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Utility-Interactive Four- Switch Three-Phase Soft-Switching Inverter with Single Resonant DC-Link Snubber and Boost Chopper

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ABSTRACT

In this paper, a novel proposal for a utility-interactive three-phase soft commutation sinewave PWM power conditioner with an auxiliary active resonant DC-link snubber is developed for fuel cell and solar power generation systems. The prototype of this power conditioner consists of a PWM boost chopper cascaded three-phase power conditioner, a single two-switch auxiliary resonant DC-link snubber with two electrolytic capacitors incorporated into one leg of a three-phase V-connection inverter and a three-phase AC power source. The proposed cost-effective utility-interactive power conditioner implements a unique design and control system with a high-frequency soft switching sinewave PWM scheme for all system switches. The operating performance of the 10 kW experimental setup including waveform quality, EMI / RFI noises and actual efficiency characteristics of the proposed power conditioner are demonstrated on the basis of the measured data.

Keywords: utility AC interactive power conditioner, boost chopper, V-connection inverter, two-switch auxiliary resonant DC link snubber, soft switching PWM

1. Introduction

In recent years, the devastating effects on our global environment have increased due to the carbon dioxide emissions and large power demand consumption. Therefore, new power generation systems including utility AC interactive power conditioners, such as fuel cell and solar power generation systems have attracted special interest in fully implementing them into cost-effective products for industrialization [1-4].

Advanced power semiconductor switching devices with new structures and materials such as IGBTs, ESBTs, SiC –SBD, SiC-JFET and SiC-SIT, are suitable for high frequency switching operations and are necessary for developing power conversion systems with miniaturization and higher efficiency and performances [5-8]. One of the biggest problems in using high switching frequency is increased EMI / RFI noises due to the stray parasitic inductances and capacitances of the power conversion circuits. Soft switching-based high-frequency sinewave pulse modulated power conversion systems [8-11], operating under the principles of zero voltage soft switching (ZVS) and zero current soft switching (ZCS) schemes, can be used efficiently in order to enhance the performances of power conversion systems. Some enhanced performances include minimization of the

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switching losses of the power semiconductor devices, reduction of EMI / RFI noises caused by the electrical dynamic voltage stress dv/dt and current stresses di/dt and realization of the high power density.

In this paper, a novel circuit configuration for a utility-interactive auxiliary resonant DC-link snubber assisted soft-switching sinewave PWM power conditioner with a three-phase V-connection inverter and boost chopper is proposed. There is also a discussion of cost effectiveness with full industrialization of this product. This proposed two-stage sinewave power conditioner has only five power semiconductor switching devices and an auxiliary resonant DC link (ARDCL) snubber circuit which can achieve ZVS, ZCS and ZVS/ZCS hybrid operation. A 10 kW experimental set-up of the proposed soft switching sinewave PWM power conditioner is demonstrated to prove its effectiveness in efficiency and reduction of EMI noise.

2. Circuit Configuration

Figure 1 shows the proposed two-switch auxiliary active resonant DC-link (ARDCL) snubber-assisted four switch three-phase inverter with a boost chopper. It can efficiently operate under the principles of a simple soft commutation scheme. In this new circuit configuration, it does not require a high smoothing DC-link capacitor because the neutral voltage point of the three-phase V-connection inverter and the auxiliary resonant DC link (ARDCL) snubber circuit is at the same point. The significant merits of this utility-interactive power three-phase AC conditioner system's use as a newly distributed renewable energy power supply are as follows: the solar photovoltaic and fuel cell power generators utilize minimum numbers of IGBT power semiconductor switching devices and circuit components, low cost, high power density, high reliability and high-efficiency. Moreover, this utility interactive sinewave PWM power conditioner is designed using a unique ARDCL snubber circuit, which has only two power semiconductor switching devices for achieving the soft-switching operation of the three-phase V-connection inverter and the boost chopper. This soft-switching boost chopper is necessary for boosting the output voltage of the low voltage fuel cell power generation system and tracking the max power control in the solar power generation system. All the active power semiconductor switches used for low voltage large current applications are implemented as a six in one power semiconductor module(IGBT power module) including *w*-phase and *u*-phase of the inverter and the bridge leg of PWM boost chopper . Additionally, a two in one module for the two-switch ARDCL snubber for soft commutations is used. Table I indicates the design specifications and power conditioner circuit parameters.

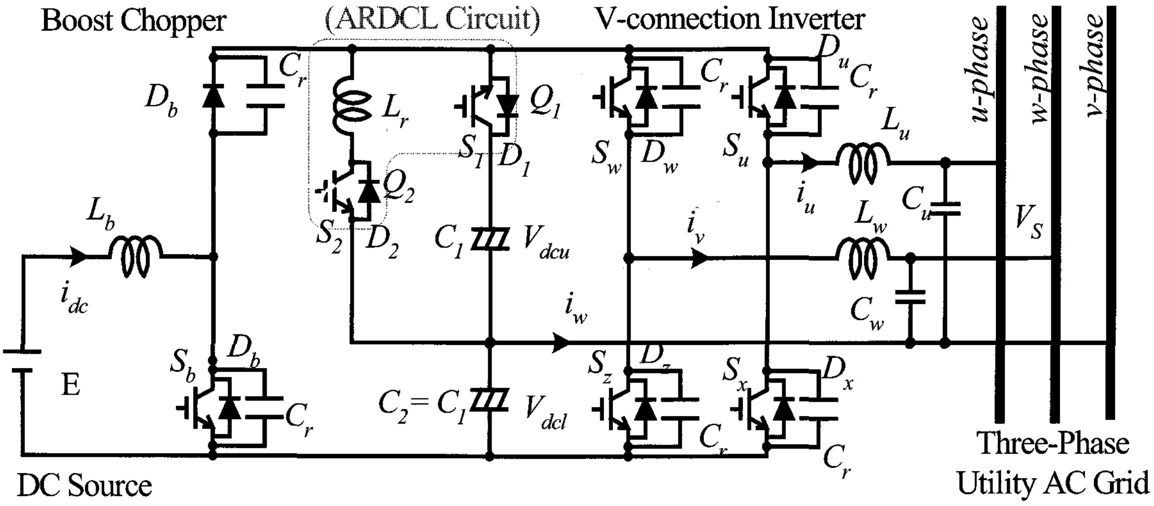


Fig. 1 Circuit configuration of the proposed power conditioner

Table 1 Design specification and power conditioner parameters

Item	Symbol	Value
Boost Inductor	L_b	525μH
Low Pass Filter Inductors	L_u and L_w	759μH
Low Pass Filter Capacitors	C_u and C_w	10μF
Edge-Resonant Inductor	L_r	4μH
Edge-Resonant Capacitor	C_r	10nF
DC-link Capacitors	C_1 and C_2	8.2mH
Utility Voltage	V_s	200V
DC Input Voltage	E	300V
Utility Frequency	f_u	50Hz
Switching Frequency	f_s	15kHz

3. Control Implementation

The control implementation of the proposed two-stage soft switching sinewave PWM power conditioner (see Fig.1) is designed on the basis of a signal processing comparator between the error signals of the reference line currents of three-phase V-connection i_{uv}^* *and* i_{wv}^* and the sawtooth carrier waveform. The control method for the main switch of the three-phase V-connection inverter, for example $Q_w(S_w/D_w)$, is shown in Fig.2. When the phase current direction i_u or i_v is from the three-phase V-connection inverter to the utility AC voltage V_s, the sawtooth waveform for the sinewave pulse modulation is set, as illustrated in Fig.2. On the other hand, the sawtooth waveform is vice versa when the phase current flows from V_s to the inverter.

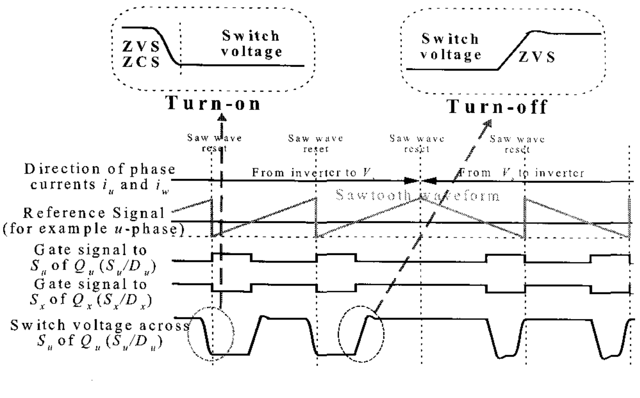


Fig. 2 Simplified schematic for PWM pattern control signal processor in main switches

Schematic block diagrams of the new soft-switching PWM control for the main active power semiconductor switching devices and the resonant inductor current of auxiliary active power switch Q_1 and Q_2 are illustrated respectively in Fig.3 and Fig.4. The new PWM control strategy is based on the system interconnection control scheme and the MPPT control scheme. In addition to this, the control scheme for the proposed soft switching power conditioner sinewave PWM system has a special PWM control scheme and a quasi-resonant inductor current control scheme. The PWM control method has the selection ability of the sawtooth carrier waveform direction for fitting the turn on timing in the main power semiconductor devices. The quasi-resonant inductor current controller has the switching timing control function in accordance with the utility AC-side current and the DC-side voltage because of the reduced power losses in the ARDCL snubber circuit.

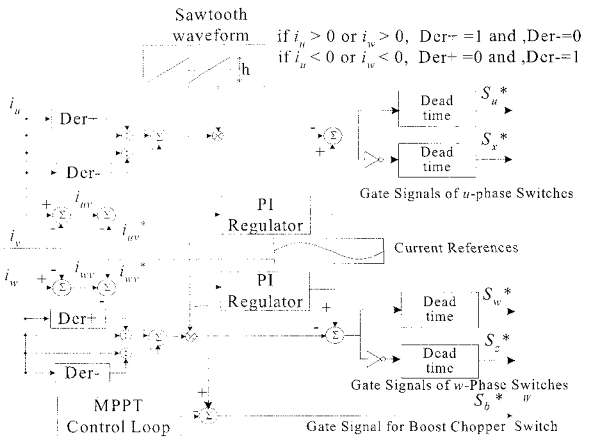


Fig. 3 PWM pattern control of three-phase V-connection inverter

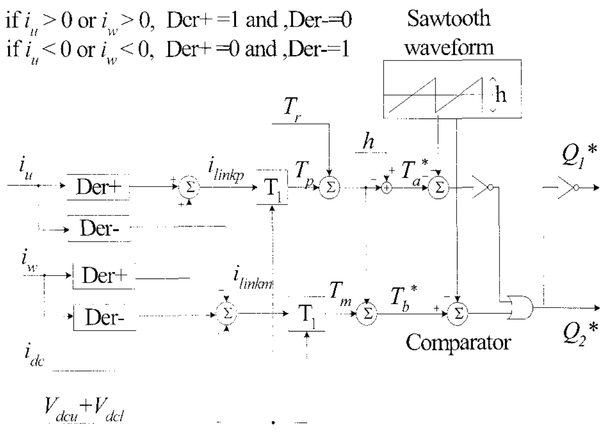


Fig. 4 Quasi-resonant Timing Control of boost chopper

where T1 = 2Lr /(Vdcu + Vdcl) and Vdcu + Vdcl is the DC-link voltage. The DC-link current i_{linkp} and i_{linkm} are defined in Fig.4. The specific time constants T_p and T_m are determined from (1) and (2), respectively;

$$T_p = \frac{2L_r i_{linkp}}{V_{dcu} + V_{dcl}} \tag{1}$$

$$T_m = \frac{2L_r i_{linkm}}{V_{dcu} + V_{dcl}} \tag{2}$$

On the other hand, the time constant T_r of the quasi-resonant mode are defined as,

$$T_m = \pi\sqrt{L_r C_1} \tag{3}$$

The reference time constants T_a^* and T_b^* for the ARDCL snubber circuit are respectively estimated by using (4) and (5).

$$T_a^* = h - \left(T_p + T_r\right) \tag{4}$$

$$T_b^* = T_m + \left(T_p + T_r\right) \tag{5}$$

Therefore, the switching pulse pattern timing sequence can be implemented from these time constants denoted by T_a^* and T_b^*.

4. Operating Principle

To achieve the complete soft switching commutation in all the power semiconductor switching devices in the proposed utility-interactive soft switching power conditioner, the ARDCL snubber circuit operates on the basis of the sawtooth carrier intercept PWM control method. The relationship between the switching signals and the sawtooth carrier waveform and the ARDCL snubber circuit operating waveforms under the condition $i_w > i_v > i_u > 0$ is illustrated in Fig.5. The ZVS and ZCS hybrid soft switching commutation can be completely achieved for turn-on switching mode transition by the single ARDCL snubber circuit. In actuality, the compared waveform used in the sawtooth PWM control scheme is the sinewaves calculated from the three-phase V-connection voltage source inverter condition. Using this sawtooth PWM control method, the complete ZVS commutation is achieved under a turn off switching commutation in both the three-phase V-connection voltage source inverter and the boost chopper by the quasi-resonant capacitor C_r. Fig.6 shows the voltage and current operation waveforms of the proposed power conditioner with ZVS soft-switching operation at their turn-off states.

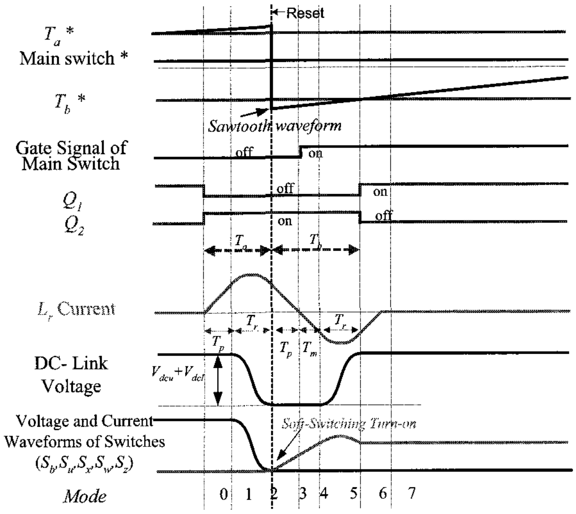


Fig. 5 Voltage and current operation waveforms at soft-switching turn on

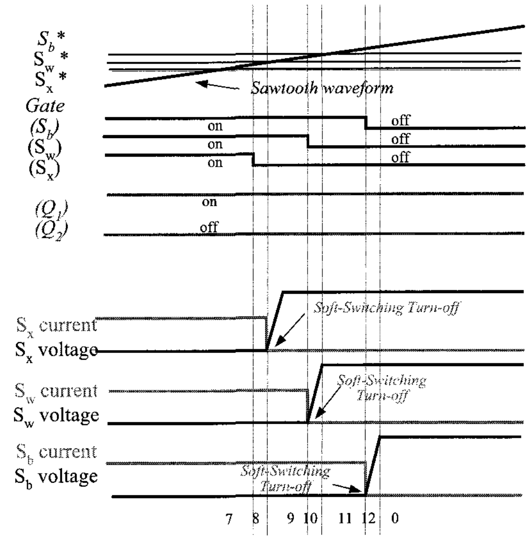


Fig. 6 Voltage and current operation waveforms with ZVS soft-switching turn-off

5. Switching Mode Transitions and Equivalent Circuits

In the operating principle of the proposed two-stage three-phase soft switching power conditioner, there are 13 operation modes as depicted in Fig.7. The operating principle of the proposed soft switching power conditioner system is described as follows:

Mode 0: The input-side current i_{dc} of the boost chopper flows through diode D_b while the per-phase output-side currents; i_u, i_w, i_v of the three-phase V-connection inverter flow through the diodes before the edge resonant commutation mode.

Mode1: The auxiliary switch $Q_2(S_2/D_2)$ of the two-switch auxiliary resonant DC-link snubber is turned on with ZCS condition while the auxiliary active switch $Q_1(S_1/D_1)$ is turned off with ZVS condition. As a result, the input DC boost chopper current i_{dc} flows through the quasi-resonant inductor L_r and the output phase currents (i_u , i_w) of the three-phase V-connection inverter, except the current i_v of v-phase, are respectively injected into the two-switch auxiliary resonant DC-link snubber circuit. When the quasi-resonant inductor current i_{Lr} reaches the utility AC-side current i_u plus the chopper DC current i_{dc}, the operating mode changes to the next mode.

Mode2: The edge resonant commutation operation produces on the basis of each resonant lossless snubbing capacitor C_r connected in parallel with each main power switch and the edge resonant inductor L_r in the two-switch active auxiliary resonant DC-link snubber. The main power switches S_b of $Q_b(S_b/D_b)$, S_w of $Q_w(S_w/D_w)$ and S_x of $Q_x(S_x/D_x)$ can all achieve turn on commutations with ZVS and ZCS by using the edge resonant commutation approach due to the two-switch active auxiliary resonant snubber.

Mode3: The resonant pulse current of the two-switch auxiliary resonant DC-link snubber starts to decrease after the quasi-resonant pulse commutation.

Mode 4: The resonant inductor current i_{Lr} changes its direction. When the value of the resonant inductor current i_{Lr} is equal to the utility AC-side current i_w, the next operating mode will start.

Mode 5: The auxiliary resonant capacitor voltage across the main power semiconductor devices D_b, S_u of $Q_u(S_u/D_u)$ and S_x of $Q_x(S_x/D_x)$ are respectively charged resonantly. When the voltage across each resonant DC-link capacitor becomes equal to the DC side voltage ($V_{dcu}+V_{dcl}$) the operating mode changes to the next mode, Mode 6.

Mode 6: Auxiliary switch $Q_1(S_1/D_1)$ and $Q_2(S_2/D_2)$ are turned on with ZCS condition and, the resonant inductor current i_{Lr} flows to the utility AC-side of power conditioner. If the resonant inductor current i_{Lr} goes to zero, the operating mode changes to the next mode, Mode 7.

Mode 7: In this operating mode, the DC current i_{dc} of the boost chopper flows through the boost chopper switching device S_b of $Q_b(S_b/D_b)$ and the utility AC-side current flows through the power semiconductor switching devices S_u of $Q_u(S_u/D_u)$and S_z of $Q_z(S_z/D_z)$

Mode 8: The quasi-resonant lossless snubbing capacitor C_r connected in parallel with the u-phase of the three-phase V- connection inverter starts to charge.

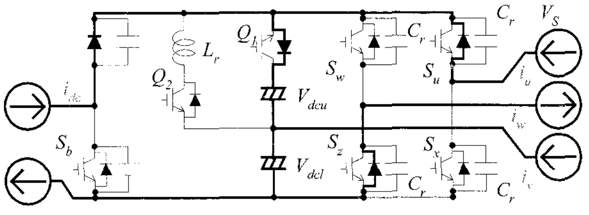
Mode 9: The main power switch S_x of $Q_x(S_x/D_x)$ is turned off with ZVS due to the resonant lossless snubbing capacitor C_r connected in parallel with it.

Mode 10: The resonant lossless snubbing capacitor C_r connected in parallel with S_w of $Q_w(S_w/D_w)$ starts to charge.

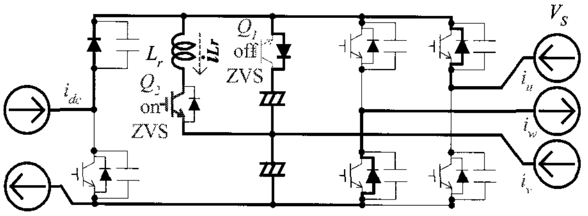
Mode 11: The main power switch S_w of $Q_w(S_w/D_w)$ is turned off with ZVS due to the resonant lossless snubbing capacitor C_r.

Mode 12: The resonant lossless snubbing capacitors connected in parallel with the diode D_b, and the main power switch S_b of $Q_b(S_b/D_b)$ starts to charge. Therefore, the main power switch S_b of $Q_b(S_b/D_b)$ is turned off with a ZVS.

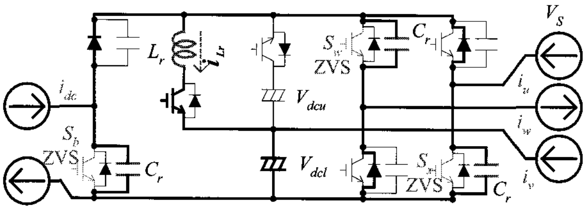
From the 13 operating transition modes of the proposed soft switching power conditioner during one sampling period, all power semiconductor switching devices in the proposed two-stage utility interactive power conditioner can achieve a complete soft switching operation.



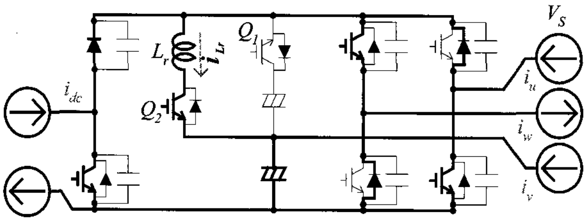
(a) Equivalent Circuit of Mode 0



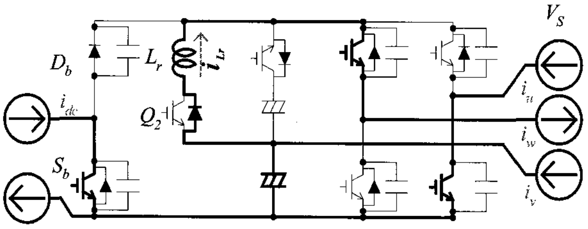
(b) Equivalent Circuit of Mode 1



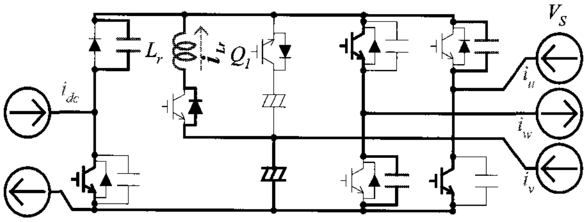
(c) Equivalent Circuit of Mode 2



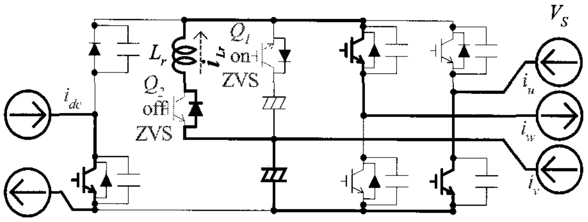
(d) Equivalent Circuit of Mode 3



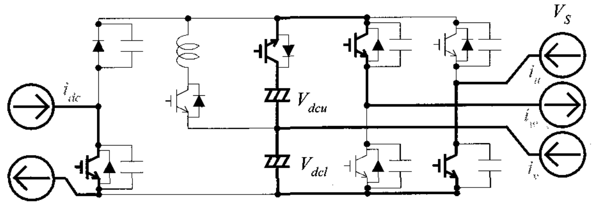
(e) Equivalent Circuit of Mode 4



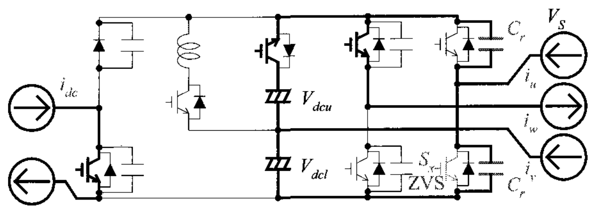
(f) Equivalent Circuit of Mode 5



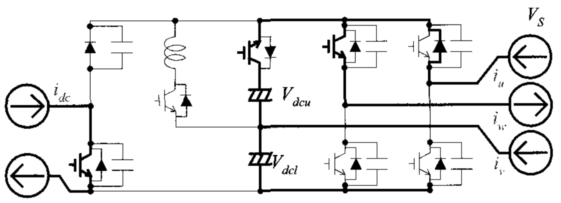
(g) Equivalent Circuit of Mode 6



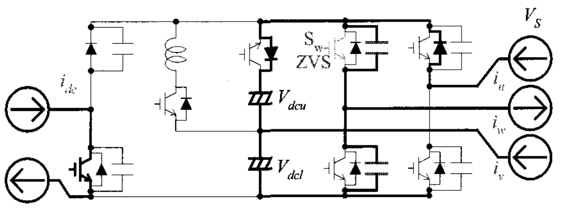
(h) Equivalent Circuit of Mode 7



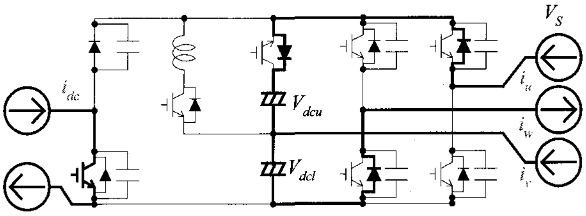
(i) Equivalent Circuit of Mode 8



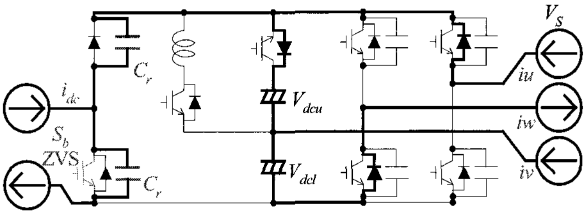
(j) Equivalent Circuit of Mode 9



(k) Equivalent Circuit of Mode 10



(l) Equivalent Circuit of Mode 11



(m) Equivalent Circuit of Mode 12

Fig. 7 Mode transitions and equivalent circuits of proposed power conditioner

6. Experimental Setup and Performance Evaluations

The whole experimental setup configuration of the proposed two-stage three-phase soft switching sinewave PWM power conditioner is described in Fig.8. In this power conditioning system, the inductor for boosting operation of the soft-switching PWM chopper and the low pass filter inductors and capacitors in the utility AC-side are designed to achieve higher operating performances. A photograph of the proposed soft switching power conditioner prototype system is shown in Fig.9. The volumetric dimensions of the proposed system are 700 mm in width, 600 mm in height and 300 mm in depth. It is designed to be compact and arranged in a specific configuration to reduce parasitic inductances and capacitances.

The voltage and current operating waveforms in the power semiconductor switching devices of the proposed system with a single active quasi-resonant snubber are measured and depicted in Fig.10. The complete soft switching commutation can be achieved at turn on and turn off under the conditions of a soft commutation switching mode transition. Furthermore, significantly reduced dv/dt and di/dt values in the main active power semiconductor devices were achieved because of the slope in the measured voltage and current waveforms. Additionally, EMI and RFI noises were also reduced effectively.

Figure 11 represents the utility AC line current waveforms of the proposed soft switching power conditioner. The utility three-phase AC currents are controlled so as to be a sinewave waveform with a unity power factor where the measured total harmonic distortion factor is 2.2% and the third harmonics distortion factor is 1.3%.

The comparative measured results of the conduction noise for the proposed two-stage soft switching and the conventional hard switching power conditioners are depicted in Fig.12. The conduction noise in the case of the proposed soft-switching power conditioner is about 5dB lower than the conventional one at 4 MHz. In spite of using a cooling system with a fan, the noise is controlled within 55dB.

Furthermore, the power conversion efficiency characteristics versus the output power of the proposed two-stage three-phase soft switching power conditioner and the conventional one are comparatively illustrated in Fig.13. The actual efficiency characteristics in the proposed soft switching power conditioner are higher, demonstrating 1.8% more efficiency than the conventional one at 10 kW.

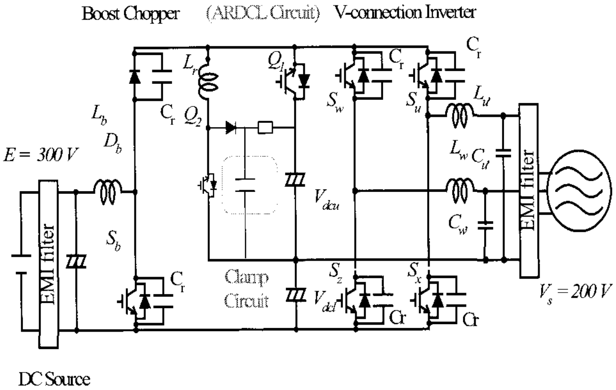


Fig. 8 Circuit configuration of experimental setup

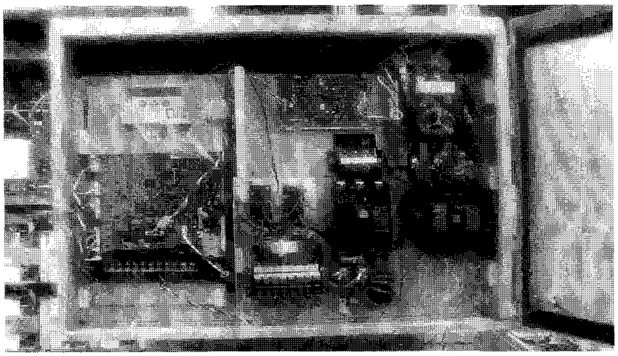
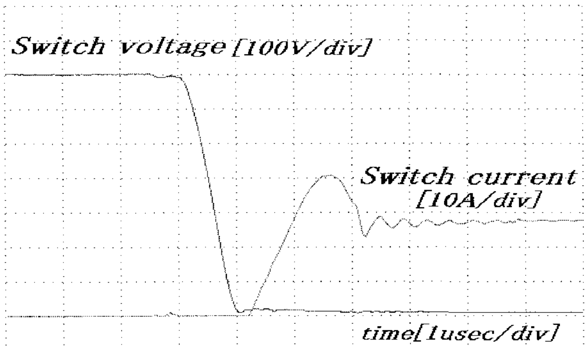
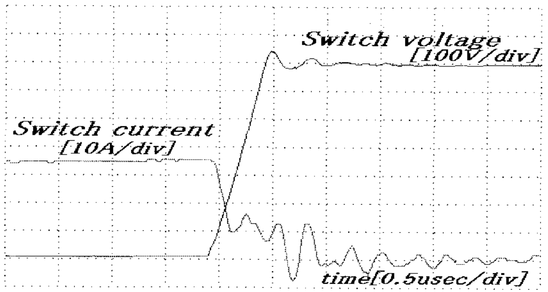


Fig. 9 Photograph for the practical design of proposed system



(a) Turn-on switching waveforms



(b) Turn-off switching waveforms

Fig. 10 Soft-switching voltage and current waveforms

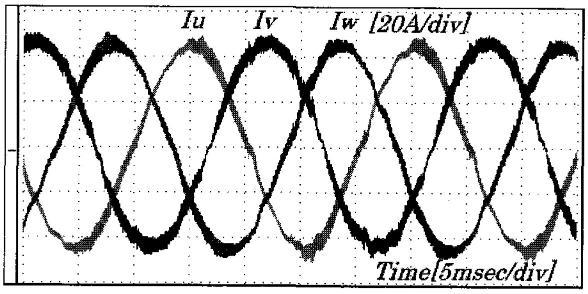


Fig. 11 Phase current waveforms of three-phase V-connection soft switching sinewave PWM inverter

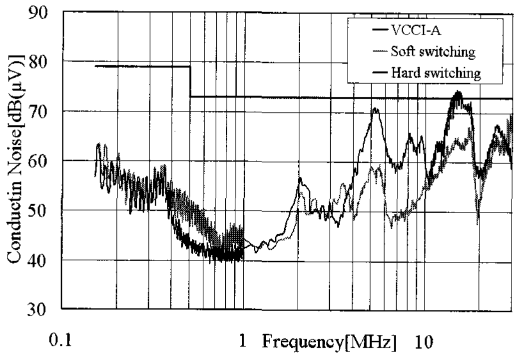


Fig. 12 Conduction noise

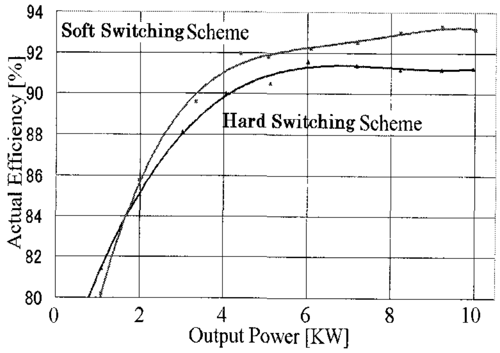


Fig. 13 Actual efficiency versus output power

7. Conclusions

In this paper, a new utility-interactive prototype topology and digital controlled auxiliary resonant DC-Link (ARDCL) snubber circuit assisted, two-stage three-phase soft switching power conditioner is proposed. It is more suitable and acceptable for fuel cell and solar power generation systems because of its IGBT power modules. This prototype was proposed and reviewed from a practical point of view. From the feasible experimental results, complete soft switching operation in all power semiconductor-switching devices was achieved. Furthermore, the actual efficiency of the proposed soft-switching power conditioner was increased by 1.8% as compared to hard-switching conventional systems. Lower noise and higher quality input sinewave current performances, on the basis of the soft switching sinewave PWM strategy, were achieved as compared with conventional hard switching power conversion systems.

References

[1] Luigi Malesani and Paolo Tenti, “High Efficiency Quasi-Resonant DC Link Three-Phase Power Inverter for Full-Range PWM“, IEEE Trans. on Indusry Applications, Vol.31,No.1,pp.141-147,1995.

[2] Prasad N. Enjeti and Ashek Rahman, “A new Single-Phase to Three-Phase Converter with Active Input Current Shapping for Low Cost AC Motor Drives ”, IEEE Trans. on Indusry Applications, Vol.29, No.4, PP.806-813, July/ August 1993.

[3] Gi-Taek Kim and Thomas A. Lipo, “VSI – PWM Rectifier / Inverter System with a Reduced Switch Count ”, IEEE Trans. on Indusry Applications, Vol.32, No.6, pp.1331-1337, November/ December 1996.

[4] Frede Blaaberjerg, Dorin O. Neacsu and John K. Pedersen, “Adaptive SVM to Compensate DC-Link Voltage Ripple for Four- Switch Three-Phase Voltage- Source Inverters”, IEEE Trans. on Power Electronics, Vol.14, No.4, pp.743-752, July 1999.

[5] Phoemsak Suksiri, Somboon Sangwongwanich and Gothom Arya,” A V-Connection-Like Inverter for Small AC Drives with Low Input Current Distortion “ Proc. of International Power Electronics Conference (IPEC), pp.130-134, 2000.

[6] Byoung-Kuk Lee, Tae-Hyung Kim, Mehrdad Ehsani, "On the Feasiblity of Four-Switch Three-Phase BLDC Motor Drives for Low Cost Comercial Applications: Topology and Control", IEEE Trans. on Power Electronics Vol.18, No.1, pp.164-172 January 2003.

[7] R.W.De Doncker, "The Auxiliary Resonant Commuttated Pole Converter", IEEE IAS Annual Meeting Records , pp.829-834 , Oct.1989.

[8] M.Kurokawa, Y.Konishi, M.Nakaoka: "Evaluations of Voltage-Source Soft-Switching Inverter with Single Auxiliary Resonant Snubber", IEE-UK Transactions on Electric Power Applications, Vol.148, No.2, pp.207-213, March, 2001.

[9] K.Taniguchi and S.Tomita,"Soft Switching Utility Interractive Inverter for Photovoltaic Energy Generation System", Proc. of IPEC, Vol.1, 187-192, 2000.

[10] S.Hoshi, K.Oguchi: "Considerations on control Strategy and Efficiency of Three-Phase Resonant Snubber Inverter", The paper of Technical Meeting on Semiconductor Power Converter (SPC) IEE-Japan, SPC-00-88, pp.72-82, November, 2000.

[11] Yong C. Jung, Hyo Li Liu, Guk C. Cho and Gyu H. Cho, "Soft Switching Space Vector PWM Inverter Using a New Quasi Parallel Resonant DC Link", IEEE Trans. on Power Electronics Vol.1, No.3, pp.503-511 May 1996.

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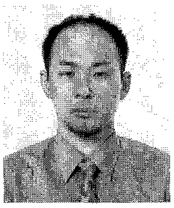

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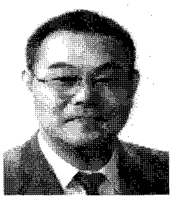

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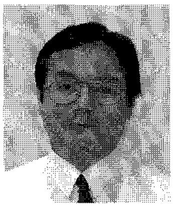

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