Three-Phase Current Source Type ZVS-PWM Controlled PFC Rectifier with Single Active Auxiliary Resonant Snubber and Its Feasible Evaluations

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Abstract - This paper presents a prototype of three-phase current source zero voltage soft-switching PWM controlled PFC rectifier with Single Active Auxiliary Resonant Commutated Snubber (ARCS) circuit topology. The proposed three-phase PFC rectifier with sinewave current shaping and unity power factor scheme can operate under a condition of Zero Voltage Soft Switching (ZVS) in the main three phase rectifier circuit and zero current soft switching (ZCS) in auxiliary snubber circuits. The operating principle and steady-state performances of the proposed three-phase current source soft-switching PWM controlled PFC rectifier controlled by the DSP control implementation are evaluated and discussed on the basis of the experimental results of this active rectifier setup.

Keywords: Three Phase Current Source PWM Rectifier, Zero Voltage Soft-Switching, Auxiliary Active Resonant Commutated Snubber Circuits, Power Factor Correction and Large Power Applications

1. Introduction

In recent years, a variety of three-phase current source inverters and active PFC rectifiers[1] using GTO, IGBTs, IEGTs and IGCTs which are designed to operate under a principle of zero voltage soft switching (ZVS) or zero current soft switching (ZCS) commutation transition schemes in addition to ZVS and ZCS schemes have been actively studied in order to minimize the switching power losses of the high power semiconductor devices and power modules mentioned above, their electrical dynamic current or voltage derivatives value and their peak stresses, voltage and current surge-related EMI/RFI noises under the condition of high frequency carrier signal-based pulse switching due to pulse modulation schemes[2],[3],[4],[5].

Of these, the three-phase current source type inverters and rectifiers operating under zero current soft switching (ZCS) transition PWM operating modes have been widely evaluated and discussed so far in the fields of high power and energy processing applications.

In actual, the three-phase current source type soft switching inverters and PFC rectifiers required for utility interactive power supplies and active power filter, and static var compensator, and unidirectional and bidirectional distributed power supplies, and uninterruptible power supply which can efficiently work under a principle of zero current soft switching commutation method have been required for large current high power applications. However, there are few papers of three-phase current source type zero voltage soft switching (ZVS) PWM power conversion circuit and systems as well as their digital control techniques for three-phase current source type soft switching inverters and rectifiers systems which are more suitable and acceptable for large current high voltage power processing systems.

In this paper, a novel prototype of three-phase current source type zero voltage soft switching PWM-based PFC rectifier with a new and simple Active Auxiliary Resonant Commutated Snubber (ARCS) circuit topology is proposed newly, which can operate under a condition of zero voltage soft switching processing in MOS gate controlled bipolar transistor devices; IGBT of the three-phase PWM-PFC rectifier. In addition, its operating principle and feasible performances of ARCS-assisted soft switching PFC rectifier suitable for high power applications such as new energy related distributed power supplies, and UPS, and telecommunication power supplies are illustrated and evaluated on the basis of experimental results as compared with those of three-phase current source type hard switching PFC rectifier using IGBT power modules.

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2. New Three-Phase Current Source Soft Switching PWM Rectifier with Auxiliary Active Resonant Commutated Snubbers

2.1. Circuit Topology

Fig. 1 shows a schematic three-phase current source type soft switching PFC rectifier using IGBT power modules. Two identical circuit blocks units of the ARCS circuits are symmetrically connected to the high-side and low-side bridge arms and the DC busline rail with the output DC filter reactor of the proposed three-phase current source type PWM-PFC rectifier in parallel with DC load. The newly-proposed ARCS for three-phase current source type PWM-PFC rectifier circuit is mainly composed of the resonant inductor, the active power semiconductor devices; IGBTs, the resonant capacitor, the resonant lossless capacitor in each main switch of the proposed three-phase PFC rectifier and five power diodes. As shown in Fig.2, if the three-phase input AC voltages and currents are under $v_R>0>v_S>v_T$ ($i_R>0>i_S>i_T$) condition, three-phase current source type soft switching PFC rectifier treated here has basically three operating modes in the periodic steady-state. To achieve complete and stable ZVS operation based on the ARCS circuit, the resonant snubber circuits acts as the lossless snubber capacitor in the mode commutation transition from State1 to State2. Between State2 to State3, the ZVS transition could be achieved for SS1 and SST. The proposed ARCS circuit only operates in the operating mode transition from State3 to State1. In order to illustrate the basic operating principle of this ARCS assisted three-phase current source type soft switching PWM-PFC rectifier circuit, its soft commutation principle is briefly described under a condition of ideal switching power semiconductor devices; IGBTs, when the input current in three-phase utility AC line is almost kept constant ($i_R>0>i_S>i_T$) during a short commutation interval due to ARCS circuits.

In the operation principle of either ARCS circuit (see Fig.1), there are 12 operation modes as depicted in Fig.3.

2.2 Operating Principle

The operating principle of this three-phase current source type ZVS-PWM PFC rectifier is described as follows;

[MODE 1] In this mode, all the active power semiconductor devices have been turned on and the input current flows through the main rectifier brigde arm diodes DR1, DT2, the main rectifier switches SR1, ST2. The additional resonant capacitor voltage *vCr1* and *vCr2* are respectively charged up to *-vTR* which is the link voltage during the MODE 1.

[MODE 1-a] If the main rectifier switches ST1 and ST2 are turned off with zero voltage switching and the aid of lossless capacitive snubbers, the voltage of the resonant capacitor across the ST2 is charged up resonantly. Moreover, the auxiliary resonant capacitor voltage *vCr1* and *vCr2* are respectively discharged resonantly.

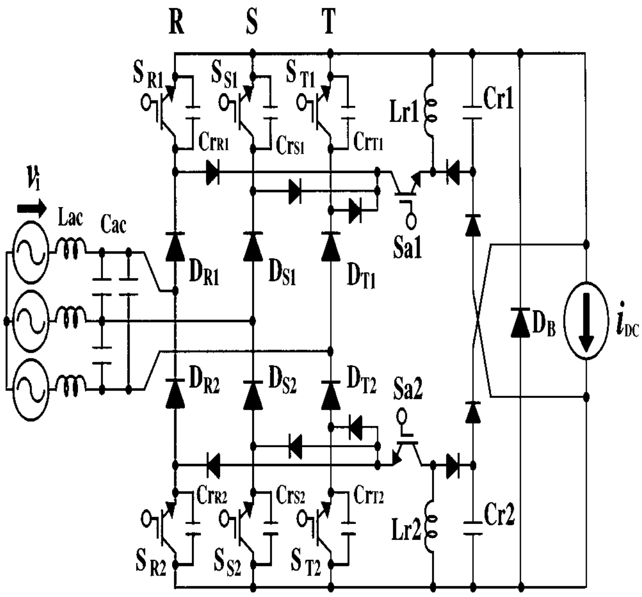


Fig. 1 Three-phase current source type soft switching rectifier with two Auxiliary Active Resonant Commutation Snubber circuits

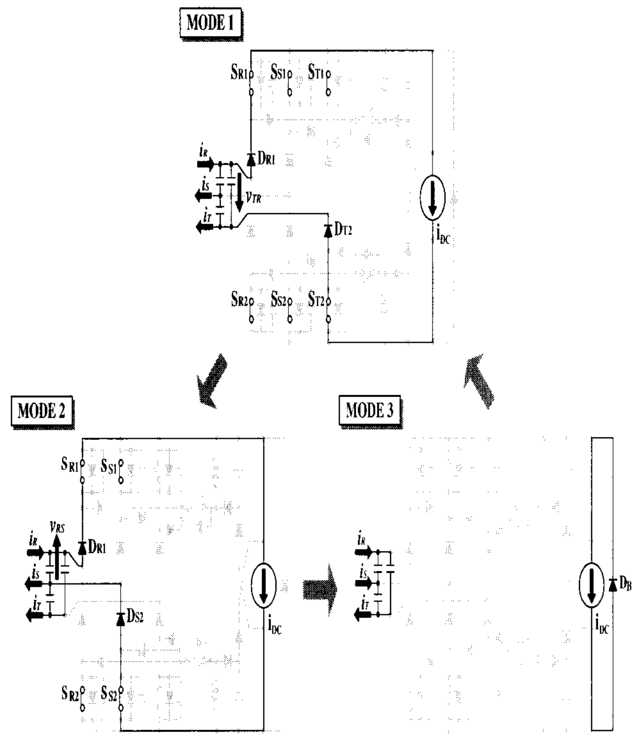


Fig. 2 Three modes in steady-states of three-phase current source type PWM rectifier under a condition of *vR>0>vS>vT*

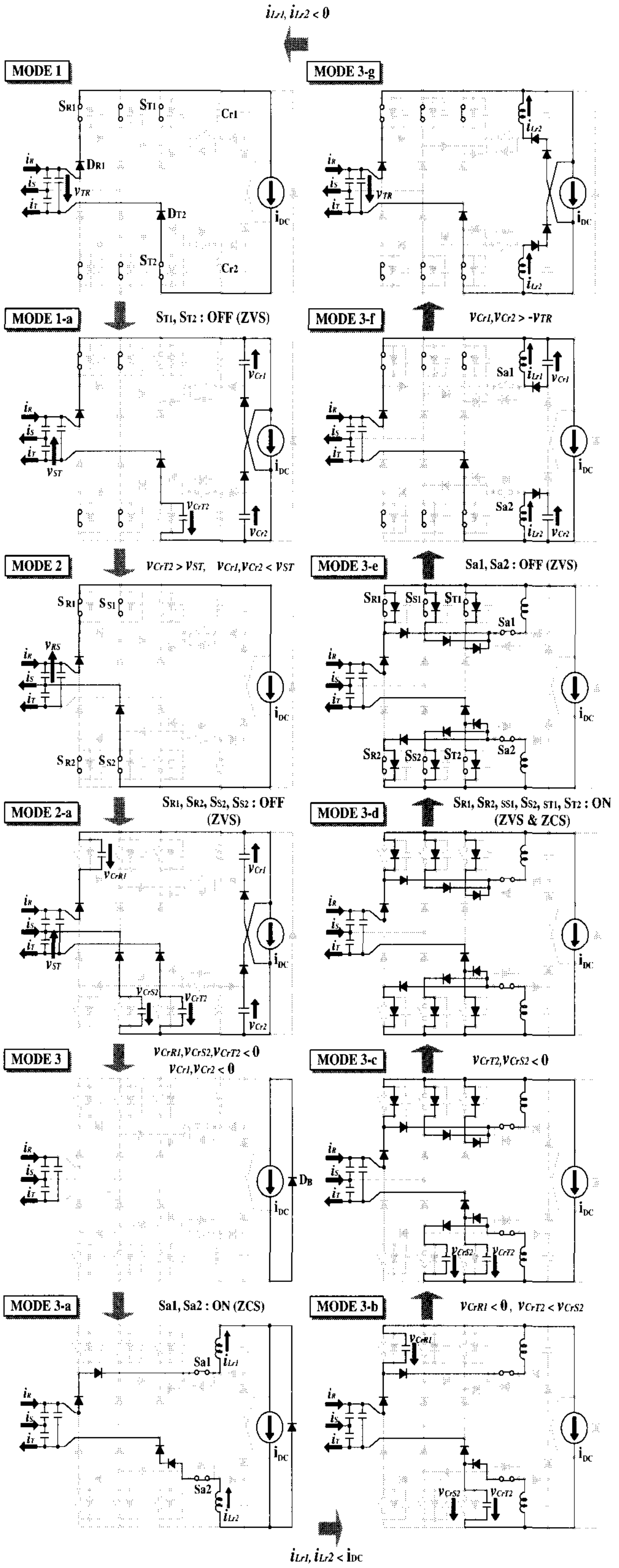


Fig. 3 Equivalent circuits for the operation stage of three-phase current source type soft switching PFC rectifier with two Auxiliary Resonant Commutation Snubber circuits

[MODE 2] If the lossless snubbing resonant capacitor voltage *vCrT2* reaches *vST*, and the auxiliary resonant capacitor voltage *vCr1* and *vCr2* reach *vST*, the MODE 2 moves to next steady state operation mode; MODE 2. In MODE 2, the input current flows through the main rectifier diodes DR1 and DS2, the main rectifier switches SR1 and SS2.

[MODE2-a] If the main rectifier active power switches SR1, SR2, SS1 and SS2 are turned off with zero voltage switching condition, the voltage of the lossless snubbing resonant capacitor across the SR1, SS2 and ST2 are charged up resonantly. In addition to, the auxiliary resonant capacitor *vCr1* and *vCr2* are discharged resonantly.

[MODE 3] If the resonant capacitor voltage *vCrR1*, *vCrS2* and *vCrT2* reach zero, and the auxiliary resonant capacitor voltage *vCr1* and *vCr2* reach zero, the operating mode moves to the next steady state mode; MODE 3. In MODE 3, the three-phase input power does not conduct to the DC output side, and the output current iDC flows through the bypass diode DB.

[MODE 3-a] If the auxiliary power switches Sa1 and Sa2 in each ARCS circuit are turned on with zero current switching, the input current in AC side flows through the auxiliary power switches Sa1 and Sa2, and the resonant inductor Lr1 and Lr2. Also, the resonant inductor current *iLr1* and *iLr2* begin to increase linearly.

[MODE 3-b] If the resonant inductor current *iLr1* and *iLr2* reach to the output current iDC, the operating mode changes to the next mode, MODE 3-b, and the input current commutates to the resonant capacitor in parallel with the SR1 and ST2 naturally. Therefore, the voltage *vCrS2* and *vCrT2* across the resonant capacitors are discharged resonantly.

[MODE 3-c] If the resonant capacitor voltage *vCrR1* reaches zero and the resonant capacitors voltage *vCrS2* reaches *vCrT2* mentioned above, the operating mode changes to the next mode; MODE 3-c. In this mode, the resonant inductor current *iLr1* flows through each body diode of the main rectifier switches SR1, SS1 and ST1, the auxiliary switch Sa1 and the resonant inductor Lr1. The input AC current flows through the auxiliary power switch Sa1 and the resonant inductor Lr1. On the other hand, the input AC current flows through the resonant capacitor CrS2 and CrT2 for the resonant capacitor voltage discharge.

[MODE 3-d] If the resonant capacitor voltages *vCrT2* and *vCrT2* reach zero, the operating mode changes to the next operating mode; MODE 3-d. In this mode, the resonant inductor currents *iLr1* and *iLr2* flow through the body diodes of all the main rectifier switches, and the input AC current flows through the main rectifier diodes; DR1, DS2 and the auxiliary switches Sa1 and Sa2 and the resonant inductors Lr1 and Lr2.

[MODE 3-e] If all the active power semiconductor devices are turned on under the condition of zero voltage and zero current soft switching transition, the operating mode changes to the next mode; MODE 3-e. During the mode; MODE 3-d, the resonant inductor current *iLr1* flows through the body diodes of the main rectifier power switches SR1, SS1 and ST1, the auxiliary switch Sa1 and the resonant inductor Lr1. The resonant inductor current *iLr2* flows through the body diodes of main rectifier power switches; SR2, SS2 and ST2, the auxiliary switch Sa2 and the resonant inductor Lr2.

[MODE 3-f] If the auxiliary power switches Sa1 and Sa2 are turned off under the condition of zero voltage soft switching, the resonant inductor current *iLr1* flows through the auxiliary resonant capacitor Cr1 and the resonant inductor current *iLr2* flows through the auxiliary resonant capacitor Cr2. This means that the resonant capacitor voltages *vCr1* and *vCr2* are charged resonantly.

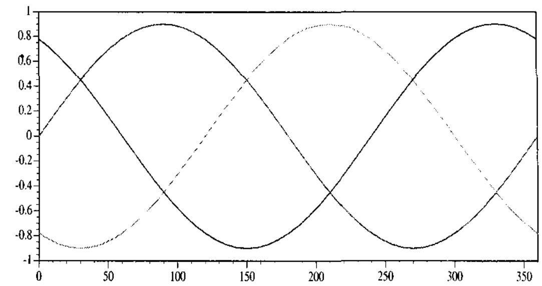
[MODE 3-g] If the resonant capacitor voltage *vCr1* and *vCr2* are charged up to *-vTR*, the resonant inductor current *iLr1* and *iLr2* commutate to the output current iDC, and these resonant inductor current *iLr1* and *iLr2* begin to decrease linearly. Furthermore, if the resonant inductor current *iLr1* and *iLr2* reach to zero, the operating mode is changed to the first steady state operating mode; MODE 1.

The operating mode transition from MODE 1 to MODE 3-g indicate the operation principle of the proposed three-phase current source-fed zero voltage soft switching rectifier during one sampling period.

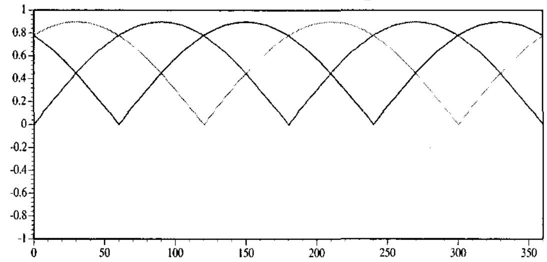
3. Three-Phase Current Source Soft Switching Rectifier with Two Auxiliary Resonant Snubbers

3.1 Control Strategy

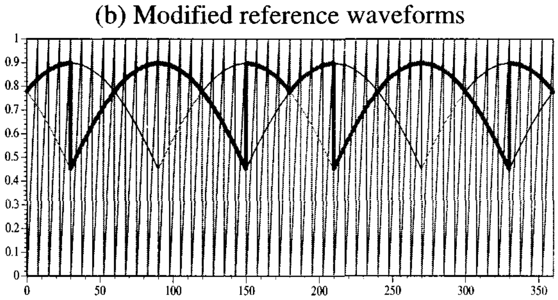
To achieve the complete soft switching commutation in all the power semiconductor devices of the proposed three-phase PFC rectifier, this three-phase current source type soft switching PFC rectifier is to be based on the saw-tooth carrier intercept control method. In actual, the compared waveform used in the saw-tooth control scheme is calculated from the reference waveforms of the three-phase current source rectifier. The reference waveforms, the modified waves of the reference waveforms and saw-tooth waveforms are respectively illustrated in Fig.4. In Fig.4 (c), the solid line indicates the reference waveform for R phase switching signal. The relationship between the switching signals and sawtooth waveform in case of the condition of $vR > 0 > vS > vT$ condition is illustrated in Fig.5. Using this sawtooth control method, the complete ZVS commutation at a turn off transition could be achieved under a turn off switching in the proposed three-phase PFC rectifier, and the ZVS and ZCS hybrid soft commutation can be completely achieved for turn on mode transition.



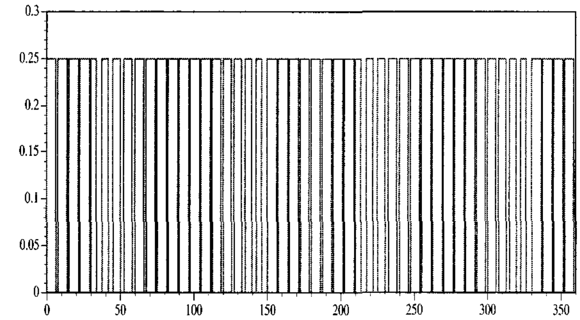
(a) Reference waveforms for input AC current



(b) Modified reference waveforms



(c) Saw-tooth waveform and reference waveforms



(d) Switching signal for R phase

Fig. 4 Sawtooth interrupt control waveforms

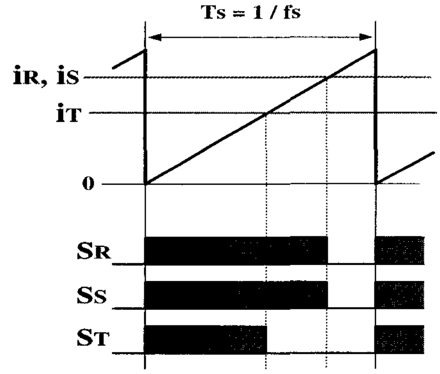


Fig. 5 Switching gate pulse timing signals and sawtooth carrier waveform

3.2 Experimental Setup

Table1 indicates the design specifications and circuit parameters of the three-phase current source-fed soft switching rectifier treated here. Fig. 6 illustrates the experimental setup of three-phase current source-fed soft switching PFC rectifier using IGBT power modules. This new conceptual soft-switching PFC rectifier system is based on DSP (TMS320LF2407) feedback control and the voltage sensor interface devices for calculating the reference waveforms. The PWM gate signal patterns for the proposed three-phase PFC rectifier and Auxiliary Resonant Commutation Snubber (ARCS) circuit are directly generated from DSP.

4. Experimental Results and Discussions

Fig. 7 shows the observed waveforms of the resonant inductor current and the voltage waveforms in the active power semiconductor devices of R phase and S phase. From this Fig., it is clear that the proposed Auxiliary Resonant Commutation Snubber circuits is operated only in turn on transition of the proposed three-phase PWM-PFC rectifier operating at soft commutation scheme. The voltage and current operating waveforms in the active power semiconductor devices of the three-phase PFC rectifier side are observed in Fig.8. It is noted that the complete soft switching transition commutation can be achieved under the turn on and off under condition of the soft switching principle of mode transitions. Furthermore, significantly reduced *dv/dt* and *di/dt* capability values in the proposed rectifier main active power semiconductor devices could be reduced respectively, because of the slope in the measured voltage and current waveforms, EMI and RFI noises can be also reduced effectively.

Fig. 9 represents the utility AC power input line to line voltage and phase current waveforms observed from the three-phase current source type soft switching PWM-PFC rectifier system. The utility AC power input current is controlled so as to be a sinewave waveform with the unity power factor. Observing these observed results, it is proved that the proposed three-phase current source-fed soft switching rectifier can be actually implemented in principle.

The measured result of power factor for the proposed and the conventional three-phase PWM-PFC hard switching rectifier is illustrated in Fig.10. From this result, the value of power factor in case of the soft switching PWM method are superior to the hard switching PWM method in higher output power factor. Furthermore, the output power vs. the power conversion efficiency characteristics between the soft switching method and the hard switching method for three-phase current source PFC rectifier are comparatively illustrated in Fig.11. Considering this Fig., it is proved that the actual efficiency characteristics in three-phase soft switching PWM-PFC operation is higher only about 2.3% than one in hard switching in all the power range of 150W~750W.

Table 1 Design specifications and circuit parameters

Iuput AC Voltage	:	Vi	200 [V]
Filter Inductor	:	Lf	500.0 [μH]
Filter Capaciter	:	Cf	20.0 [μF]
DC Smoothing Inductor	:	Ld	13.8 [mH]
Sampling Frequency	:	fs	6.0 [kHz]
Input Frequency	:	fo	60 [Hz]
Resonant Inductor	:	Lr	5.4 [μH]
Resonant Capacitor	:	Cr	0.068 [μF]

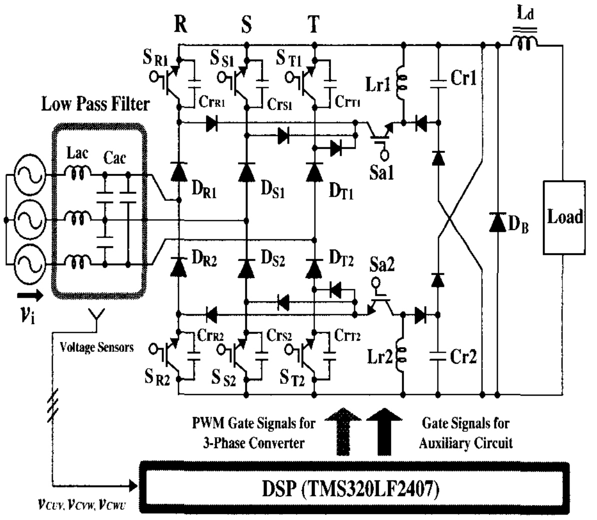


Fig. 6 Experimental setup of three-phase current source soft switching PWM rectifier with two auxiliary resonant commutation snubbers

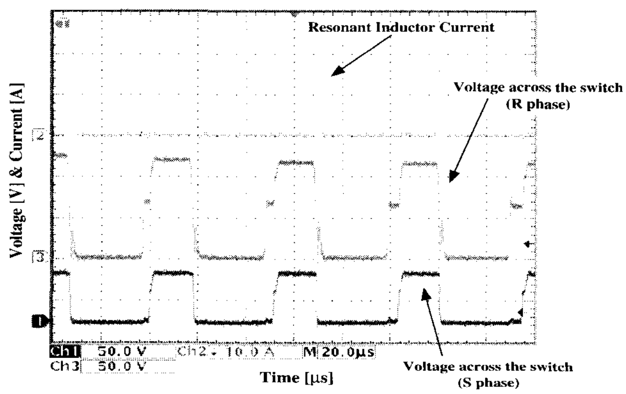


Fig. 7 Voltage waveforms across the switching devices and resonant inductor current waveforms

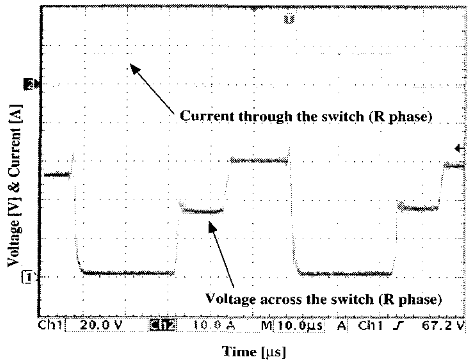


Fig. 8 Voltage waveform across the switching devices and current waveforms across the switching devices

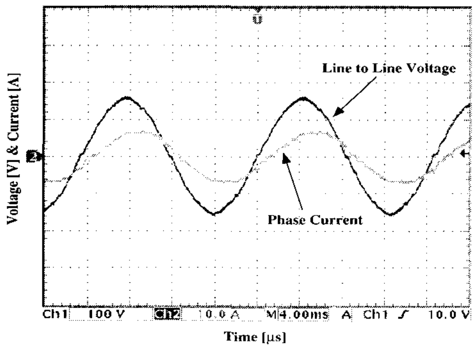


Fig. 9 Input line to line voltage and phase current waveforms of this soft switching PFC converter

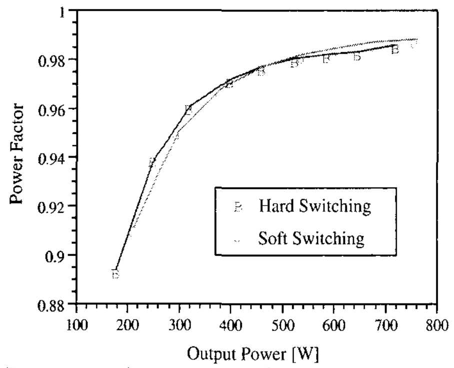


Fig. 10 Compararative power factor vs. output power characteristics

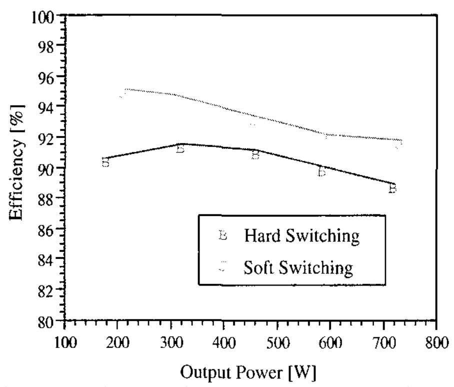


Fig. 11 Comparative total system efficiency characteristics for various output power

5. Conclusions

In this paper, a new prototype topology of two Auxiliary Resonant Commutation Snubbers (ARCS) assisted three-phase current source type soft switching PWM-PFC rectifier using IGBT power modules which is more suitable and acceptable for high power and energy utilization systems has been proposed and discussed. It was proven from the feasible experimental results that the complete soft switching operation in all the active power semiconductor switching devices. Moreover, it is exactly confirmed that only 2.3% is improved in efficiency. The low noise and high quality input sinewave current performances on the basis of the soft switching pulse modulation strategy could be in principle reduced as compared with the hard switching one.

In the future, the advanced three-phase current source soft switching PWM-PFC rectifier system using the new power semiconductor devices such as high-frequency CSTBT, Trench Gate PT-IGBTs with low saturation voltages, IEGTs and IGCTs should be evaluated from a practical point of view for high power distributed power supply applications.

References

[1] M.C. Chandorkar, D.M. Divan and R.H. Lasseter, "Control Techniques for Multiple Current Source GTO Converters", IEEE Transactions in Industry Applications, Vol.31, No.1, pp.134-140, Jan./Feb., 1995

[2] Gerry Moschopoulos and Geza Joos, "A Novel Soft-Switched PWM Current Source Rectifier/Inverter", Proceedings of 25th IEEE Annual Power Electronics Specialists Conference, pp.978-984, June, 1994

[3] Braz J. Cardoso Filho, Steffen Bernet and Thomas A. Lipo, "A New Control Strategy for the PWM Current Stiff Rectifier/Inverter with Resonant Snubber", Proceedings of 28th IEEE Annual Power Electronics Specialists Conference, pp.574-579, June, 1997

[4] Hiroki Ishikawa and Yoshihiro Murai, "Improvement of Performance of a Series Resonant DC Link PWM Inverter", Proceedings of Power Conversion Conference, pp.319-324, August, 1997

[5] Yoshihiro Konishi, Naoya Baba, Masaki Ishibashi and Mutsuo Nakaoka, "Three Phase Current-Fed Soft-Switching PWM Converter with Switched Capacitor Type Resonant DC Link", Proceedings of the Seventh International Conference on Power Electronics and Variable Speed Drives (PEVD), pp.145-151, September, 1998

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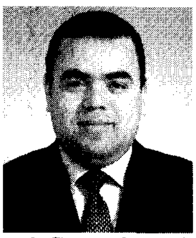

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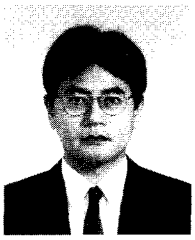

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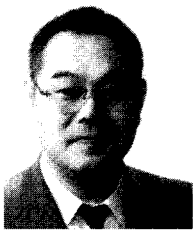

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