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An Active Auxiliary Quasi-Resonant Commutation Block Snubber-Assisted Three Phase Voltage Source Soft Switching PFC Rectifier using IGBTs

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ABSTRACT

This paper presents a novel prototype of an active auxiliary quasi-resonant snubber(Auxiliary Quasi-Resonant Commutation Block-Link; ARCB) -assisted three phase voltage source soft switching space voltage vector modulated PFC rectifier, which uses Zero Voltage Soft Switching (ZVS) commutation. The operating principles of this digitally-controlled three phase soft switching PWM-PFC rectifier system with an instantaneous power feedback scheme are illustrated and its steady-state performance is evaluated using computer-aided simulation analysis.

Keywords : Three phase voltage source active rectifier, Active quasi-resonant switching block snubber, Soft switching commutation, Space voltage vector modulation, Instantaneous power feedback scheme.

1. Introduction

In recent years, three phase voltage source inverters and rectifiers which incorporate a variety of soft switching resonant snubber schemes have attracted special interest. They have been studied for several reasons: to minimize the switching power losses of semiconductor switching power devices such as IGBTs, MOS-FETs and SITs; to reduce their electrical dynamic voltage and current peak stresses; and to reduce the voltage and current surge related EMI/RFI, due to high dv/dt related parasitic capacitive leaked current and high *di/dt* related electrical insulation breakdown of transformers, filter inductors, and stator windings of AC motors using high frequency switching PWM[1]-[5]. In this paper, a new prototype of voltage source type three phase PFC rectifiers with auxiliary quasi-resonant commutated block snubbers (ARCB) is proposed. The prototype is based on an instantaneous power feedback DC voltage regulation control scheme. The principles of its steady state operation are described and its performance is illustrated and discussed using computer-aided simulation analysis.

2. New Active Auxiliary Resonant Snubber

2.1 Circuit Description

Fig. 1 shows three topologies of the proposed ARCB circuits for single/three phase inverters and rectifiers. These are the quasi-resonant snubber circuit blocks that

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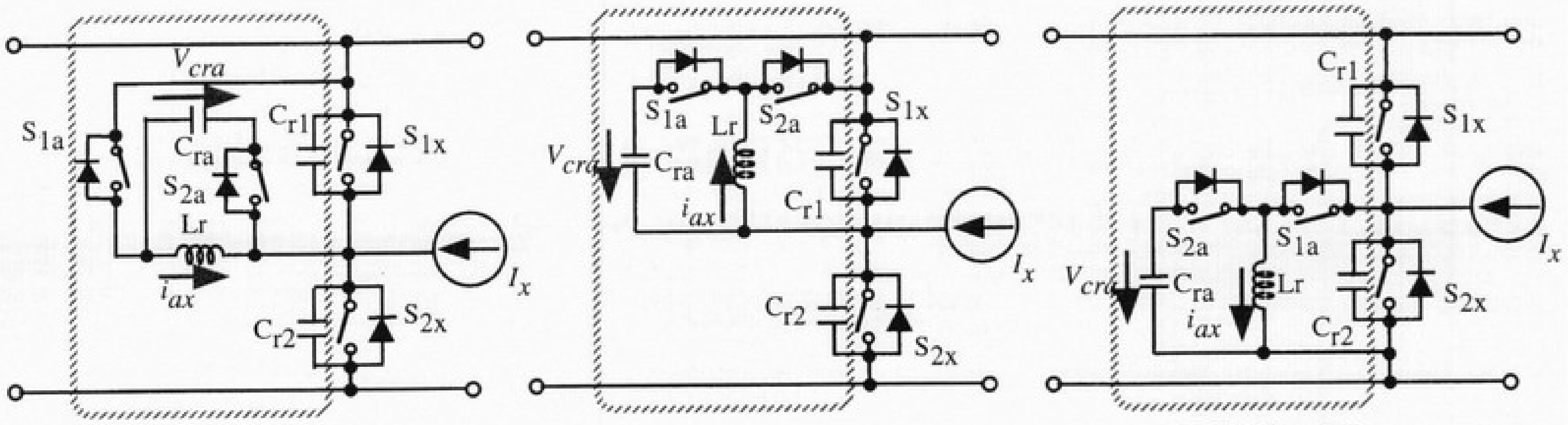


ARCB-Type I ARCB-Type II ARCB-Type III

Fig. 1 Auxiliary resonant commutation block snubber circuits

are connected to the high side or low side switching bridge arms in the inverter/rectifier. These resonant snubber circuits are composed of: lossless snubber capacitors C_{ra} in parallel with each active switching power device, an auxiliary resonant inductor L_r, an auxiliary resonant capacitor C_{ra} and two auxiliary switching power devices S_{ax}. The ARCB snubber circuits are only driven during each PWM transition period, and are enabled to achieve a complete ZVS/ZCS at turn-on and ZVS at turn-off on the main active switching power devices used for the inverters/ rectifiers. The unique features of the ARCB circuits treated here, are described as follows:

(i) A DC bus line clamped switch is not necessary.
(ii) Every auxiliary circuit is driven independently in each phase for soft switching.
(iii) Large capacitors are not necessary to give the DC bus line a neutral point.
(iv) Generic two in one power modules can be used for auxiliary switching power devices.
(v) The circuits have a simple topology.

2.2 Steady State Operation Principle of Auxiliary Resonant Commutated Block

Fig. 2 represents the typical operating voltage and current waveforms of the main active switching power devices and auxiliary switching power devices in an ARCB circuit-Type II. As shown in Fig. 3, there are 9 operation modes in this resonant snubber circuit. The operating principle of the ARCB circuit, the steady-state commutation from upper switches to lower switches can be described as follows;

[Mode A-0] A phase current I_x is freewheeling through the anti-parallel diode D_{1x}, while S_{1x} remains on and S_{2x} is off.

[Mode A-1] The auxiliary switch S_{1a} is turned on using th zero current switching(ZCS) technique. The currer through D_{1x} begins to decrease linearly, and then, th resonant inductor current i_{ax} increases linearly. When i becomes greater than the phase current I_x, the energ stored in the resonant inductor L_r becomes great enough t charge and discharge the lossless snubber capacitors C and C_{r2}. At this point, the main switch S_{1x} can be turne off using zero voltage switching (ZVS).

[Mode A-2] After turning off S_{1x} using ZVS, the high-sid resonant capacitor C_{r1} begins to charge toward the dc-lin

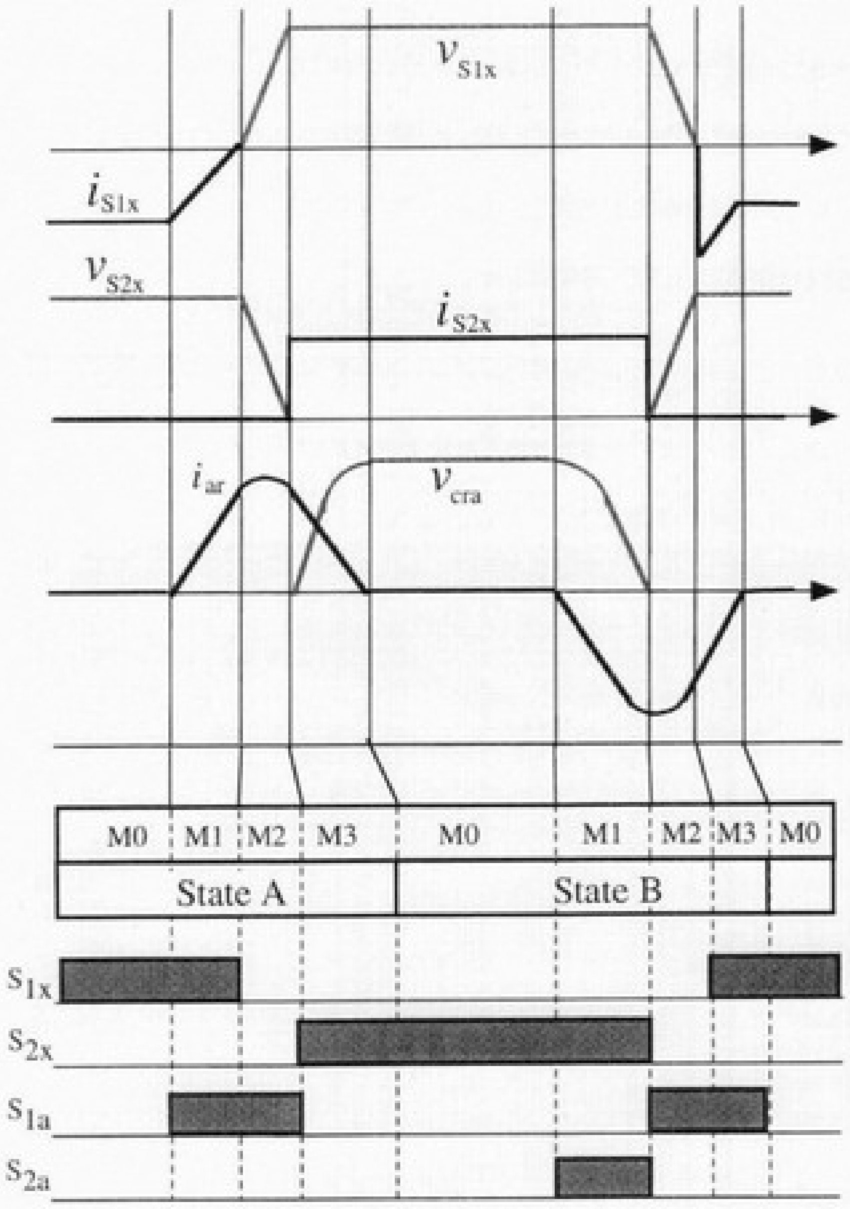


Fig. 2 Operation waveforms of ARCB (Ix>0)

voltage V_{dc} while the low-side resonant capacitor C_{r2} begins to discharge towards zero. This charge-discharge is based on a quasi-resonance due to the resonant inductor L_r and the capacitors C_{r1} and C_{r2}.

[Mode A-3] When the voltage across C_{r2} becomes zero, S_{2x} turns on using ZVS/ZCS. On the other hand, S_{1a} turns off using ZVS. The quasi-resonant operation starts between the resonant inductor L_r and the resonant capacitor C_{ra}, the resonant inductor current i_{ax} begins to decrease to zero and the voltage across C_{ra} starts to increase.

[Mode B-0] When i_{ax} is reduced to zero, the stored energy in the auxiliary resonant capacitor C_{ra} is high enough to charge and discharge the quasi-resonant capacitors. Phase current I_X continues flowing through the main switch S_{2x}.

[Mode B-1] When the next PWM command is generated, the auxiliary switch S_{2a} is turned on using ZCS. The strength of the resonant inductor current, which is negative, begins to increase and the voltage across C_{ra} starts to decrease. When V_{cra} becomes zero, S_{2a} is turned off using ZVS and i_{ax} flows through the anti-parallel diode D_{1a}.

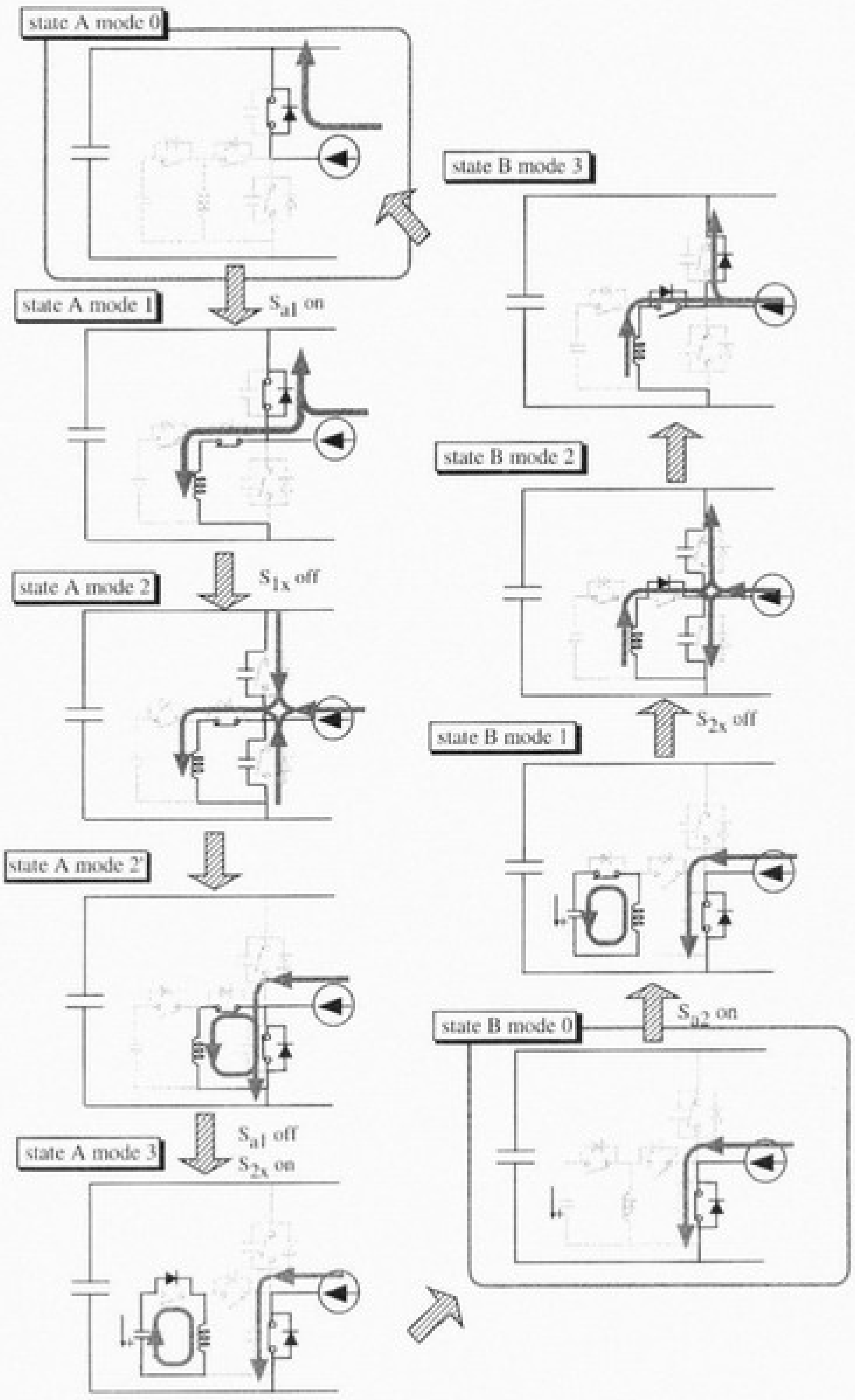


Fig. 3 Equivalent circuits of each transition mode (Ix>0)

[Mode B-2] When the main switch S_{2x} is turned off, the resonant capacitor C_{r2} begins to charge to a full dc-link voltage V_{dc} while C_{r1} begins to discharge toward zero. This is based on a quasi-resonance due to the resonant inductor L_r, and the capacitors C_{r1} and C_{r2}.

[Mode B-3] When V_{Cr1} become zero, D_{1x} will conduct and the strength of i_{ax} begins to decrease. When i_{ax} becomes zero, D_{1a} will be turned off. This snubber goes back to mode A-0.

In the procedure mentioned above, the resonant capacitors C_{r1} and C_{r2} are connected in parallel with the active power switches S_{1x} and S_{2x}. These switches are incorporated into the high-side or low-side bridge arms. The capacitors act as quasi-resonant switching transitions due to the lossless capacitive snubber and the resonant inductor.

3. The Three Phase Soft Switching PFC Rectifier

3.1 Circuit Design of Quasi-Resonant Snubber

To select the optimum parameters of the ARCB circuit, it is necessary to meet the following conditions.

(i) The voltage across the lossless snubber capacitors must swing resonantly from zero to V_{dc} or from V_{dc} to zero every switching period.
(ii) The initial resonant boost current Ib1 must be minimized.
(iii) The duration of the ARCB operation must be minimized. It must be less than 1/10 of one sampling period T_S.
(iv) The *dv/dt* capability must be designed to be less than 500 V/μs.
(v) The maximum value of V_{ca} must always be less than the rating value of the active power switching devices.

To meet the condition (i), it is necessary that the voltage swing of the lossless snubber capacitor C_{rx} is greater than V_{dc} for the quasi-resonant mode [mode A-2/mode B-2]. In the case of Ix>0 as shown in Fig.3, V_{cra} reaches V_{dc} or zero naturally. On the other hand, in the case of Ix<0, the initial resonant boost current I_{b1} at mode A-1 must obtain the full voltage swing of V_{crx} at mode B-2, and I_{b1} related influence on the time interval of the quasi-resonant operation and the maximum value of V_{cra}. circuit's parameters of the ARCB are obtained from the equivalent circuit equations of every operation mode and can be described by equations (1), (2) and (3).

For mode A-1 and mode B-1,

$$\frac{di_{ax}}{dt}=\frac{V_{dc}-r_L\cdot i_{ax}}{L_r} \tag{1}$$

For mode A-2 and mode B-2,

$$\frac{dV_{c1x}}{dt}=-\frac{i_{ax}+I_X}{2\cdot C_r} \qquad \frac{di_{ax}}{dt}=-\frac{V_{cx}+r_L\cdot i_{ax}}{L_r} \tag{2}$$

For mode A-3 and mode B-3,

$$\frac{dV_{cra}}{dt}=-\frac{i_{ax}}{C_{ra}} \qquad \frac{di_{ax}}{dt}=-\frac{V_{cx}+r_L\cdot i_{ax}}{L_r} \tag{3}$$

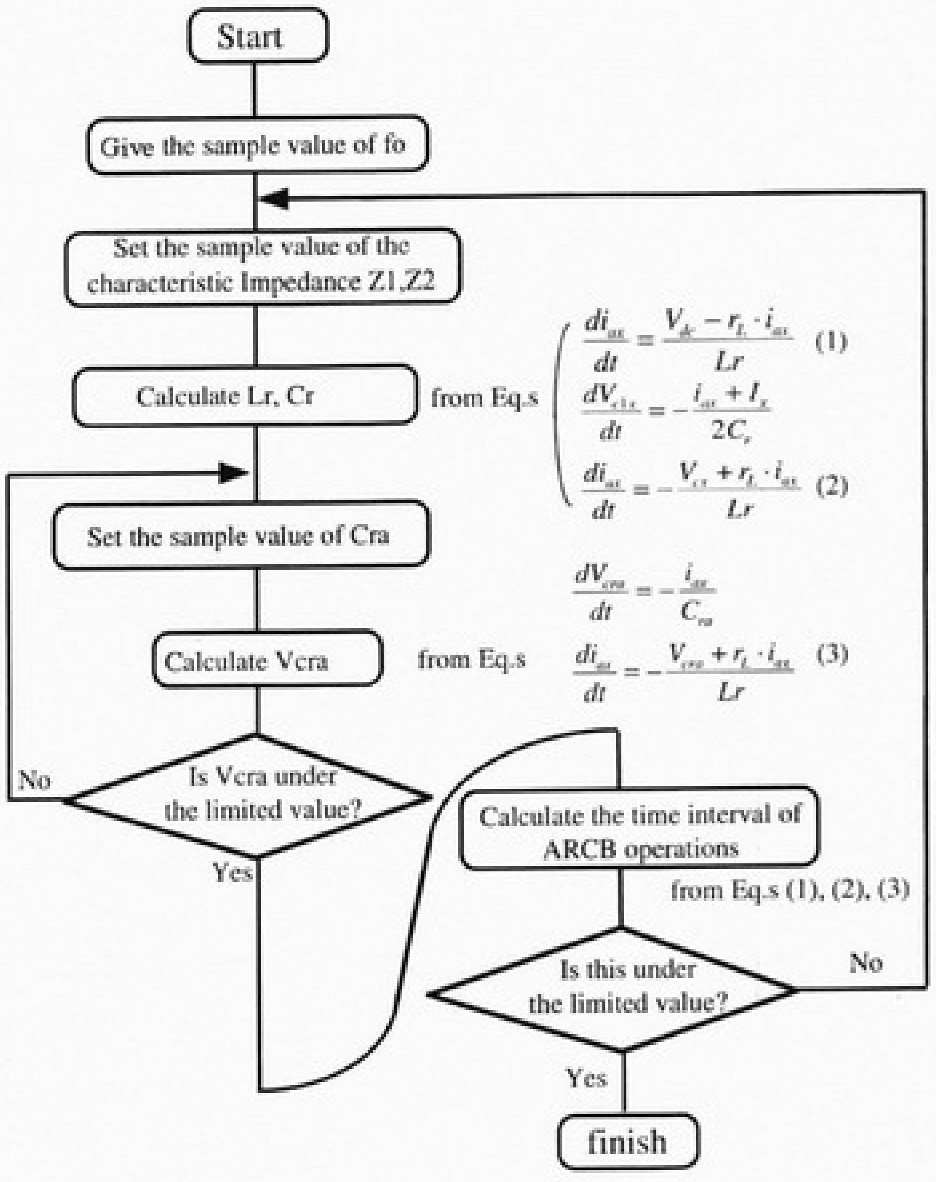
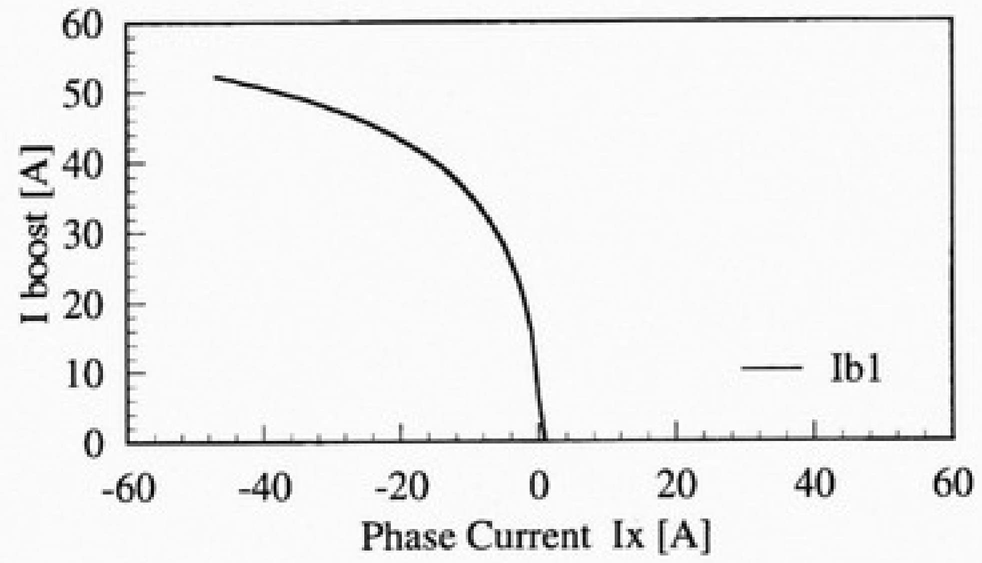
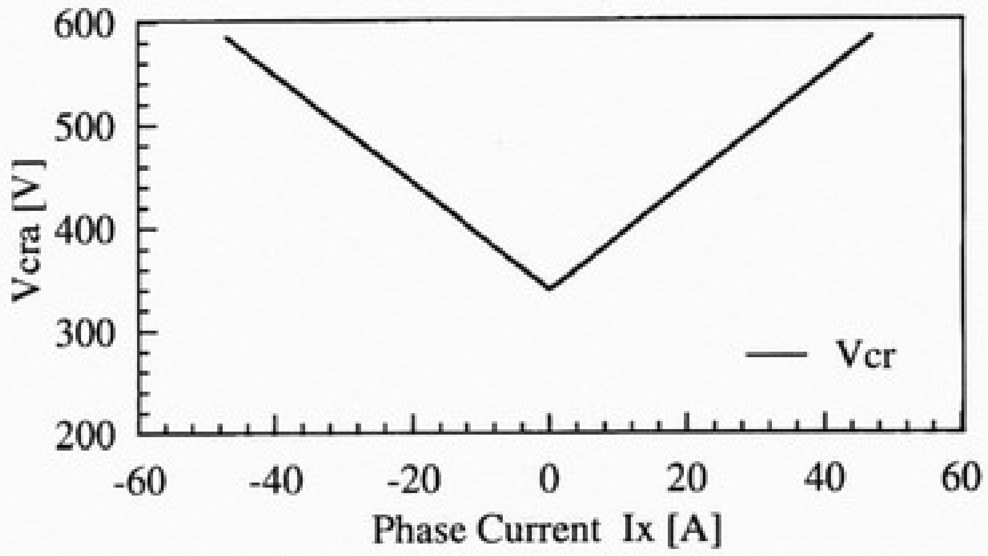


Fig. 4 Circuit parameters design flow chart

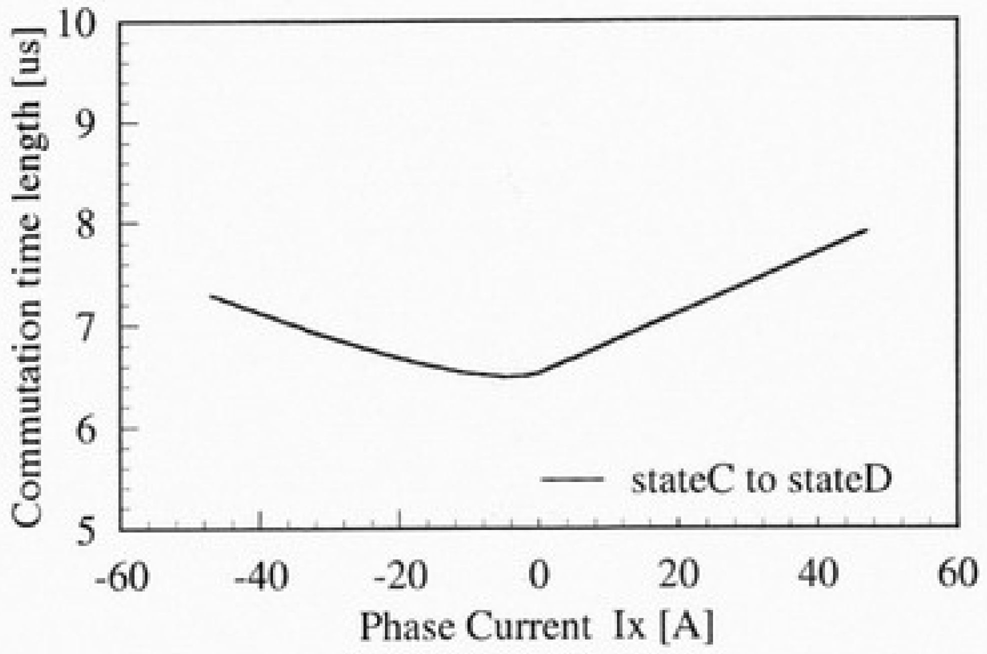
The condition that the time interval of mode A-2/modeB-2 should be fixed to 1/4 during a resonant period specified by C_r and L_r. Fig.4 shows the flow chart for the circuit parameter design. In this figure, fo is the quasi-resonant frequency and Z1 and Z2 are the characteristic impedances between C_r and L_r and C_{ra} and L_r, respectively. Given the following parameters of the ARCB-assisted soft switching three phase voltage source type PFC rectifier: AC input voltage = 200Vrms, DC



(a) I_x vs. I_{b1} characteristics



(b) I_x vs. V_{cra} characteristic



(c) I_x vs. commutation time length

Fig. 5 Calculated characteristics of ARCB

Table 1 Simulation parameters

DC Capacitor :Cn	5000 [μF]
Resonant Inductor : Lr / r_L	12 [μH] / 0.1 [Ω]
Resonant Capacitor : Cr	0.16 [μF]
Resonant Capacitor : Cra	0.43 [μF]
Boost Current : I_{b1}(Ix>0)	52 [A]
Sampling Frequency : fs	16 [kHz]
AC Reactor : Lac / r_{ac}	500 [μH] / 0.1 [Ω]
AC line to line Voltage : e_{ac}	200 [Vrms]
Output Frequency : fe	60 [Hz]
DC Output Voltage :Vdc	400 [V]
Rated Output Power	10 [kW]

output voltage = 400V, rating power = 10kW, sampling frequency: = 16kHz; the relation between I_X and the time interval of the ARCB operation can be calculated. Additionally, the resonant circuit parameters can be calculated and designed based on the circuit equations. The specified circuits' parameters are indicated in Table 1, the relations between I_X vs. V_{cra}, I_X vs. I_{b1} and I_X vs. the time interval of ARCB operations are shown in Fig. 5.

3.2 Simulation Analysis

Fig. 6 depicts a schematic system configuration of an ARCB-assisted soft switching three phase PFC rectifier and its digital controller which includes an instantaneous

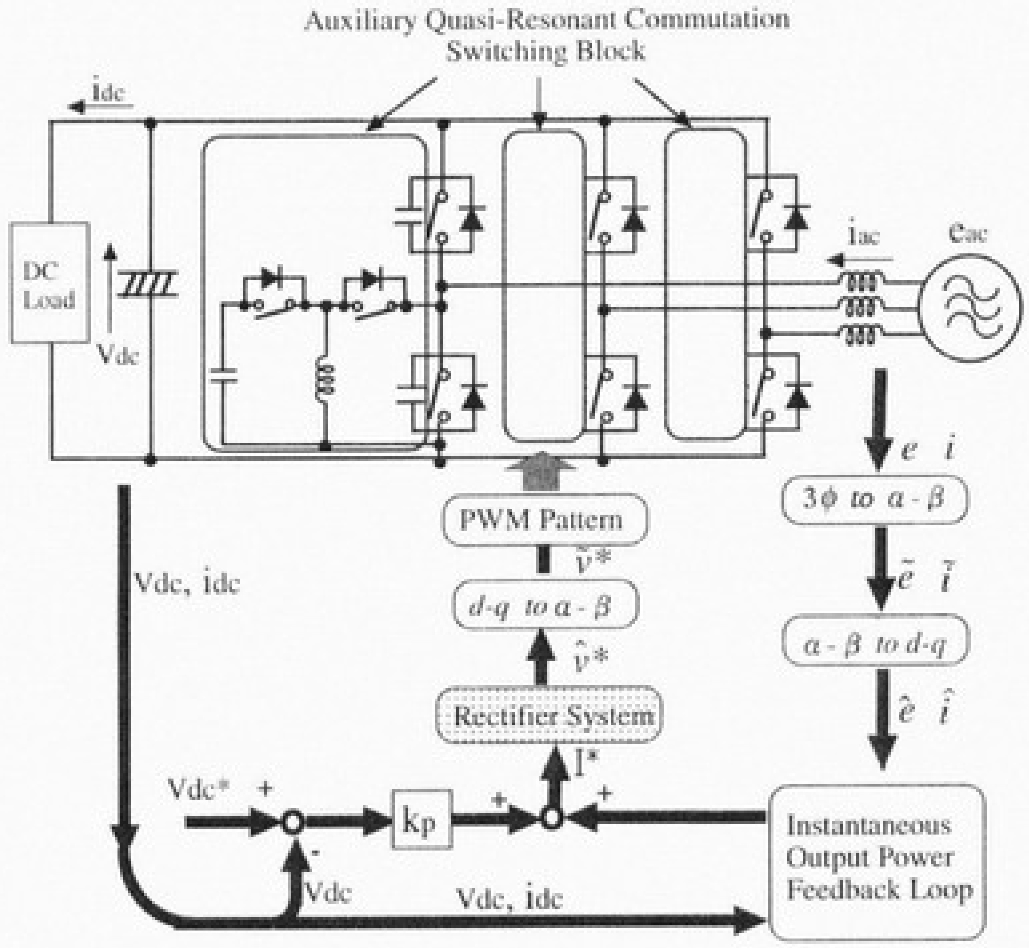
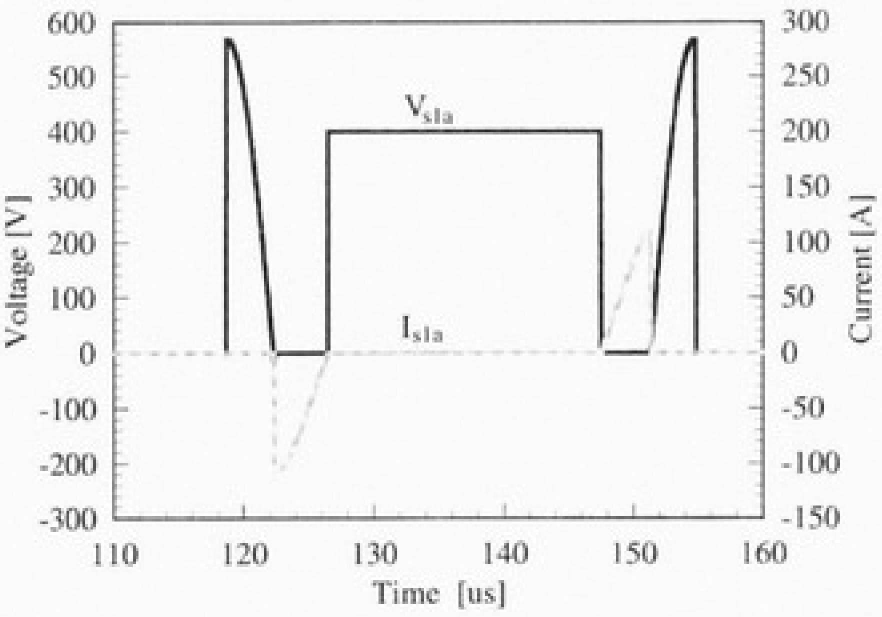
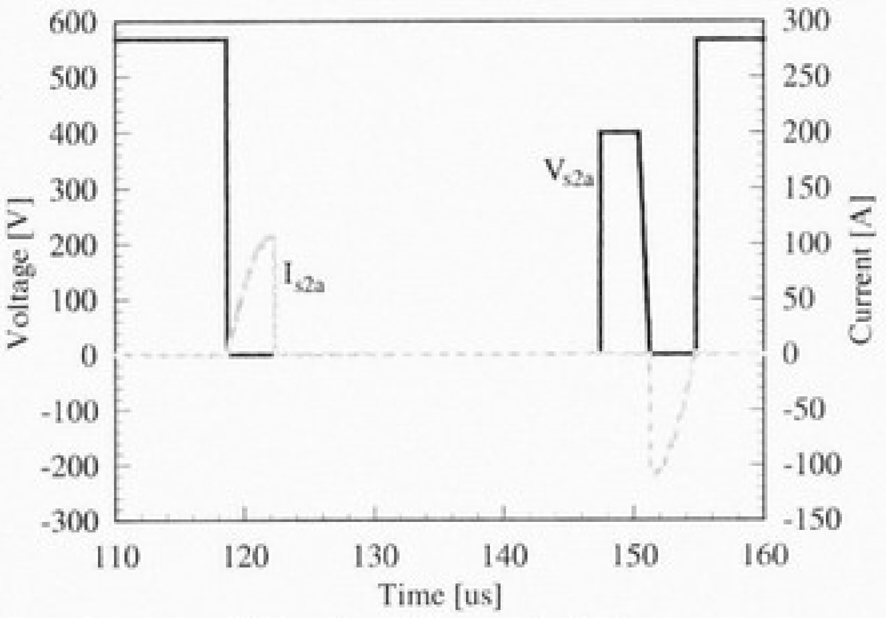


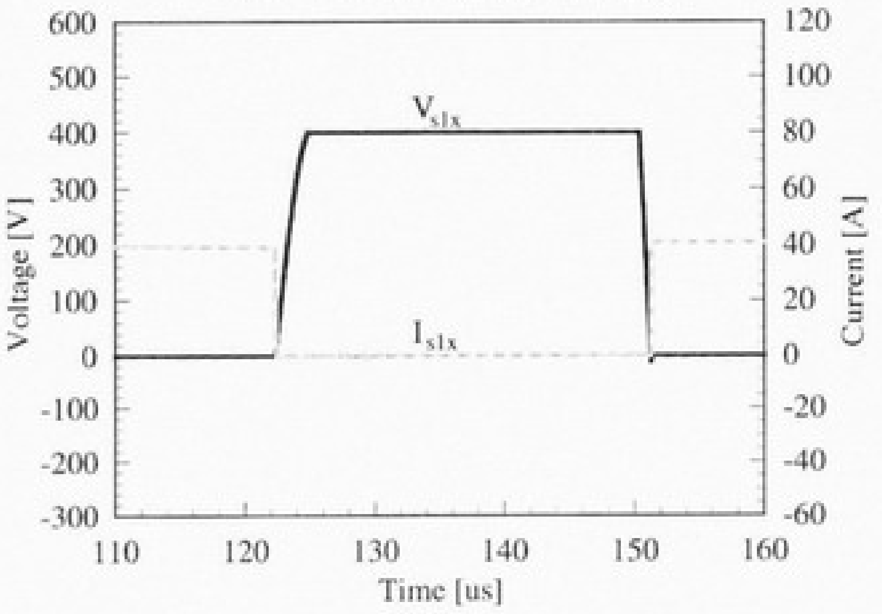
Fig. 6 ARCB soft switching PWM-PFC rectifier



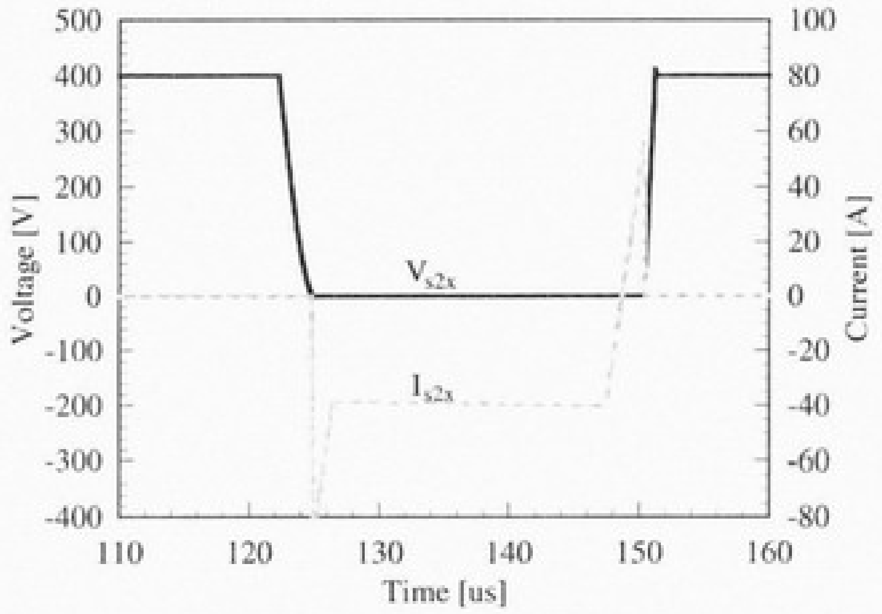
(a) Auxiliary switch S_{1a}



(b) Auxiliary switch S_{2a}



(c) High –side main switch S_{1x}



(d) Low-side main switch S_{2x}

Fig. 7 Switching waveforms of power devices ($I_X < 0$)

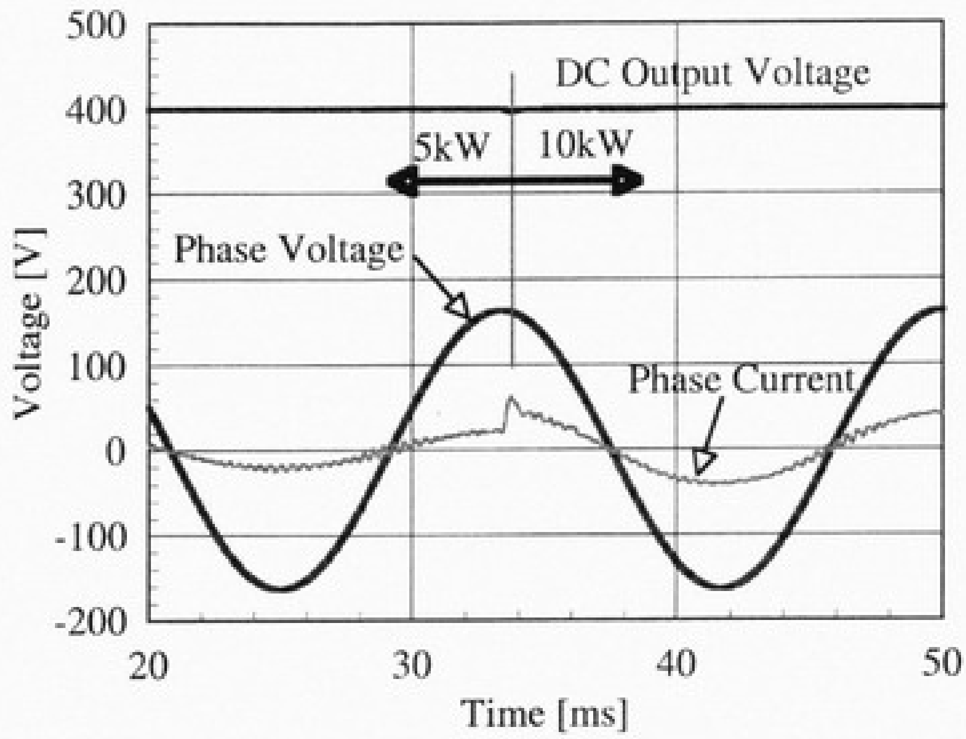


Fig. 8 Input and output waveforms of soft switching PFC rectifier

output power feedback loop. This configuration is remarkably robust. It is unaffected by instantaneous fluctuations of the DC load voltage[4]. Fig. 7 (a) and (b) represent of the DC load voltage[4]. Fig. 7 (a) and (b) represents the typical voltage and current simulation waveforms of auxiliary active switching power devices; IGBTs. From these operating waveforms, it is clear that ZCS turn-on and ZVS or ZCS turn-off can be achieved for two auxiliary active switching power devices in an ARCB snubber. Fig.7 (c) and (d) illustrate the voltage and current waveforms of the high-side (S_{1x}) and low-side (S_{2x}) switching power devices in the rectifier bridge arms. Both ZVS/ZCS at turn-on and ZVS at turn-off are achieved, respectively. The utility AC input phase voltage and sinusoidal phase current of the proposed ARCB- assisted soft switching PFC rectifier are illustrated in Fig.8 for an abrupt change in the load from 5 kW to 10 kW. These simulation results suggest that the proposed soft switching circuit topology is a candidate for certain kinds of power converters, as well as for different phase numbers, output power levels, and frequency and future semiconductor devices technologies, such as SiC based MOS structure.

4. Conclusions

In this paper, a new soft switching circuit cell termed “auxiliary quasi-resonant commutation block snubber; ARCB” has been proposed for voltage source type three phase active PFC rectifiers. We have confirmed its operating principles using computer-aided simulation analysis. The results of our simulation confirm that zero voltage/current soft switching operation of this rectifier is possible in both main and auxiliary active switching power devices. Additionally, we note that the ARCB-assisted soft switching circuit topology proposed here is effective.

Future research should seek to evaluate the actual efficiency of the unique proposed soft switching rectifier technology and inverter topology compared to simulation and experimental results.

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