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Two-Switch Auxiliary Resonant DC Link Snubber-Assisted Three-Phase Soft Switching PWM Sinewave Power Conversion System with Minimized Commutation Power Losses

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ABSTRACT

This paper presents a high-efficient and cost effective three-phase AC/DC-DC/AC power conversion system with a single two-switch type active Auxiliary Resonant DC Link (ARDCL) snubber circuit, which can minimize the total power dissipation. The active ARDCL snubber circuit is proposed in this paper and its unique features are described. Its operation principle in steady-state is discussed for the three phase AC/DC-DC/AC converter, which is composed of PWM rectifier as power factor correction (PFC) converter, sinewave PWM inverter. In the presented power converter system not only three-phase AC/DC PWM rectifier but also three-phase DC/AC inverter can achieve the stable ZVS commutation for all the power semiconductor devices. It is proved that the proposed three-phase AC/DC-DC/AC converter system is more effective and acceptable than the previous from the cost viewpoint and high efficient consideration. In addition, the proposed two-switch type active auxiliary ARDCL snubber circuit can reduce the peak value of the resonant inductor injection current in order to maximize total system actual efficiency by using the improved DSP based control scheme. Moreover the proposed active auxiliary two-switch ARDCL snubber circuit has the merit so that there is no need to use any sensing devices to detect the voltage and current in the ARDCL snubber circuit for realizing soft-switching operation. This three-phase AC/DC-DC/AC converter system developed for UPS can achieve the 1.8% higher efficiency and 20dB lower conduction noise than those of the conventional three-phase hard-switching PWM AC/DC-DC/AC converter system. It is proved that actual efficiency of the proposed three-phase AC/DC-DC/AC converter system operating under a condition of soft switching is 88.7% under 10kw output power.

Keywords: Three-phase soft-commutation converter, Two-switch active auxiliary resonant DC link snubber, Commutation current control, Zero-voltage switching, Zero current switching, High efficiency low noise

1. Introduction

The developments of the active auxiliary resonant snubber circuit topologies for the high efficient and

low noise soft-switching sinewave three-phase PWM inverters and PWM rectifiers have attracted special interest. Under the requirements of increasing communication energy plants and facility power, the implementation and improvement of the soft-switching PWM conversion circuits using active auxiliary resonant snubber circuits to the energy utilization use are needed.

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The soft commutation snubber-assisted three-phase soft switching power conversion circuit as the power regenerative lossless snubbers for the voltage source inverters and rectifiers can generally decrease the switching losses of power semiconductor switching devices, reduce the conduction and radioactive noises caused by the voltage and current surges of the turning off and the turning on of the unit. A variety of auxiliary resonant snubber-assisted three phase soft-switching power conversion circuit and system technologies have been proposed and discussed for the three-phase voltage source bridge type sinewave PWM inverters and sinewave PFC rectifiers^[1-4]. In general, these advanced snubbers used for the new generation power conversion conditioners require complex and high cost active auxiliary resonant commutation snubber circuits composed of some unidirectional and bi-directional auxiliary power semiconductor switching devices, passives resonant circuit composed of the diodes, capacitor and inductor and sensor-interfaced electronic circuits. The conduction power losses of the additional auxiliary active power semiconductor devices and high frequency resonant snubber circuit components, however, occupy a large portion of total power losses in spite of less switching losses of the power switches. Thus, it is more difficult to commercialize their snubber modules practically because of their high cost, complex control scheme including voltage and current sensors, large volumetric, physical size, heavy weight, lower actual efficiency and reliability.

It is not any easier to achieve high actual efficiency for the three-phase soft switching AC/DC-DC/AC conversion circuits as compared to the conventional three-phase hard-switching power converter. However, these soft commutation snubber assisted three-phase power conversion circuits attract more and more attention for effective reduction on the electromagnetic noises from a practical point of view. A variety of high frequency soft switching realization methods, which are proposed and discussed previously, is generally divided into three categories: Auxiliary Resonant Bridge Leg (ARBL) snubber schemes, Auxiliary Resonant Commutation Pole (ARCP) snubber schemes^[1], Auxiliary Resonant DC Link (ARDCL) snubber schemes^{[2][3]}, Auxiliary Resonant AC

Link (ARACL) snubber schemes^[4]. For high power applications like industry, telecommunication, new energy utilization plants, the relatively higher power loss dissipations of the bridge leg associated ARCP snubbers are generally smaller than those of the DC busline associated ARDCL snubbers. However, because the ARCP snubbers need the bi-directional active power switch-based auxiliary resonant commutation circuit in series with the edge resonant inductor with neutral point of the electrolytic capacitors for voltage source three-phase bridge leg. It makes the soft switching power conversion circuits and system topologies and their improved modifications become complex and expensive. On the other hand, the auxiliary soft commutation snubber circuit based on ARDCL snubber is schematically much simpler than the ARCP snubber schemes. Consequently, the ARDCL snubbers are expected to be reliable, compact as well as low cost. These have attracted special interest for small scale and medium scale high power conditioners in the new energy utilization such as fuel cell, solar photovoltaic power generation, the emergency power supply and UPS.

There is a significant practical problem in the previously developed ARDCL snubber, however, associated with large conduction power loss generation due to the resonant current conditions necessary for soft commutation realization. In general, it is more difficult to improve the actual efficiency of the ARDCL snubber-assisted three-phase power conversion systems due to this resonant current related power losses. As a result, the actual efficiency of the power system is lower as compared to the actual efficiency of the three-phase hard switching PWM sinewave AC/DC-DC/AC conversion system.

Thus, in this paper, the novel control method to reduce the power losses in the two-switch ARDCL snubber circuit for the three-phase AC/DC-DC/AC converter system is proposed and discussed. It is noted that the proposed two-switch ARDCL snubber circuit provides the efficient pulse-train sequences on the basis of the state variables detections of the input and output current and the DC busline voltage of the three-phase sinewave PWM AC/DC-DC/AC converter system. The pulse timing sequences are produced by DSP. The resonant current

through the edge resonant inductor of the single two-switch ARDCL snubber circuit treated here is managed and controlled by the DSP software to provide an optimum minimum value needed for ZVS of the main switches. The conduction power losses in the two-switch ARDCL snubber circuit can be sufficiently decreased when using the three-phase soft switching AC/DC-DC/AC converter. The two-switch ARDCL snubber circuit implementation in the three-phase soft switching AC/DC-DC/AC converter system has the remarkable merits, that there is no requirement to use any sensing devices and complex interface circuits of ARDCL snubber circuit voltage and current detection. The simple and low cost two-switch ARDCL snubber circuit is used. Therefore, the resonant DC link snubber circuit topology proposed here becomes simpler, the number of circuit components and semiconductor switches are minimized.

The proposed control approach in the two-switch ARDCL snubber circuit developed by the authors is applied to the total power conditioner system composed of the three-phase PWM rectifier as three phase PFC converter and three-phase sine wave PWM inverter, which are designed for 10kVA UPS systems. It is noted that ARDCL snubber circuit assisted three-phase PWM rectifier and three-phase sine wave PWM inverter are originally built and tested for total AC/DC-DC/AC converter. The actual efficiency of the developed three-phase soft switching AC/DC-DC/AC converter system can improve from 86.9% to 88.7%. The conduction noise in three-phase soft switching sine wave PWM AC/DC-DC/AC converter is reduced by about 20dB.

2. System Description

Fig. 1 shows the newly proposed main system configuration of the three phase soft switching sine wave PWM AC/DC-DC/AC converter circuit with a single two-switch ARDCL snubber circuit. The AC/DC-DC/AC conversion circuit consists of a three-phase sine wave PWM bridge and PWM-PFC rectifier cascaded three-phase inverter with only one two-switch ARDCL snubber circuit. The snubber circuit includes two auxiliary active power switches and edge-resonant LC circuit components including the losses snubber capacitors in parallel with each active power switch in the three-phase bridge arms and legs. The two-switch ARDCL snubber circuit is composed of the active power switches; IGBTs Q1(SW1/D1), Q2(SW2/D2), the only one quasi-resonant capacitor C_f in DC busline side, and only one single edge resonant inductor L_r with a ferrite core and litz wiring assembly. The voltage across the DC capacitor C_f is to be maintained so as to be a half of the voltage across the DC capacitor C_{dc} . Each resonant capacitor C_r is respectively connected in parallel with each main active power switch of the three-phase bridge legs.

3. Circuit Operation

3.1 Switching Pattern of Main Active Switches

Fig. 2 shows typical voltage and current waveforms to explain the operation principle for one phase in the three-phase bridge legs during 4-cycle switching period.

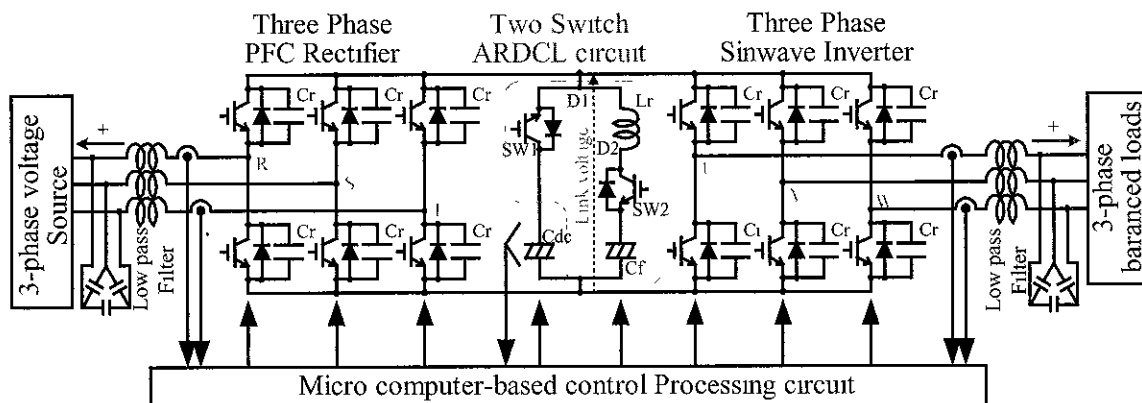


Fig. 1 A Schematic Total Configuration of 3-phase Soft Switching Double Converter System

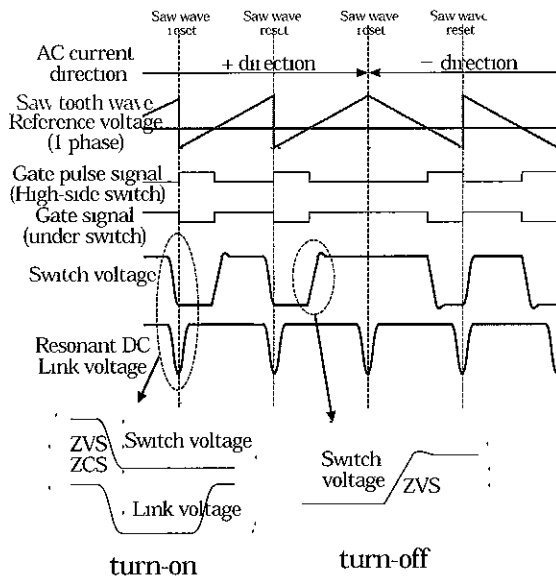


Fig 2 Operation waveforms during 4-cycle switching period

for the PWM rectifier and PWM inverter. To produce sine wave PWM, the gate pulse signal timing sequences are provided by comparing high frequency saw-tooth carrier wave (16KHz) with each phase sine wave reference voltage of 60Hz/50Hz three-phase sine wave reference voltage signals. The saw-tooth carrier wave slope positive or negative (see Fig 2) depends on the direction of AC load current of each bridge phase.

The DC busline link voltage is actively lowered with an edge resonant mode. The DC busline link voltage is zero by the common soft commutation snubber circuit for PWM rectifier and PWM inverter. This waveform in Fig. 2 achieves hybrid soft switching ZVS and ZCS of the main active power semiconductor switches for the turn-on commutation mode.

The proposed system (Fig 1) power switches operate with ZVS and ZCS turn-on commutation mode due to using the proposed snubber circuit. On the other hand, the ZVS commutation of this power converter can be achieved at turn-off mode switching transition by the loss less resonant snubbing capacitors connected in parallel with the active power switches.

3.2 Operation Principle of Two-Switch Auxiliary Edge-Resonant DC Link Snubber

The equivalent circuit of the proposed ARDCL commutation snubber circuit operation is introduced in this section.

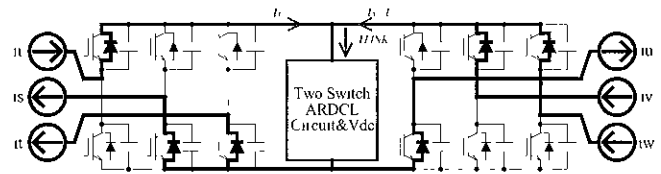


Fig 3 Current flow loop before the saw tooth carrier wave reset time

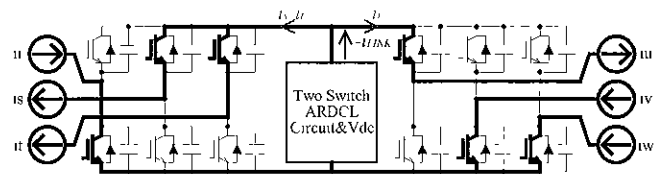


Fig 4 Current flow loop after the saw tooth carrier wave reset time

3.2.1 Current flow direction before and after the saw-tooth carrier wave reset time

Fig 3 shows the current flow direction before saw-tooth carrier wave reset instant (see Fig 2). Fig 4 shows the current flow direction after saw-tooth carrier wave reset instant. Before the reset point i_{LINK} is $i_r+i_v+i_w (=i_r-i_u)$. In this circuit state, all the phase active power switches in the bridge arms or the bridge legs operate with soft-switching commutation at turn-on transition. After saw-tooth carrier wave reset point the utility AC power source and load current directions are defined in Fig 4. i_{LINK} is $-i_u-i_s-i_t (= -i_r+i_u)$. Thus, the current i_{LINK} through the proposed ARDCL snubber before and after the saw tooth carrier wave reset time, i_{LINK} is the same and these current directions become reverse.

3.2.2 Simplified modeling main power circuit

The three-phase PWM rectifier and three-phase PWM inverter in the soft switching PWM converter system with soft commutation snubber circuit used commonly are simplified by using a DC link current source i_{LINK} during one sampling interval, as its operation is complicated during the reset period of saw tooth carrier wave. This simplified resonant snubber-assisted power inverter or rectifier circuit modeling is shown in Fig 5. This circuit is basically used for the three-phase PWM AC/DC-DC/AC converter system with only one two-switch auxiliary resonant DC link snubber, which is represented in Fig 1.

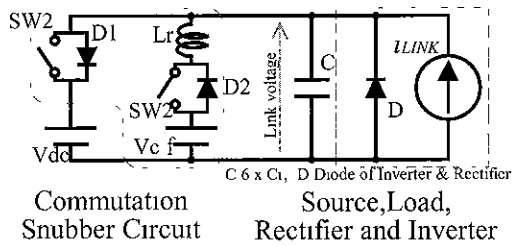


Fig 5 Simplified auxiliary edge-resonant DC link snubber using two-switch topology

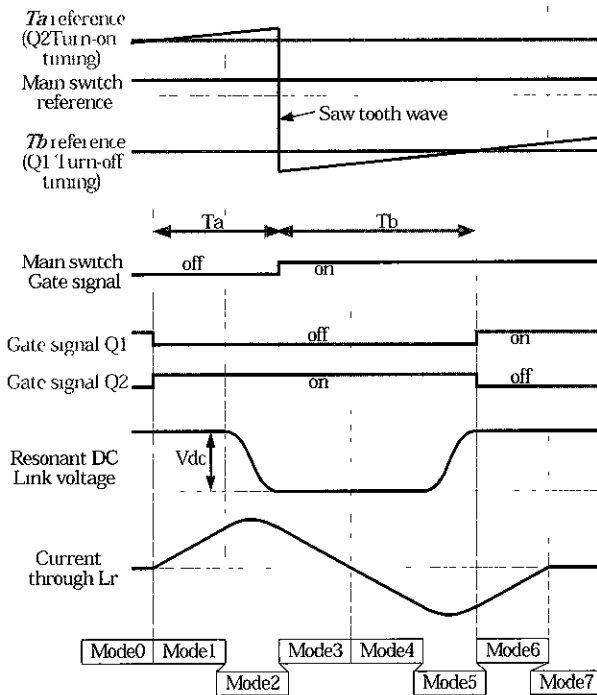


Fig 6 Timing pulse signal sequences and typical voltage and current operation waveforms for soft commutation transient states

Fig 6 represents the gate pulse signal timing sequences and operation waveforms around the time interval, when the soft commutation edge resonant snubber circuit in the DC link busline rail begins to operate. Fig 7 represents the mode transition in the soft commutation operation and the operating equivalent circuits for the transition mode. The gate voltage pulse signals of the power semiconductor device switching block Q1 (SW1/D1) and Q2 (SW2/D2) are respectively produced by comparing the saw tooth carrier wave with T_a and T_b signals designated in Fig.6. The time interval generation of T_a and T_b will be in detail described in Section 4

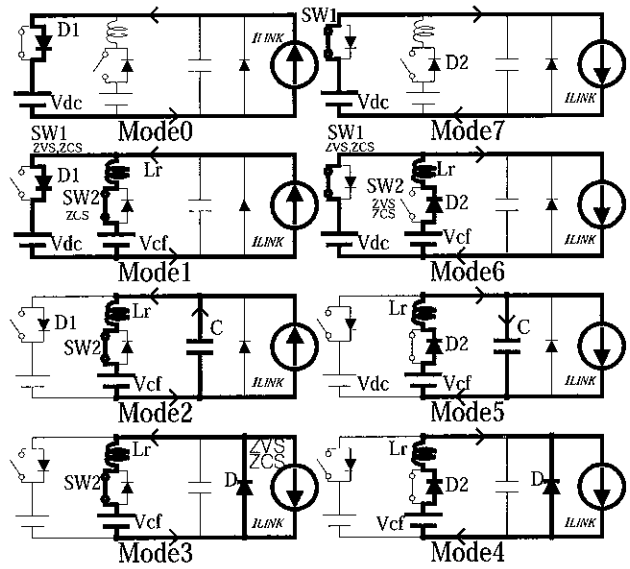


Fig 7 Operation mode transient states and equivalent circuit for the operation modes

The ARDCL soft commutation snubber circuit in Fig 5 operates as follows:

- (1) Modes 0,1: The proposed ARDCL commutation snubber starts to operate, when the power switching block Q2 (SW2/D2) turns on from the usual state
- (2) Mode 2: When the current through the edge resonant inductor L_r reaches I_{LINK} , the DC link voltage resonantly reduces toward zero with the aid of L-C resonance.
- (3) Modes 3,4: While the DC link voltage between inverter and rectifier is brought to zero, the current flowing through the injected resonant inductor L_r decreases gradually. This current begins to flow in reverse direction
- (4) Mode 5: When the current through the resonant inductor L_r recovers to I_{LINK} , the DC link voltage is again reset to its initial value.
- (5) Mode 6: The edge resonant inductor current is delivered to the load to restore the normal state in Mode 7.

Since each main active power switches in the bridge arms or bridge legs turn on, when the DC link voltage is equal to zero, the stable soft switching commutation of the ARDCL can be performed. The active auxiliary power switches; Q1 (SW1/D1), Q2 (SW2/D2) can achieve ZVS and ZCS during soft switching commutation period

4. Control Scheme For Efficient Soft Commutation

In the ARDCL soft commutation snubber-assisted three-phase PWM AC/DC-DC/AC converter circuit shown in Fig 1, the switching pulse timing selections of the active power switches, Q1, Q2 determined by Ta and Tb periods is an important signal. The simple two-switch ARDCL type soft commutation snubber-assisted three-phase PWM AC/DC-DC/AC converter circuit system (See Fig 1) can be controlled by PWM pattern provided on the detection of both voltages across the PWM AC/DC-DC/AC converter and input/output Cdc as sinewave currents values.

Fig 8 illustrates the typical voltage and current waveforms to explain the edge operation principle for the current through the resonant inductor Lr and auxiliary resonant DC link voltage in the operating modes 0-7 illustrated in Fig 7. Two time periods of Ta and Tb (see Fig 6) are respectively divided into a period Tl during which the current through Lr changes in a constant way and a period Tr during which the edge-resonance occurs.

The absolute value i_{LINK} of the total sum i_{LINK} of the switching current through all the periods is calculated from (1) as indicated in Fig 3 and Fig. 4. The specific period Tl in the operating modes Mode1, Mode3, Mode4 and Mode6 are determined from (2). On the other hand, another specific period Tr in the operating modes, Mode2 and Mode5 are found from (3). Observing these equations mentioned above and Fig 8, Ta and Tb periods are respectively estimated by using (4) and (5). Thus, the switching timing pulse train sequence can be produced from the consideration, that these periods denoted by Ta and Tb may be implemented

$$i_{LINK} = \frac{|is| + |it| + |iw| + |iv| + |iu|}{2} \quad (1)$$

where is, it, iw currents through utility three-phase AC power source side

iu, iv, iw the currents through three-phase load side.

$$I_l = \frac{2 L_l i_{LINK}}{V_{dc}} \quad (2)$$

$$I_r = \pi \sqrt{L_l C} \quad (3)$$

$$T_a = T_l + T_r \quad (4)$$

$$T_b = 2 T_l + T_r \quad (5)$$

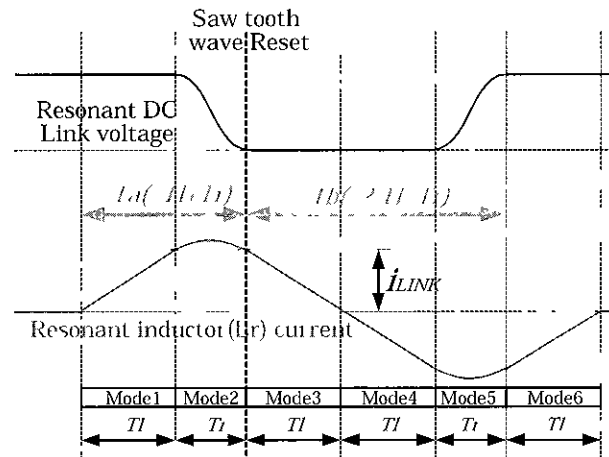


Fig 8 Instantaneous voltage of auxiliary edge-resonant DC link busline and current through quasi-resonant inductor Lr

5. Experimental Results and Discussions

5.1 Three-Phase Soft Commutation Double Power Conversion Circuit and System

Fig 9 shows the main schematic diagram of the three-phase soft-switching sinewave PWM AC/DC-DC/AC conversion system used for the experimental setup circuit. The input and output voltages in the three-phase AC/DC-DC/AC conversion system are three-phase AC200V-RMS and the power capacity of this trial-produced three-phase soft switching sinewave PWM AC/DC-DC/AC converter is designed for 10kVA, while the voltage across DC capacitor Cdc is designed for 400V and the switching frequency of the saw-tooth carrier wave is specified to 16kHz. In order to reduce sinewave current ripple of the saw-tooth carrier based switching frequency, Lin and Cin of input low pass filter, the transformer Tout and Cout of the output low pass filter are connected to the input/output in the three-phase PWM rectifier and three-phase PWM inverter, auxiliary resonant DC link snubber circuit for the only one soft commutation circuit of rectifier and inverter. Furthermore, small EMI filter is actually connected to both input/output port sides to alleviate the electromagnetic conductive noise. Such an arrangement of the three phase soft switching PWM AC/DC-DC/AC conversion system is the same as the three-phase hard switching PWM AC/DC-DC/AC converter circuit which is required for comparative studies.

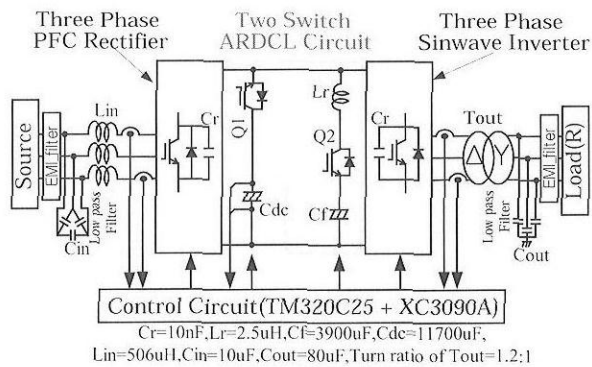


Fig. 9. Experimental setup implementation.

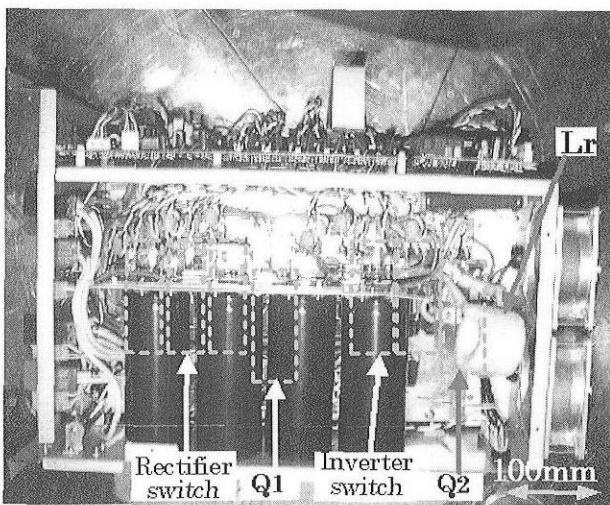


Fig. 10. Actual photograph of main three-phase double power conversion circuit system with a single two-switch ARDCL commutation snubber.

5.2 Schematic Arrangement of Three-Phase Double Power Conversion Circuit

Fig. 10 represents the external appearance of the soft switching sinewave PWM mode three-phase AC/DC-DC/AC converter circuit used in the experiment. The evaluated three-phase soft-switching AC/DC-DC/AC conversion circuit system is designed to realize the parasitic inductance less structure

5.3 Actual Verification of Soft-Switching Operation

Fig. 11 illustrates DC busline link voltage and current waveforms when the load power is 2kw, 5kw and 10kw. The period during which the current flowing through the resonant inductor L_r and auxiliary resonant DC link

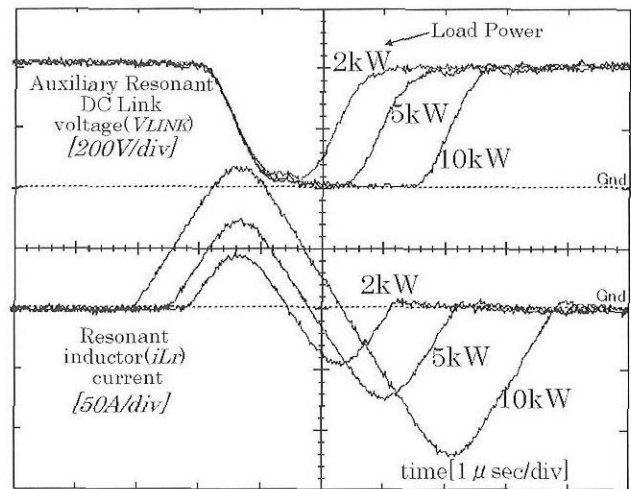
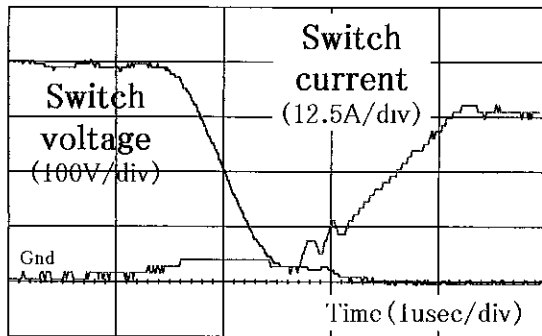


Fig. 11. Auxiliary resonant DC link busline voltage and resonant inductor current.

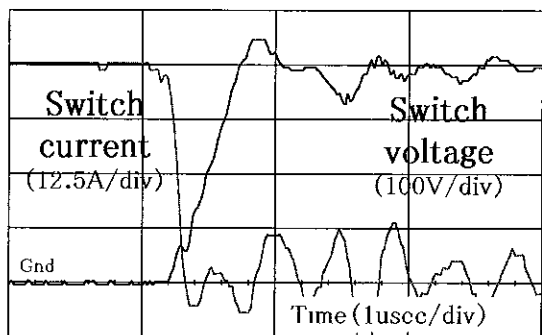
voltage are zero with respect to the rated power of the load. It is confirmed the particular ARDCL-snubber based soft commutation control strategy is more effective and acceptable.

Fig. 12 shows the observed switching voltage and current waveforms of the main active power switches in the bridge arms or the bridge legs of the three-phase voltage source soft switching PWM AC/DC-DC/AC converter. These waveforms represent the soft switching commutation principle of this three-phase AC/DC-DC/AC converter. Observing these operating waveforms, the switching achieves ZVS and ZCS at turn on and achieves ZVS at turn off. The switching Losses and the electromagnetic noises will be reduced for these waveforms (Fig.12).

Fig. 13(a) represents the utility input AC line current waveform of the three-phase soft switching PWM-PFC rectifier side Fig. 13(b) shows the output load voltage waveform of the sinewave PWM inverter side. It is noted that waveforms are low THD for an output voltage of the three-phase PWM inverter with two-switch auxiliary resonant DC link ARDCL soft commutation snubber circuit. Observing these operating waveforms, it can be confirmed that sinewave PWM control strategy in the line current of PWM rectifier can be performed with a unity power factor and sinewave current shaping in three-phase AC power source side.



(a) Switch voltage and switch current under a condition of turn-on mode transition in DC busline link



(b) Switch voltage and switch Current

Fig 12 Switching voltage and current

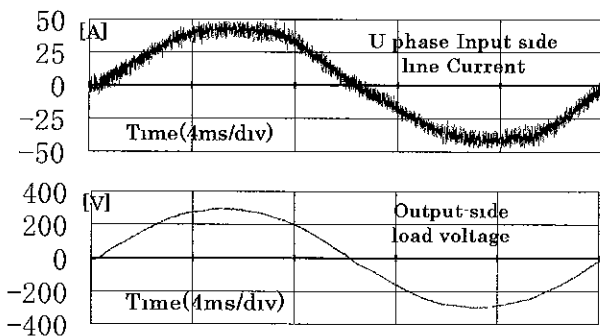


Fig 13 Utility-AC side input line current and output of line voltage waveforms

5.4 Overall Actual Efficiency Evaluations

Fig 14 shows the comparative experimental data on actual efficiency of this soft switching and the hard switching sinewave PWM control based three-phase PWM AC/DC-DC/AC converter circuit system (see Fig 1)

As a result, total actual efficiency of the three-phase

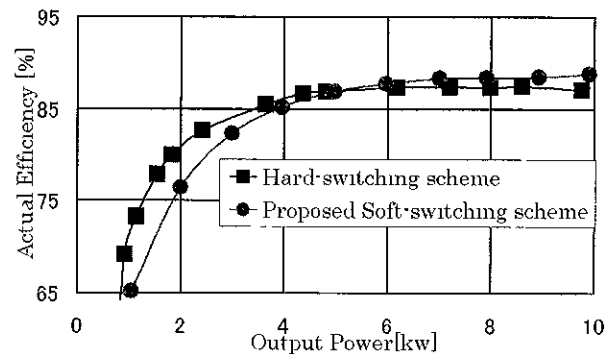


Fig 14 Actual total of efficiency vs output power characteristics of three-phase soft switching PWM double converter system with two-switch ARDCL-soft commutation snubber

proposal PWM AC/DC-DC/AC conversion system including PWM rectifier and PWM inverter (see Fig 1) is 88.7% on the load capacity of about 10kw. Total actual efficiency of the three-phase hard switching PWM AC/DC-DC/AC conversion system including PWM rectifier and PWM inverter is 86.9% on the load capacity of about 10kw. This can prove the improvement of 1.8% in total actual system efficiency in the total three-phase AC/DC-DC/AC converter system.

5.5 Comparative Noise Evaluations

Fig. 15 shows electromagnetic noises comparative data between soft switching PWM and the hard switching PWM three-phase AC/DC-DC/AC converter system. The measurements of the conductive noises for three-phase hard and soft switching PWM power conversion schemes are carried out from 10kHz to 30MHz. It is clearly observed that the overall conduction noise can be reduced over the frequency ranges mentioned above. Especially, in the frequency bands over 0.5MHz to 10MHz, the significant improvement can be actually achieved for the soft switching PWM AC/DC-DC/AC power converter system. The conduction noise in the particular saw-tooth carrier-based soft switching PWM three-phase AC/DC-DC/AC converter system using IGBT power module packages is effectively lowered by about 20dB, as compared with that of the hard switching PWM three-phase AC/DC-DC/AC power converter system using IGBT power module packages.

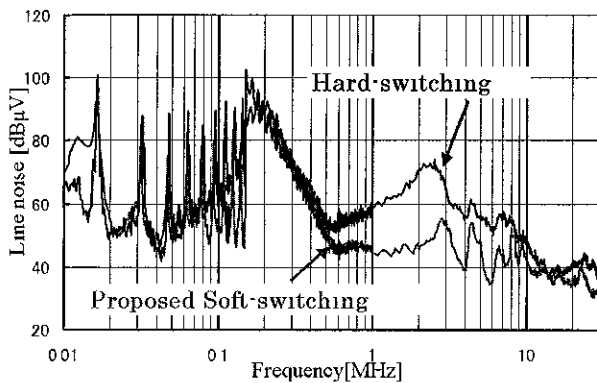


Fig 15 Comparative rectifier side conduction noise spectrum between hard-switching and soft-switching schemes

6. Conclusions

In this paper, the novel specific control method for reducing the total power losses due to the soft commutation circuit based on the simplest two-switch active auxiliary resonant DC link (ARDCL) snubber was originally introduced for realizing the cost effective three-phase voltage source type soft switched AC/DC-DC/AC converter (PWM rectifier and PWM inverter). It was confirmed that all the main and auxiliary power semiconductor switches in bridge legs of the three-phase PWM AC/DC-DC/AC converter with two-switch active auxiliary resonant DC link (ARDCL) snubber circuit can achieve the soft switching commutation over the wide operating ranges from the light load to the heavy load. In addition, the resonant inductor injection current of the auxiliary resonant DC link (ARDCL) snubber, which is needed for the stable ZVS commutation of all the power semiconductor switches in the main bridge arms or bridge legs was substantially specified to a minimum value in accordance with load current. The three-phase soft switching PWM AC/DC-DC/AC converter system using IGBT power module packages can improve the total actual efficiency from 86.9% to 88.7% under the condition of three-phase soft switching PWM 10kW output. The proposed AC/DC-DC/AC converter has also improved the conduction noise characteristics by about 20dB in experiment for the three-phase soft switching PWM AC/DC-DC/AC converter designed for 10kVA. It was verified from practical point of view that the proposed

three-phase soft switching PWM AC/DC-DC/AC converter system is much simpler than other types of soft switching commutation methods which include ARACL snubber topology, ARCP snubber and the other types of ARDCL snubber with coupled inductor or pulse regenerative transformer, because of the minimized resonant circuit components and power semiconductor switching devices in the AC/DC-DC/AC converter system in addition to the minimized resonant current for the ARDCL snubber assisted three-phase soft switching PWM AC/DC-DC/AC converter system without voltage and current sensor in ARDCL circuit. The dissipated power losses of the main and auxiliary power switch in the three-phase soft-switching PWM AC/DC-DC/AC converter system was decreased as compared to that of the three-phase hard switching PWM AC/DC-DC/AC converter system. As a result, the miniaturized active power semiconductor switches with the air cooling heat sinks and cooling fan could be also effectively applied for this power converter system.

The simplest two-switch ARDCL snubber-assisted three-phase AC/DC-DC/AC converter system implemented in the experimental setup, was built and tested, and put into practice for UPS due to the practical merits mentioned above.

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