Feasibilty Study of Distributed Auxiliary Resonant Commutation Snubber Linked Three Phase Voltage Source ZVS Inverter with Digital Servo Control Implementation

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ABSTRACT - This paper presents performance and loss analysis of Auxiliary Resonant Commutation Snubber-linked (ARCS) three phase voltage source soft switching inverter which is operated under a condition of Zero Voltage Switching (ZVS). The system performances of this ARCS soft switching inverter which is controlled on optimal type I digital servo scheme are illustrated and evaluated on the basis of experimental results.

1. INTRODUCTION

In recent years, the voltage-source three phase inverters and converters which can operate under the principle of zero voltage or zero current transition soft switching schemes have been researched and developed vigorously. The main aims of softswitching scheme are to minimize the switching losses of switching power devices (IGBTs, MOS-FET, etc.), their electrical dynamic voltage and current stresses as well as voltage and current surge related to EMI noises under high frequency switching.

Of these, the three phase voltage-source PWM inverters and converters operating under ZVS condition are roughly divided into four categories; resonant commutated snubber-link, resonant AC link, resonant DC link and resonant switching block link. The comparative studies of the soft switching units mentioned above have been done by many power electronic researches.

In this paper, the performances of three phase voltage source type I optimal digitally controlled inverter with auxiliary resonant commutated snubbers (ARCS), which is more suitable for high power applications compared with resonant DC linked soft switching inverter, is presented and compared with the conventional hard switching inverter.

2. CIRCUIT DESCRIPTION

Fig.1 shows the equivalent circuit of a bridge leg in a single phase of ARCS linked three phase voltage source soft switching inverter . To illustrate the operating principle of this ARCS inverter, the resonant commutation from D_{2x} to S_{1x} is discussed. For simplicity, two assumptions are made as follows;

(1) All the power switching devices incorporated into the inverter are ideal.

(2) Load current equals to the positive Ix as indicated in Fig.1 which is kept constant during a short commutation interval.

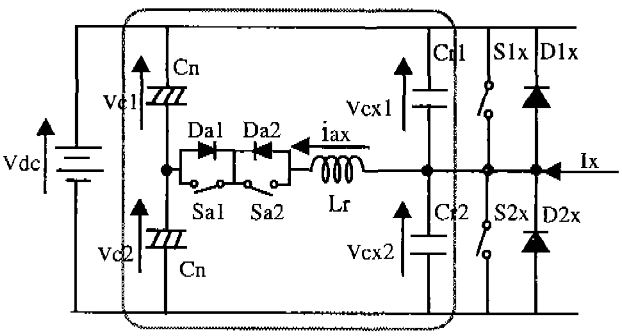


Fig.1 ARCS circuit of one-phase bridge leg

Fig.2 displays theoretical operating voltage and current waveforms of the main switching devices and auxiliary switching devices in this ARCS circuit. As shown in Fig.3, there exist 10 operation modes. The operating principle of ARCS circuit in a steady-state can be described as follows:

State A : mode 0 ($t < t_0$)

A positive load current I_x is freewheeling through D_{2x}, while S_{2x} remains on and S_{1x} is off.

State A : mode 1-1(t_0 - t_1)

S_{a2} is turned on under zero current switching (ZCS) condition. The current through D_{2x} begins to decrease linearly as the current through the resonant inductor I_{aX} increases linearly.

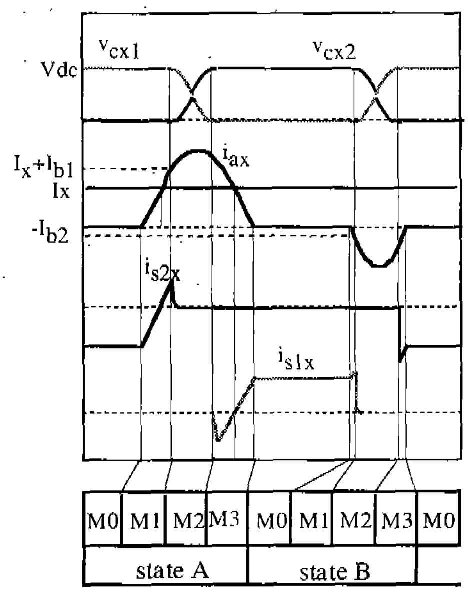


Fig.2 Theoretical voltage and current waveforms of ARCS circuit

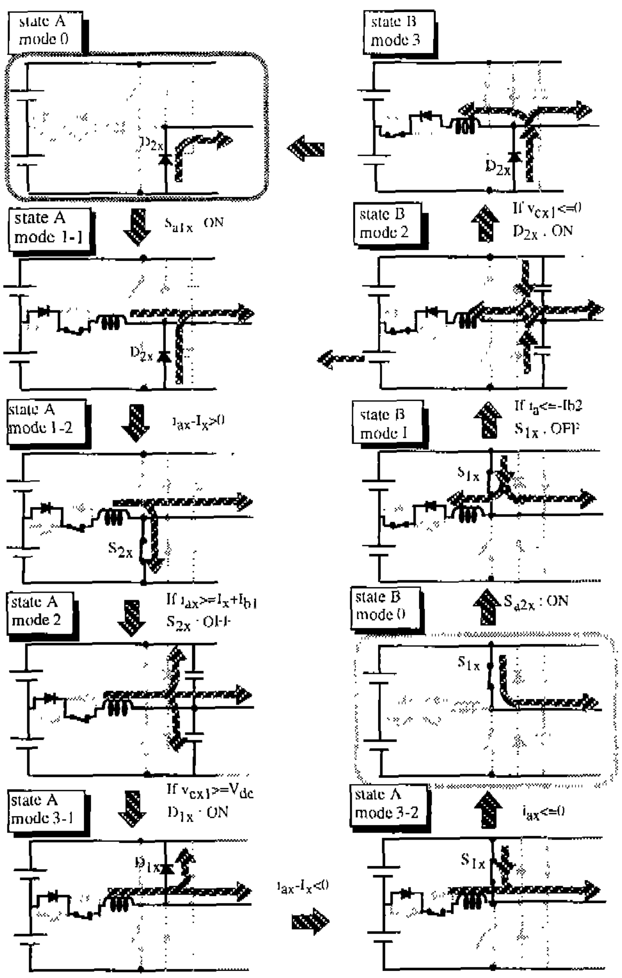


Fig.3 Equivalent circuit for each operation stage of ARCS

State A : mode 1-2(t_1 - t_2)

At t_1, the current via D_{2x} decreases to zero when the resonant inductor current I_{aX} is equal to the load current I_X. The current flowing into S_{2x} begins to increase. The resonant inductor current becomes greater than the load current and continues rising up to I_X+I_{b1}. At this point, stored energy in Lr is large enough to charge and discharge the resonant capacitors.

State A : mode 2(t_2 - t_3)

After turning off S_{2x} with ZVS, the resonant capacitor C_{r1} begins to discharge to zero while the other resonant capacitor C_{r2} begin to charge towards the dc-link voltage. This is a resonance between the resonant inductor Lr and the resonant capacitors C_{r1} and C_{r2}.

State A : mode 3-1(t_3 - t_4)

At t_3, D_{1x} begin to conducting and resonant inductor current begins to decrease linearly. On the other hand, S_{1x} can be turned on at complete ZVS/ZCS hybrid conditions.

State A : mode 3-2($t_4 - t_5$)

At t_4, the current via D_{1x} is commutated to S_{1x} and resonant inductor current decreases linearly.

State B : mode 0($t_5 - t_6$)

At t_5, the resonant inductor current becomes zero and D_{a1x} is turned off. The load current is totally transferred to S_{1x}.

State B : mode 1($t_6 - t_7$)

S_{a1} is turned on under ZCS condition. The resonant inductor current begins to increase linearly towards the minus direction and continues to rise until the stored energy is high enough to charge and discharge the resonant capacitors C_{r1} and C_{r2}.

State B : mode 2($t_7 - t_8$)

After turning off S_{1x} under ZVS condition, the resonant capacitor C_{r1} begins to charge to full dc-link voltage while C_{r2} begin to discharge towards zero.

State B : mode 3($t > t_8$)

At t_8, D_{2x} conducts and a resonant inductor current begins to decrease linearly towards the minus direction. When the resonant inductor current becomes zero, D_{a2x} is turned off and transfers back to state A : mode 0.

In this operation, the resonant capacitor C_{r1} or C_{r2}, which is parallel with the active switch D_{1x} or D_{2x} incorporated into the bridge leg, behaves as a lossless capacitive snubber due to a quasi-resonance.

3. FEASIBILITY STUDY OF INVERTER SYSTEM

Experimental Set-up

Fig.4 shows the total system configuration of ARCS

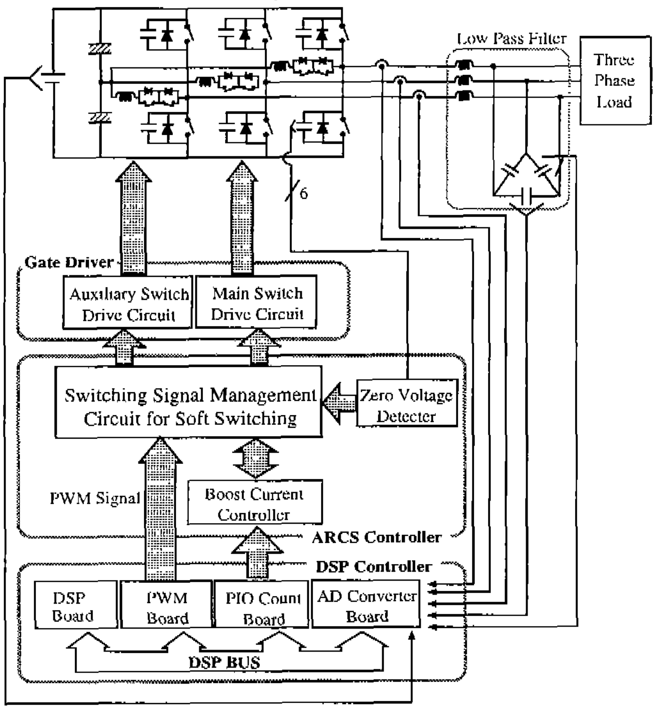


Fig. 4 Block Diagram of Experimental Apparatus

linked three phase soft switching inverter with type I optimally controlled digital servo scheme. This inverter system is composed of a DC voltage Source (AC-DC rectifier : in some cases, three phase PFC rectifier), three-phase full bridge inverter stage, ARCS stage with the neutral point of DC busline for each leg in the inverter, low pass filter, DSP controller and ARCS controller including voltage and current sensors. DSP controller consists of DSP board (including Ti:TMS320C35), AD converter board, PIO board and PWM board. ARCS control circuit consists of Switching Signal Management Circuit, Zero Voltage Detector and Boost Current Controller.

The ARCS connected with each inverter arm works independently from the other inverter arms. DSP controller generates 3 phase PWM signals on the basis of optimal type I digital control scheme and ARCS controller sends the inverter switching signals immediately when the voltage across the switching power device comes down to zero (turn on) or when inductor current reach the initial resonant current I_x+I_{b1} (turn off). By this operation, resonant commutation which cause ZVS operation is perfectly achieved.

A conventional hard-switching PWM control scheme can be easily obtained by using this experimental set-up, directly connecting with DSP controller and inverter main circuit drive circuit. The dead time in the hard switching can be easily selected on the basis of DSP controller hardware setting.

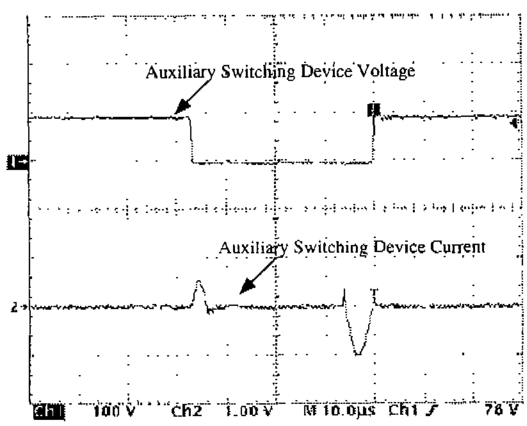
Experimental Results of ARCS Soft-Switching Inverter System

In order to verify the total system performances, the ARCS inverter system was tested under resistance load condition as well as inductive load and rectifier load conditions. Table1 indicates the design specifications and drive setting of this soft-switching inverter system and conventional hard switching inverter system.

The voltage and current waveforms in the ARCS stage are displayed in Fig.5. The voltage across the auxiliary switching power devices, IGBTs, in the resonant commutation snubber block are clamped exactly at half of the DC bus line voltage level.

Table 1 Design specifications

DC Bus line Voltage :Vdc	200[V]
Devided DC Voltage Capacitor :Ci	8200[mF]
Resonant Inductor : Lr	12[mH]
Resonant Capacitor : Cr	0.08[mH]
Boost Current : I boost	9[A]
Filter Reactor : Lf	500[mH]
Filter Resistance : Rf	0.1[W]
Filter Capacitor : Cf	20.0[mF]
Output AC Voltage : Vac	100[Vrms]
Output Frequency : Fe	60[Hz]
Carrier Frequency : Fs	16[kHz]
Load Resistance : Rl	10 [W]

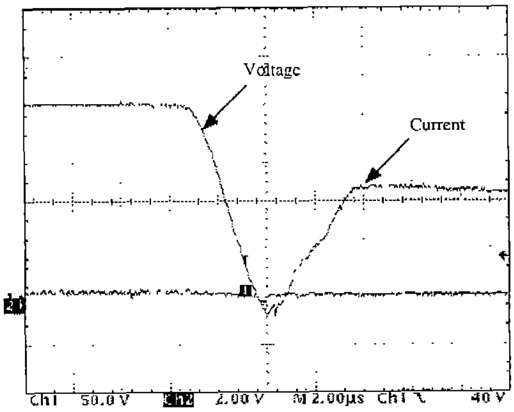


100V/div, 20A/div, 10uS/div

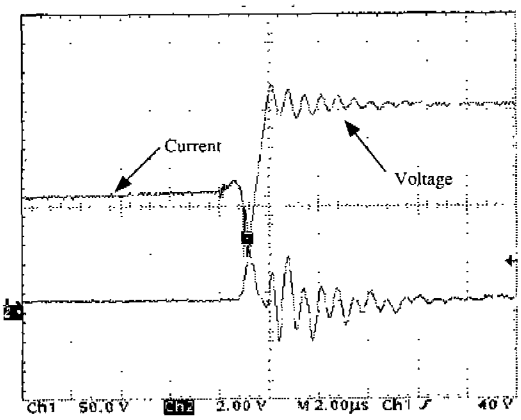
Fig.5 Measured waveforms of ARCS circuit

Fig.6 shows current and voltage traces of the main power switching devices in the inverter stage during the turn off and turn on periods. Fig.7 illustrates the switching voltage and current waveforms of the conventional hard-switching voltage sourcc inverter. From these figures, it is clearly proved that all the main and auxiliary power switching devices can completely achieve soft switching, ZVS, for the main devices in the inverter stage in addition to ZCS for auxiliary devices in the ARCS stage.

Fig.8 shows the output voltage waveforms of this soft-switching inverter system for the case of a three phase resistive load. The output voltage waveforms of conventional hard switching inverter system are shown in Fig.9. The spike on the waveforms caused by high-speed hard switching operation can be observed. The measured total Harmonic Distortion; in the case of soft switching, THD is 0.23%, on the other hand, for the case of hard switching, THD is 0.37%.



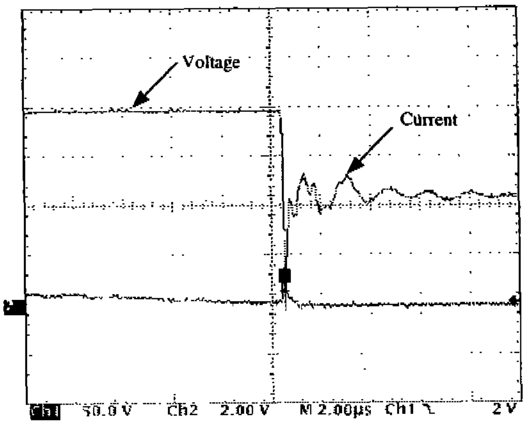
(a) Turn on operation



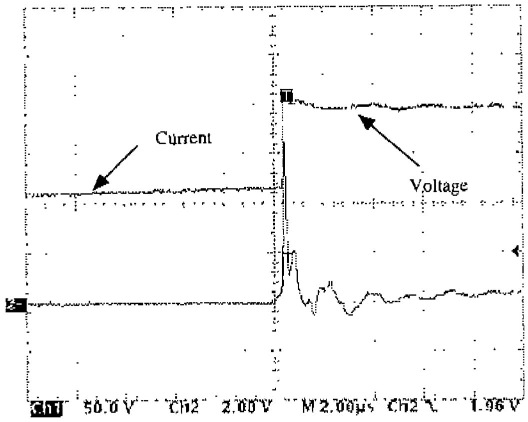
(b) Turn off operation

50V/div, 10A/div, 2uS/div

Fig.6 Turn on and turn off operationg waveforms of the soft switching inverter main devices



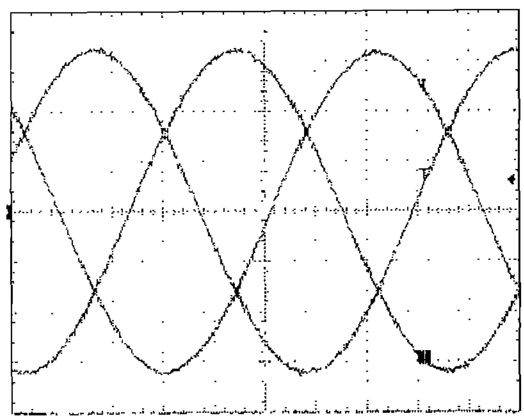
(a) Turn on operation



(b) Turn off operation

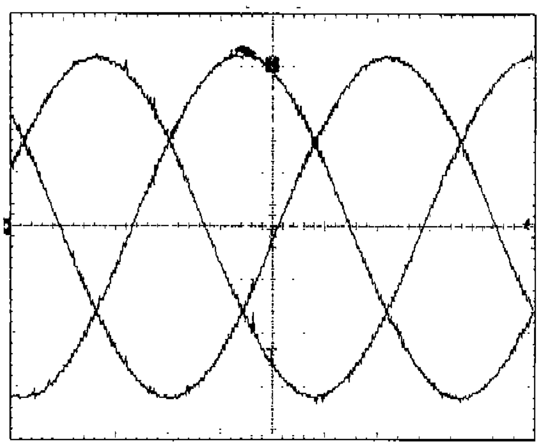
50V/div, 10A/div, 2uS/div

Fig.7 Turn on and turn off operationg waveforms of main dcvices in hard switching inverter



50V/div, 2mS/div

Fig.8 Output voltage waveforms of softswitching inverter



50V/div, 2mS/div

Fig.9 Output voltage waveforms of conventional hard switching inverter

Measured Loss Estimation of ARCS System

The power losses of the ARCS inverter system have to be separated to ARCS stage losses and main inverter stage losses by using a conversion method from thermal loss to electrical loss. This method of estimating the electrical losses in the switching power devices from their temperature rise is very effective in a practical system. The average value of power conversion loss including transient switching losses and conduction losses of the inverter stage can be obtained. As shown in Fig.10, the losses in the ARCS stage and inverter stage, as the sampling frequency is changed from 3 to 16[kHz], are obtained under the fixed resistive load condition with the output current at 10.3[A]. These results suggest that the losses of the inverter stage in ARCS soft switching inverter system are not affected by their switching losses in a wide range of sampling frequencies.

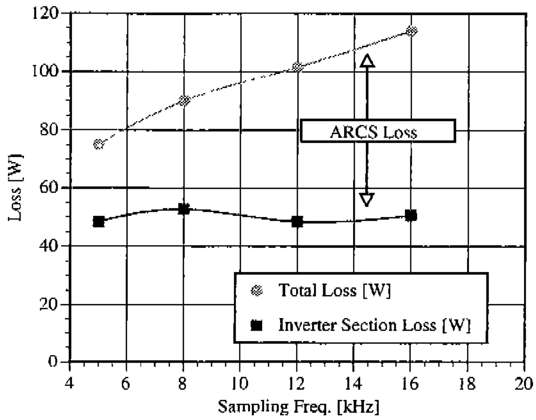


Fig.10 Measured ARCS soft switching inverter losses

Fig 11 shows the total system efficiency of ARCS soft switching inverter and hard switching inverter under 16[kHz] sampling frequency. These results suggest that the total efficiency of ARCS soft switching inverter is superior to that of the hard switching inverter under a power rating of more than several [kW] of output power.

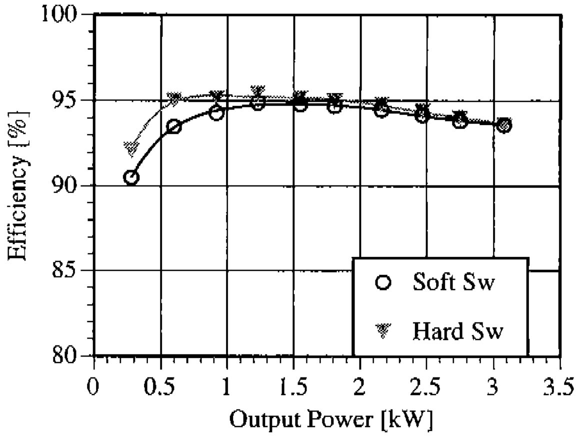


Fig.11 Total system efficiency

CONCLUSIONS

This paper has described the operating principle and features of ARCS linked three phase voltage source soft-switching inverter with the optimal type I digital servo controller to track a specified output reference voltage. It was proved that the proposed soft switching inverter can efficiently operate with high performance ZVS-PWM in order to minimize the switching losses, dynamic electrical stresses as well as EMI noises as compared with that of conventional hard switching inverter.

In the future, three-level soft-switching inverter and converter using ARCS which are more suitable and acceptable for high-power applications is to be investigated and evaluated from a practical point of view.

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