A Simple Resonant DC Link Snubber-Assisted Bi-directional Three-phase PWM Converter for Battery Energy Storage Systems

Eiji Hiraki and Mutsuo Nakaoka

Abstract – In this paper, a prototype of an active auxiliary quasi-resonant DC link (QRDCL) snubber assisted voltage source bi-directional power converter (AC to DC and DC to AC) operating at zero voltage soft-switching (ZVS) PWM mode is presented for a Battery Energy Storage System (BESS). The operating principle of this QRDCL circuit and multifunctional control-based converter system, including PWM inverter mode in which energy flows from the battery bank to the three-phase utility-grid in addition to an active PWM converter mode in which energy flows from the utility-grid to the battery banks are described respectively by the control implementation on the basis of *d-q* coordinate plane transformation. The multifunctional operation characteristics of this three-phase ZVS PWM bi-directional converter with QRDCL is demonstrated for a BESS under the power conditioning and processing schemes of energy supply mode and energy storage mode, and compared with a conventional three-phase hard switching PWM bi-directional converter for a BESS. The effectiveness of the three-phase ZVS PWM bi-directional converter with QRDCL is proven via the simulation analysis.

Keywords – battery energy storage system, active auxiliary quasi-resonant DC link snubber, soft-switching, utility interactive bi-directional converter, instantaneous space voltage vector control

1. Introduction

Nowadays, multi-diverse developments of electronic power conversion conditioning and processing systems have been more remarkable in the fields of all kinds of industrial application systems as well as medical equipment, transportation, telecommunication, new energy utilizations systems and so forth. Raising the switching frequency of the power semiconductor devices, such as MOS-FETs, IGBTs and SITs, is indispensable for achieving high performances of switching mode power electronic conversion circuit and systems. On the other hand, high frequency switching power conversion circuits and systems cause an increase of the electromagnetic interference (EMI) related noise, voltage surge due to high *di/dt* and high frequency leak current due to *dv/dt*, and switching power losses.

To reduce these problems, soft-switching technique and several types of active auxiliary quasi-resonant DC link (QRDCL) topologies have been proposed and investigated, which are more suitable and acceptable for three-phase PWM inverters and active PWM converters. However, most of these active auxiliary QRDCL snubber circuits generally require three active power semiconductor devices in addition to passive power devices for clamping the peak DC bus-line voltage equal to the supply voltage [4, 5].

In this paper, a utility interactive three-phase bi-directional ZVS PWM converter, which has a simple and low cost active auxiliary QRDCL snubber circuit topology including only two active power semiconductor is introduced and evaluated for Battery Energy Storage Systems (BESS), which is acceptable for load levelling in power systems [1-3, 6]. Its operating performances are compared with conventional hard-switching converter for proposed soft-switching power conditioner in BESS.

2. Voltage clamped quasi-resonant DC link

2.1 Circuit operation principle

Fig. 1 introduces the basic circuit configuration of the simple active QRDCL snubber circuit treated here. This snubber circuit has two active power devices (voltage clamp switch S_{a1} and its sub switch S_{a2}), two diodes (D_1 and D_2), resonant inductor L_r and two resonant capacitors (main capacitor C_{r1} and sub capacitor C_{r2}). Resonant inductance L_r is sufficiently smaller than load inductance including the

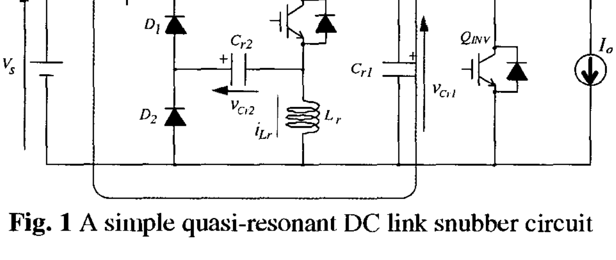

Fig. 1 A simple quasi-resonant DC link snubber circuit

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tput stage low pass filter. So, the three-phase inverter or ctifier and its load circuit can be basically replaced by S_{INV}, $_{INV}$, and constant DC current source I_o (I_o>0 or I_o<0).

Fig. 2 illustrates equivalent circuits of active quasi-esonant snubber circuit during one cycle operation. And Fig. 3 indicates the typical voltage and current waveforms for operating sequences. Note that nine operation modes are shown in these figures. The circuit operation in periodic steady state is described as follows

[Mode 0] (S_{a1} with on, S_{a2} with off)

Load current I_o flows through S_{a1} or D_{a1}. In this mode, the active auxiliary QRDCL snubber circuit does not work.

[Mode 1] (S_{a1} with on, S_{a2} with on)

When S_{a2} turns on under zero voltage soft-switching (ZCS) condition, resonant inductor current i_{Lr} increases resonantly.

[Mode 2] (S_{a1} with off, S_{a2} with on)

When i_{Lr} reaches the specified resonant initialising current I_i, S_{a1} turns off under ZVS condition. The voltage across C_{r1} decreases resonantly.

[Mode 3] (S_{a1} with off, S_{a2} with on)

When main resonant capacitor voltage v_{Cr1} reaches zero, D_{INV} turns on under ZVS condition, i_{Lr} flows L_r-D_{INV}-S_{a2} resonant circuit loop. In this mode, the equivalent power switch of the inverter S_{INV} turns on under a principle of ZVS.

[Mode 4] (S_{a1} with off, S_{a2} with off, S_{INV} with on)

After S_{INV} turns on, S_{a2} turns off under ZVS condition, i_{Lr} flows the resonant circuit loop L_r-D_2-C_{r2}, then the voltage across C_{r2} increases and i_{Lr} decreases resonantly.

[Mode 5] (S_{a1} with off, S_{a2} with off, S_{INV} with on)

When i_{Lr} becomes a reverse direction, the resonant loop changes to L_r-C_{r2}-D_1-S_{INV}. The voltage across C_{r2} decreases resonantly.

[Mode 6] (Sa1 with off, S_{a2} with off, S_{INV} with on)

As v_{Cr2} reaches zero, D_{a2} turns on. i_{Lr} freewheels the

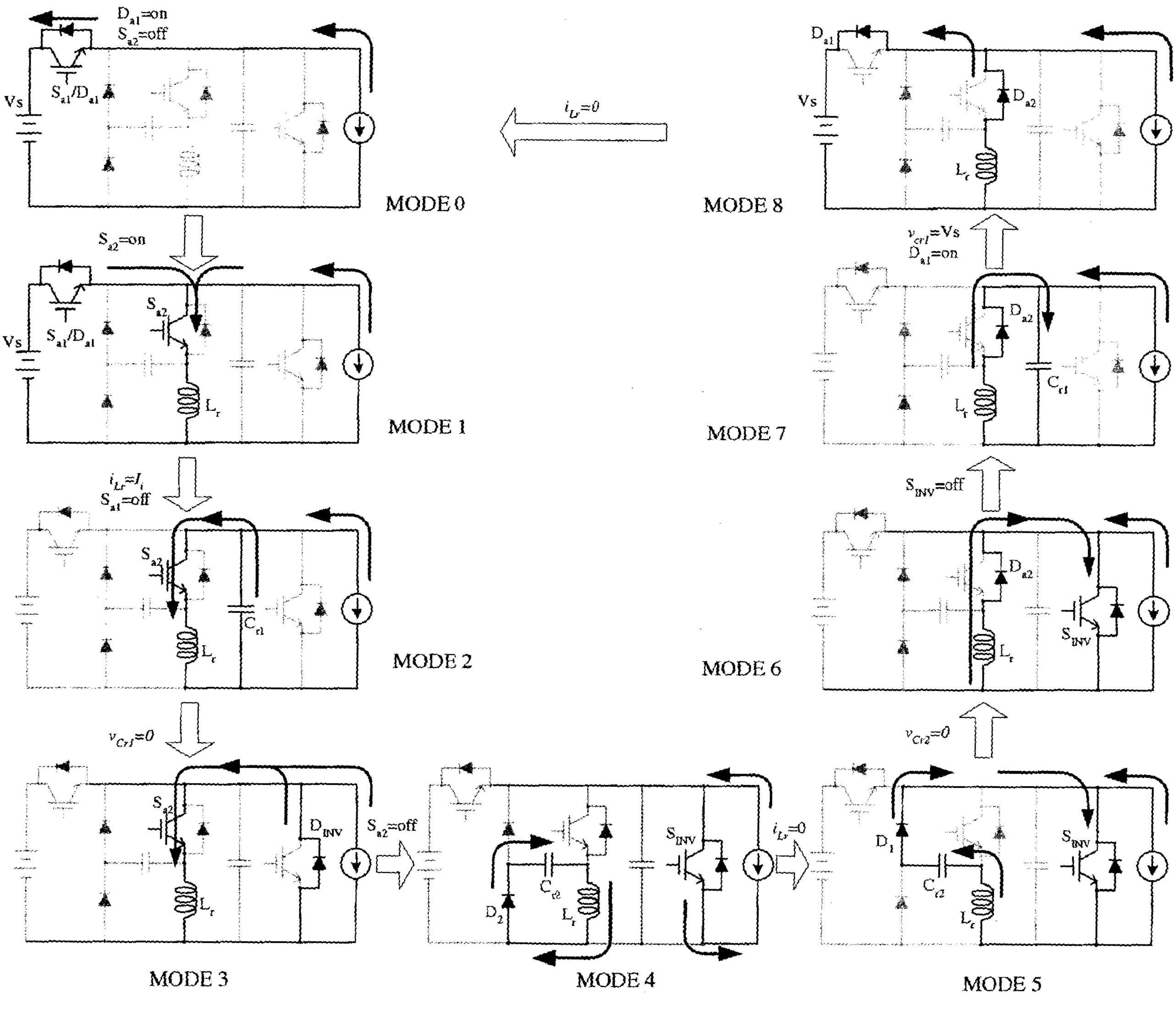


Fig. 2 Operating mode and equivalent circuits

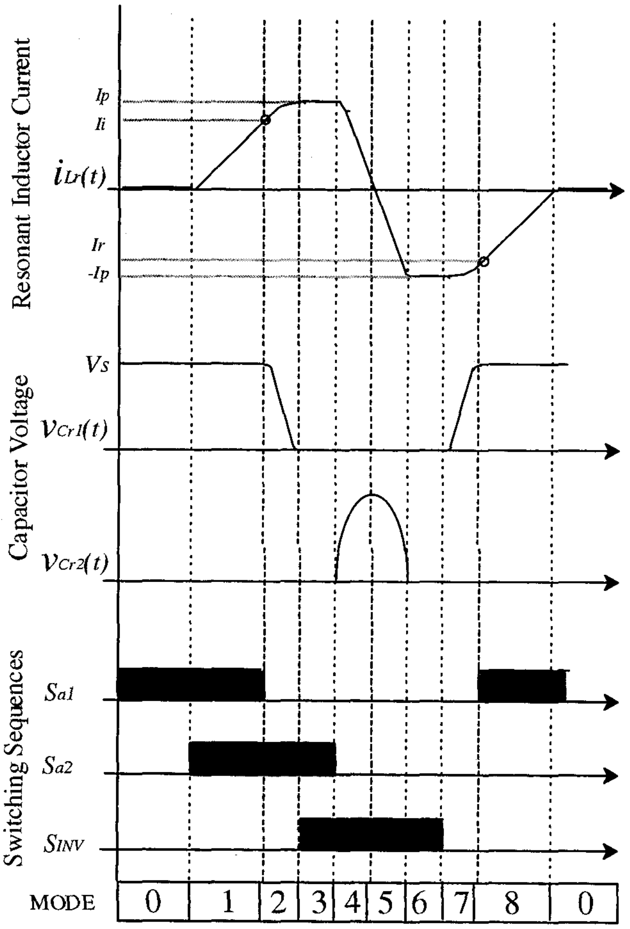


Fig. 3 Operating waveforms of active auxiliary QRDCL

resonant circuit loop L_r-D_{INV}-S_{a2}. This operating mode continues when the inverter-switching pattern is changed.

[Mode 7] (S_{a1} with off, S_{a2} with off)

When the inverter switching pattern changes in accordance with the external signals, a new sub-resonance starts in the L_r-C_r circuit and v_{Cr1} increases resonantly.

[Mode 8] (S_{a1} with on, S_{a2} with off)

D_{a1} turns on when reaching v_{Cr1} to DC supply voltage Vs. in this case, the voltage across C_{r1} is exactly clamped to Vs. When i_{Lr} becomes zero, the operation mode returns to Mode 0.

Note that one control operation period of the active auxiliary QRDCL snubber corresponds to the dead time of hard switching technique. Minimizing the total operation time of the active auxiliary QRDCL snubber is indispensable for obtaining high performance of the soft-switching power converter.

2.2 Circuit parameter design consideration

The circuit parameters of an active auxiliary QRDCL snubber are determined on the basis of the following design policy.

(a) The voltage across C_{r1} must step down to zero in Mode 2, and it must completely boost up to the supply voltage Vs in Mode 7 (see Fig. 3).

(b) The resonant inductor peak current i_{Lr} should be as small as possible to reduce the power losses of resonant circuit.

(c) The regenerating interval of the resonant inductor current in Mode 8 must be a small value.

(d) The resonant initial current I_i should be as small as possible to minimize the Mode2 period.

(e) The maximum voltage of the auxiliary capacitor C_{r2} has to be Vs or less.

To meet the conditions mentioned above, the circuit parameters are to be designed as follows. From Mode 7, the main resonant frequency of the active auxiliary QRDCL circuit is defined as

$$F_{r1} = \frac{1}{2\pi\sqrt{L_r \cdot C_r}} \tag{1}$$

The voltage across C_{r1} that corresponds to the lossless snubber capacitor is estimated as

$$v_{Cr1}(t) = \sqrt{\frac{L_r}{C_{r1}}}\left(I_p - I_{OX}\right)\cdot \sin \omega_{r1} t \tag{2}$$

where I_{ox} is the load current at the inverter switching point. In Mode 4, the voltage across sub-resonant capacitor C_{r2} is estimated by

$$v_{Cr2}(t) = I_p \sqrt{\frac{L_r}{C_{r2}}} \sin \omega_{r2} t \tag{3}$$

where I_p is the resonant peak current.To meet design item (a) mentioned above, it is indispensable that the resonant peak current I_p of the QRDCL circuit should be given by

$$I_p \geq \frac{Vs}{2\pi L_r F_{r1}} + I_{OX} \tag{4}$$

From design criteria (b), (c) and (d), I_p should get a minimum value. That is,

$$\begin{gathered} I_{CO} \geq \frac{Vs}{2\pi L_r F_{r1}}, \\ (I_{CO} = I_p - I_{OX}) \end{gathered} \tag{5}$$

To prevent a reverse flow of load current, the following conditions are considered

$$I_O = I_{OX} = -I_{O.max} \tag{6}$$

$$I_{CO} \geq -I_O - I_{OX} \tag{7}$$

With these results, we can get

$$I_{CO} = 2I_{O.max} \tag{8}$$

The resonant inductor L_r and the main resonant capacitor C_{r1} are respectively estimated from Eq. (9) and Eq. (10)

$$L_r = \frac{Vs}{2\pi F_{r1} I_{CO}} \tag{9}$$

$$C_{r1} = \frac{1}{(2\pi)^2 F_{r1}^{\ 2} L_r} \tag{10}$$

The maximum sub-resonant capacitor voltage $v_{cr2.max}$ has to be clamped to a specified DC bus-line voltage Vs

$$Vs \geq v_{Cr2.max} = I_p \sqrt{\frac{L_r}{C_{r2}}} \tag{11}$$

where $\sqrt{L_r/C_{r2}}$ is the sub-resonant characteristic impedance.

From Eq. (11), we can get

$$C_{r2} = L_r \frac{I_{p.max}^2}{Vs^2} \tag{12}$$

Therefore, $I_{p.max}$ is given by

$$I_{p.max} = \sqrt{\left(4I_{O.max}\right)^2 + \left(\frac{Vs^2 C_{r1}}{L_r}\right)} \tag{13}$$

The design specifications of zero voltage soft-switching power converter for a BESS are determined for the following conditions in this simple resonant DC link snubber: 200Vrms/60Hz three-phase utility AC power input, the output capacity 20 kVA, DC bus-line voltage Vs = 440 V, $I_{o.max}$ = 80 A, and main resonant frequency F_{r1}=200 kHz. From these conditions, the circuit parameters of an active auxiliary QRDCL snubber circuit are designed to be

I_{co} = 160 A, L_r = 2.2 μH,
C_{r1} = 0.3 μF, C_{r2} = 0.9 μF

3. Utility-interfaced bi-directional ZVS PWM converter for a BESS and its control strategy

3.1 Schematic configuration

Fig. 4 shows a schematic system configuration of a utility-interactive three-phase soft-switching bi-directional converter with an active auxiliary QRDCL snubber for a BESS. The output terminal of this bi-directional converter is connected to a utility-grid AC power line through the low pass filter. In this system, two control modes, energy supply mode and energy storage mode are considered, including normal inverter mode and active converter mode. As shown in Fig. 5 these two operating control methods are appropriately selected by loaded power P_L in the utility grid. In this figure, P_S is the utility power, P_C is the processing power for BESS. In case of the load power under P_L=35kW, this power processing system can be operated under energy storage mode. On the contrary, in case oad power is more than 50kW this power conversion system is operated under energy supply mode. So, it is understood that a load levelling operation can be completely achieved.

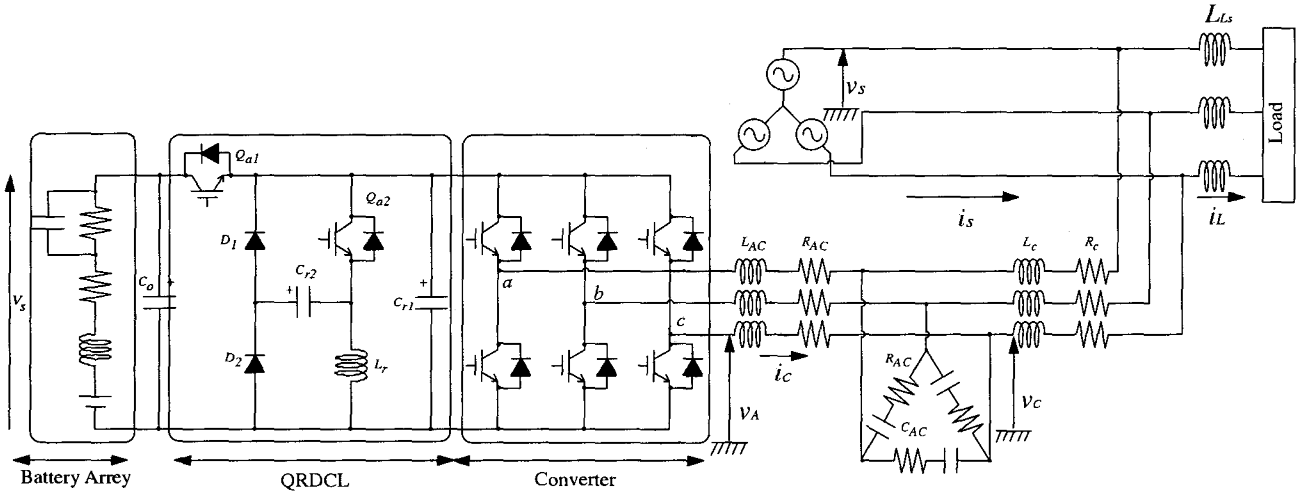


Fig. 4 Multi-functional soft-switching BESS with active QRDCL

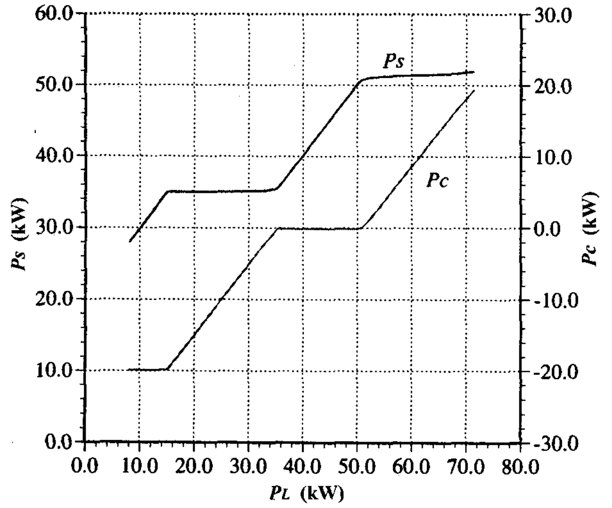


Fig. 5 Load averaging characteristics

3.2 Digital control implementation

A control strategy that can obtain a multi-functional operation scheme of the bi-directional converter is presented and implemented. Its reference voltage is theoretically estimated and realized by means of instantaneous space voltage vector modulated PWM control implementation. The state vector equation for the BESS shown in Fig. 4 is described by defining the output voltage vector of the converter as $v_a(t)=[v_{Aa}(t) \quad v_{Ab}(t) \quad v_{Ac}(t)]^T$, the AC reactor current vector as $i_C(t)=[i_{Ca}(t) \quad i_{Cb}(t) \quad i_{Cc}(t)]^T$, the utility grid voltage vector is $v_C(t)=[v_{Ca}(t) \quad v_{Cb}(t) \quad v_{Cc}(t)]^T$, and the utility interactive current vector as $i_L(t)=[i_{La}(t) \quad i_{Lb}(t) \quad i_{Lc}(t)]^T$.

$$L_{AC}\frac{d}{dt}i_C(t)=v_A(t)-v_C(t)-\mathrm{R}_{AC}\cdot i_C(t) \tag{14}$$

This state vector equation is transferred to the rotating *d-q* axis plane

$$L_{AC}\frac{d}{dt}\hat{i}_C(t)=\hat{v}_A(t)-\hat{v}_C(t)-\begin{bmatrix} R_{AC} & -\omega_e L_{AC} \\ \omega_e L_{AC} & R_{AC} \end{bmatrix}\cdot\hat{i}_C(t) \tag{15}$$

Here, $\hat{v}_A(t)=[v_{Ad}(t) \quad v_{Aq}(t)]^T$, $\hat{i}_C(t)=[i_{Cd}(t) \quad i_{Cq}(t)]^T$, $\hat{v}_C(t)=[v_{Cd}(t) \quad v_{Cq}(t)]^T$, $\hat{i}_L(t)=[i_{Ld}(t) \quad i_{Lq}(t)]^T$.

Since sampling time Ts in this power processing scheme is much smaller, a differential value of the reference output current vector is approximately expressed by

$$\frac{d}{dt}i_c(t)=\frac{1}{T_S}\left(\hat{i}_c(i+1)-\hat{i}_c(i)\right) \tag{16}$$

Thus, the reference output voltage of a utility interactive three-phase bi-directional converter is given by

$$\hat{v}_A^{\,*}(i+1)$$
$$=\hat{v}_C(i)+\frac{1}{T_S}L_{AC}\hat{i}_C^*(i)+\begin{bmatrix} R_{AC}-\frac{L_{AC}}{T_S} & -\omega_e L_{AC} \\ \omega_e L_{AC} & R_{AC}-\frac{L_{AC}}{T_S} \end{bmatrix}\cdot\hat{i}_C(i) \tag{17}$$

Here, the reference currents for the energy supply mode and the energy storage mode are respectively estimated as

$$\hat{i}_C(t)=\begin{bmatrix} I_{PW} \\ 0 \end{bmatrix}=\frac{P_L-P_{L\,max}}{E}\begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{18}$$

and

$$\hat{i}_C(t)=\begin{bmatrix} I_{PW} \\ 0 \end{bmatrix}=\frac{P_L-P_{L\,min}}{E}\begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{19}$$

respectively,
where P_{Lmax} : maximum load power for load levelling,
P_{Lmin}: minimum load power for load levelling,
P_L: average load power.

Fig. 6 represents the control block diagram in the case of an energy supply mode and an energy storage mode. Furthermore, this multi-functional BESS using three-phase bi-directional converter can operate in active power filter mode as well as instantaneous reactive power compensation mode and instantaneous voltage sag regulation mode, by developing a system control strategy.

4. Simulation results and evaluations

To verify the operation and principal effectiveness of three-phase voltage source bi-directional ZVS PWM converter for the BESS, the computer-aided simulation is carried out under a condition of sampling frequency of 12kHz. Fig. 7 illustrates the operating output DC bus-line

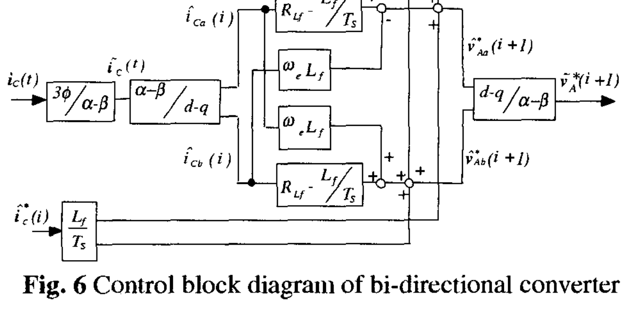
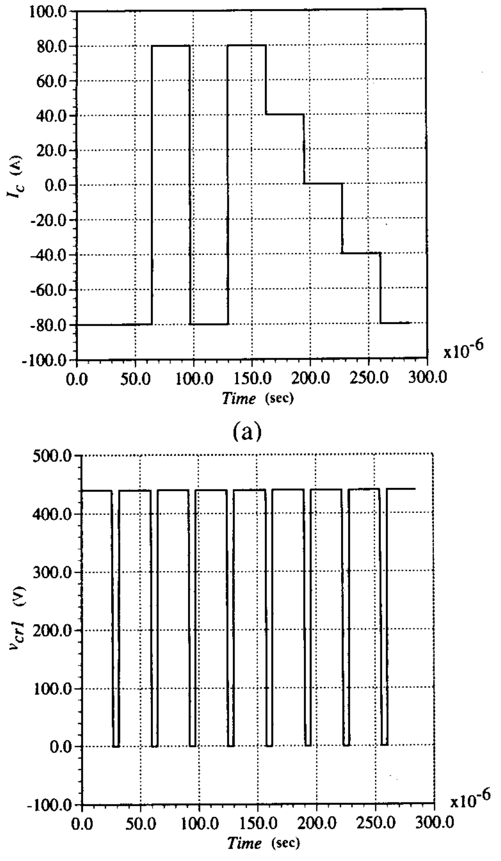


Fig. 6 Control block diagram of bi-directional converter



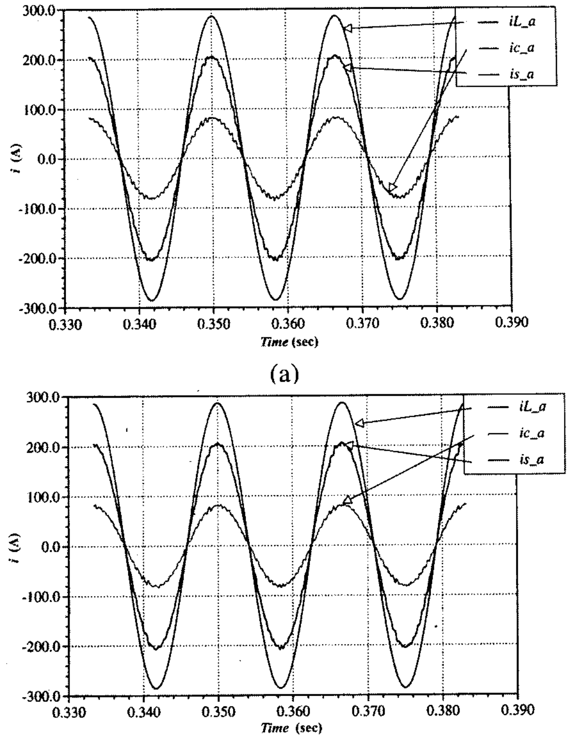
(a)

(b)

Fig. 7 Typical waveforms of QRDCL snubber: (a) fluctuation of processing current, (b) DC bus-line voltage

voltage of the simple active auxiliary QRDCL circuit treated here by changing load current to confirm its circuit operating phenomena. Fig. 7(a) shows the fluctuation pattern of BESS processing current, and Fig. 7(b) depicts DC bus-line voltage *Vs*. Observing these figures, this active auxiliary QRDCL snubber circuit is able to step down *Vs* to zero and boost up from zero to *Vs*, in spite of heavy or light load operations, to design the optimum initial current I_i. Fig. 8(a) represents the operating waveforms of a-phase current and voltage of the proposed BESS using soft-switching PWM converter under a 70 kW load condition of the energy supply mode, and are compared with operating voltage waveforms of a hard switching power conversion system as shown in Fig. 8(b). In the same procedure, the operating current waveforms of the BESS with the load power of 15kW in the energy storage mode are compara-tively depicted in (a) and (b) of Fig. 9.

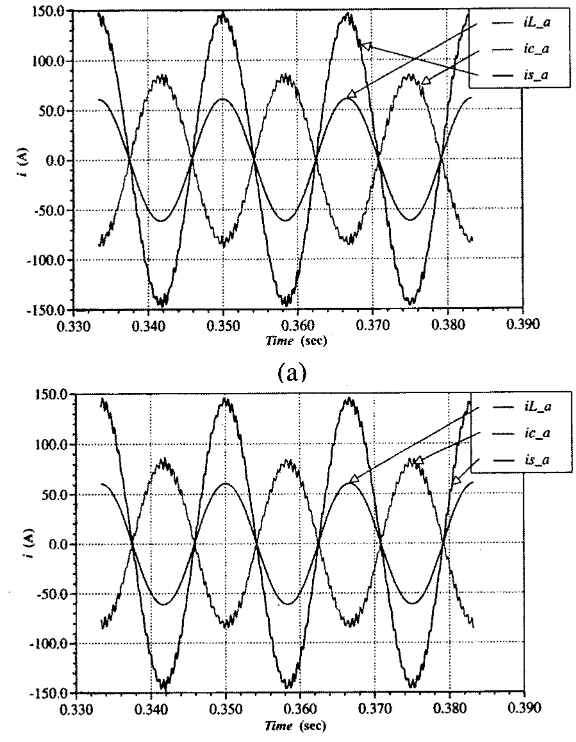
From these figures, it is evident that proposed BESS using soft-switching bi-directional power converter works as good as hard switching BESS. Because ZVS transition mode is established at every switching sequence, EMI/EMC level and switching power losses must become relatively low compared to a hard-switching system.



(a)

(b)

Fig. 8 Typical utility grid current waveforms under 70kW load power in energy supply mode: (a) soft switching, (b) hard switching



(a)

(b)

Fig. 9 Typical utility grid current waveforms under 15kW load power in energy storage mode: (a) soft switching, (b) hard switching

6. Conclusions

In this paper, the principle of a simple active QRDCL circuit topology and a three-phase bi-directional ZVS PWM power converter using this active auxiliary QRDCL snubber circuit has been introduced for a BESS. A control implementation system, designed under a *d-q* coordinate plane transformation-based digital control scheme was also introduced. On the basis of the computer-aided simulation analysis, proposed BESS system using a three-phase bi-directional soft-switching converter has been proved to have a remarkable effectiveness in its controllability and an environmental adoptability as good as that of a hard switching system.

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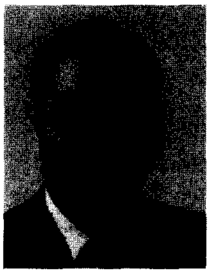

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