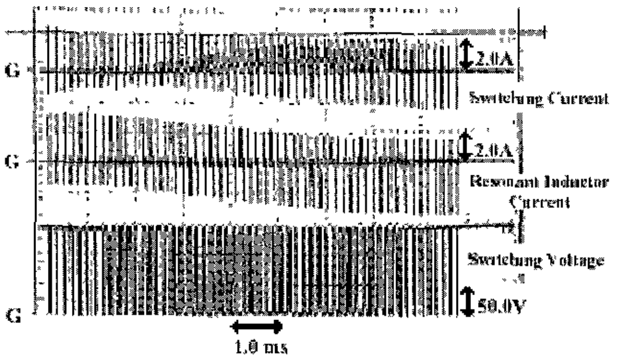
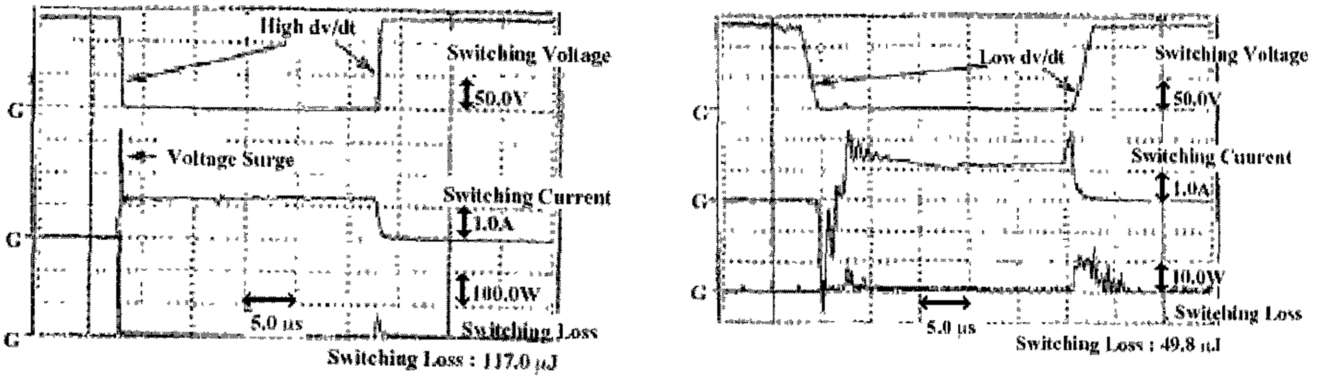


Fig 12 The resonant inductor current waveforms and voltage and current waveforms across main switch Su1 of 3-level 3-phase voltage source soft switching inverter.



(a) In case of hard switching

(b) In case of soft switching

Fig 13 Switching operating waveforms of main active switch Su1

6. Conclusions

In this paper, some topologies of active auxiliary resonant commutation leg snubber-based 3-level 3-phase voltage source soft switching inverters have been presented The comparative evaluations of these inverters have been discussed This paper have selected the most simple and effective topology of auxiliary resonant commutated leg snubbers-assisted 3-level 3-phase voltage source soft switching inverter by using efficiency calculation simulator constructed here In addition to this, the operating principle and features of a novel type auxiliary resonant commutated leg snubber assisted 3-level 3-phase voltage source soft switching inverter have been discussed described and discussed Furthermore, it was proved from an experimental setup that auxiliary resonant commutation leg snubber linked 3-level 3-phase voltage source soft switching inverter was more cost effective which can efficiently operate under a principle of high performance ZVS in order to minimize switching power losses.

In the future, the comparative feasible studies between active resonant DC link and active resonant commutation arm link associated 3-level 3-phase voltage source soft switching inverters should be developed for high voltage and high power applications such as utility interactive power supplies and active power filter and static var compensators

The advanced 3-level 3-phase soft-switching inverters and PFC converters using the new power semiconductor switching devices such as Trench Gate PT-IGBTs, IGCTs, High Conductivity IGBTs (HiGTs) and IEGTs should be evaluated from a practical point of view.

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