Three-Phase Voltage-Source Soft-Switching Inverter with Auxiliary High Frequency Transformer Linked Power Regeneration Resonant Snubbers

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ABSTRACT- In this paper, a prototype of the auxiliary resonant commutated snubber circuit (ARCS) with a high frequency transformer power regeneration loop is described for voltage source type sinewave inverter system. This is a new soft switching topology developed for three phase voltage source soft-switching inverter, active power filter and reactive power compensator has significant advantage of current rating reduction for auxiliary active switching devices. In addition, this paper presents a novel prototype of voltage-source soft switching space vector-modulated inverter with ARCS mentioned above, which is more suitable and acceptable for high-power utility interactive power conditioning, along with a digital control scheme. The steady-state operating analysis of ARCS has the remarkable features and the practical design procedure of this resonant snubber are illustrated on the basis of computer simulation analysis. The operating performance evaluations in the steady-state of this three phase voltage source soft switching inverter are discussed and compared with the three phase voltage source hard switching inverter.

1. INTRODUCTION

In recent years, for the purpose of minimizing the switching losses of power semiconductor devices and their electrical stresses including the voltage and current surge-based EMI noises at high frequency switching PWM operation mode, the voltage-fed three phase PWM inverter or PWM the voltage-fed three-phase rectifier using MOS-gate controlled power semiconductor switching devices such as MOSFETs, IGBTs, MCTs, and MOS-SITs, which take advantage of zero voltage or zero current soft switching operation have been developed and discussed. The three phase voltage-fed inverters and rectifiers operating at zero voltage soft switching transition PWM modes are roughly divided into four; resonant commutated arm-link, resonant AC link, resonant DC link and resonant switching block link.

In this paper a prototype of the auxiliary resonant commutated snubber circuit with high frequency transformer power regeneration loop is described as a new soft switching topology ,which has significant advantage of current rating reduction of auxiliary active switching devices. In addition, this paper presents a novel prototype of voltage-fed type soft switching space vector-modulated inverter with ARCS. The steady-state operating analysis of ARCS with HF-TR has remarkable features and a practical design procedure of this resonant snubber are illustrated on the basis of computer simulation analysis. The steady-state operating performance evaluations of three phase voltage source soft switching inverter are discussed as compared with three phase voltage source hard switching inverter.

2. AUXILIARY RESONANT COMMUTATED SNUBBER CIRCUIT

Operation of resonant commutation circuit

The auxiliary resonant commutated snubber circuit capable of achieving power regeneration is shown in Fig.1. The ARCS circuit is composed of two auxiliary active switches(Sax1,Sax2), two lossless snubber capacitors (Crx1,Crx2), Diodes (Dax3, Dax4) for quasi-resonance power regenerating current feedback, and high frequency transformer with two-windings.The typical operating voltage and current waveforms of the ARCS in Fig.1 is illustrated in Fig.2. Its equivalent circuits corresponding to the operating modes are shown in Fig.3 . Fig.3 describes the operation mode State A-B.

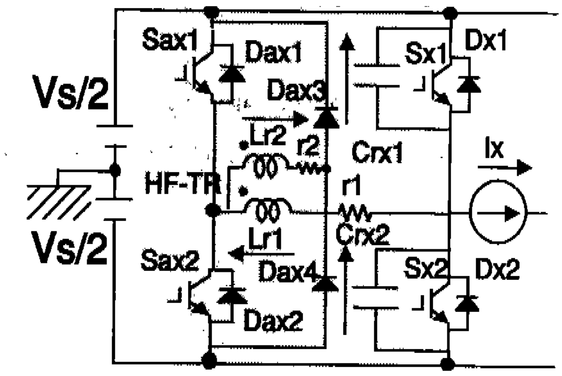

Fig.1. Auxiliary resonant commutated snubber with HF-TR

The operation of this resonant snubber in State A is described blow.

<State A:Mode0> Sx1 is in on state and the load is connected to the DC power supply.

<State A:Mode1> When Sax2 is closed ,A current starts to flow through the primary side of the HF-TR. Dax1 is turned on.

<State A:Mode2> When Sx1 is turned off, the current i_x plus i_{Lr1} discharges Crx2 up to zero and charges Crx1 up to Vs.

<State A:Mode3> During this mode, Dx2 conducts currents i_{Lr1} plus i_x. Sx2 is allowed to conduct. When Dax3 is turned off, this mode is completed.

<State A:Mode4> During this mode, the current i_{Lr1} of a few miliamperes flows through Sax2.

<State A:Mode5> In practice, Sax2 is turned off with only a little zero current, and is naturally commutated to Dax1. At $i_{Lr1}=0$, Dax1 is turned off.

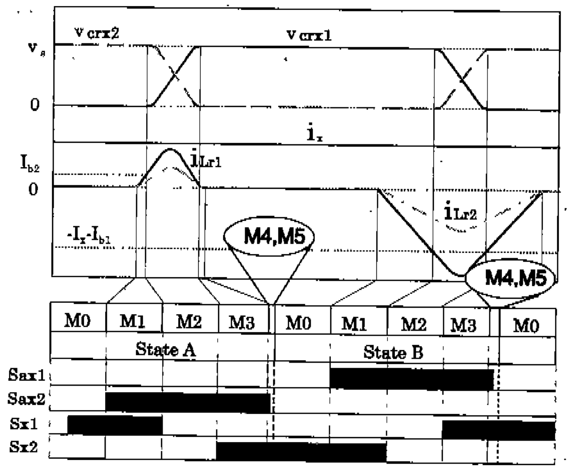

Fig.2. Operating voltage and current waveforms of auxiliary resonant commutated Snubber circuit

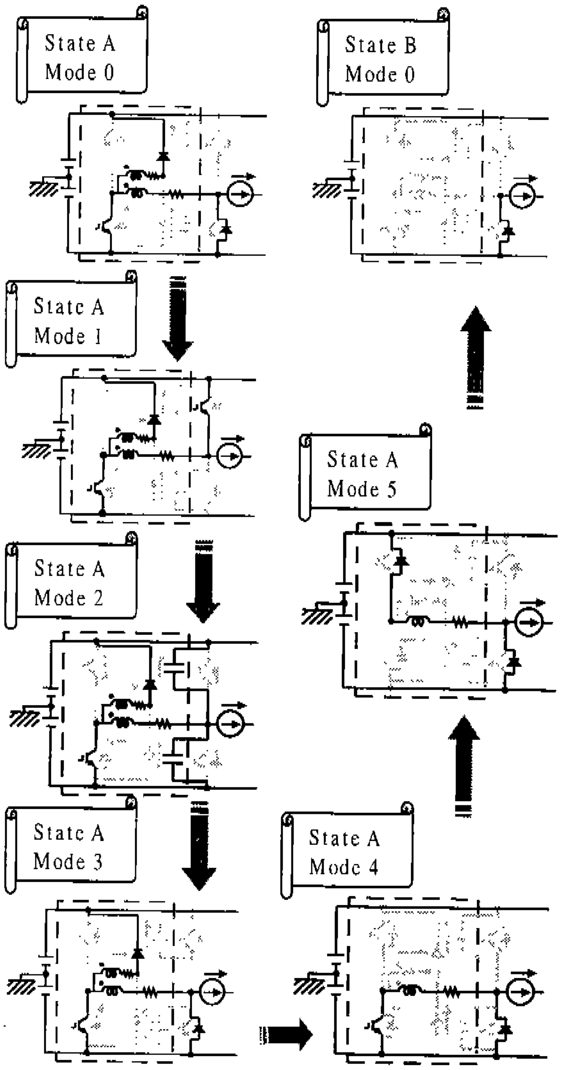

Fig.3. Operating mode transition of auxiliary resonant commutated snubber circuit with HF-TR loop (State A—State B)

Design Method of Auxiliary Resonant Commutated Snubber

A method to select the suitable circuit parameters is described in this chapter. First of all, the mode equations (mode1, mode2) are described, respectively as follows:

Operating Mode 1

$$\frac{di_1(t)}{dt} = \frac{N-1}{L_r(1-k^2)N} V_s \quad \text{.......................}(1)$$

where, N=2.0

Operating Mode 2

$$\frac{di_1(t)}{dt} = -\frac{1}{L_r N} V_s + \frac{1}{L_r} v_2 - \frac{1+N}{L_r N} Ri_1$$

$$\frac{dv_2(t)}{dt} = -\frac{i_1 + i_x}{2C_r} \quad \ldots (2)$$

From the those equations, function (3) and (4) are described.

$$t = \frac{L_r(1-k^2)Ni_1}{(N-1)V_s} \quad \text{.........................}(3)$$

$$t = \frac{1}{G}\{a\cos(-\frac{DL_r}{K\sqrt{p^2+q^2}}) + a\tan\frac{p}{q}\} \quad \text{......}(4)$$

where,

$$G = \frac{\sqrt{|B^2 - 4A/L_r|}}{2A}, \qquad D = \frac{V_S - (1+N)Ri_x}{L_r N}$$

$$K = e^{\frac{15}{8}\frac{r}{L_r}*10^{-6}}, \qquad q = V_S - DL_r$$

$$p = \frac{1}{G}(FV_S - DFL_r - \frac{i_{b2} + i_x}{2C_r}), \qquad F = \frac{B}{2A}$$

$$A = 2C_r, \qquad B = \frac{(1+N)2C_r R}{L_r N}$$

Those functions are illustrated by using the characteristics under the conditions as shown in Fig.4 and Fig.5. In this paper, 1.5μs as the minimum time of mode 1 was chosen. Because we assume that the DSP control system and DSP has a limitation of performance. 2.5μs as the maximum time of mode 1 was chosen, because we demand the operating time of auxilialy circuit to 1/10 during the sampling period. The area which satisfies these rules is shown in Fig.4. Next, the time in mode 2 is also chosen as 2.5μs by that rule. Fig.5 is the graph which is Lr=3.0μH. In those figures, the gray zone is an effective area. The effective circuit parameters are selected in this areas.

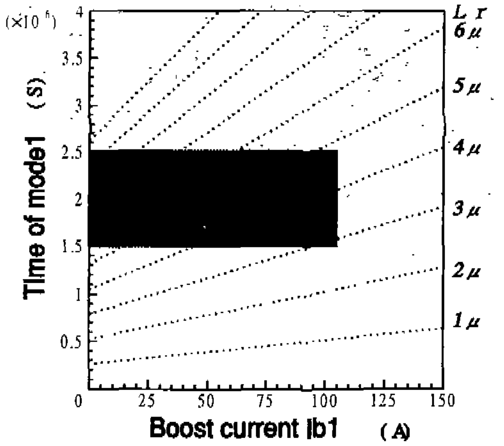

Fig.4 Relations between time and i_{b1} with parameters Lr

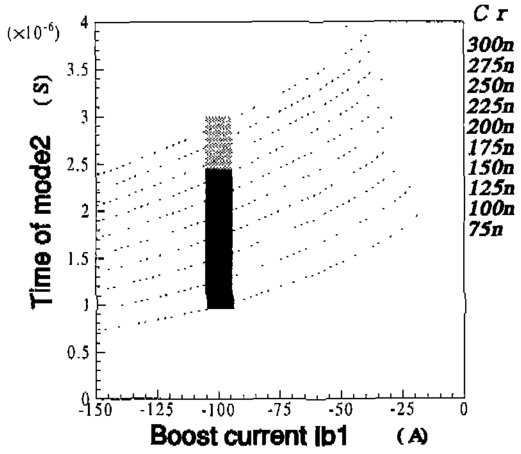

Fig.5 Relations between time and i_{b1} with parameters Cr (Lr=3.0μH)

3. THREE PHASE VOLTAGE-SOURCE ZVS-PWM INVERTER SYSTEM

The main power circuit of three phase voltage-fed ZVS-PWM inverter using auxiliary high frequency transformer-linked power regeneration resonant snubber connected to each bridge leg is shown in Fig.6.

The control system based on an optimal digital servo control scheme is implemented in Fig.7. Under the time-sharing allocated space voltage vector modulation scheme, this scheme is more suitable upon d-q synchronous rotating coordinate transformation frame. The real time control will become easy on the basis of conventional modern control theory because the control variable seems to lie on DC value.

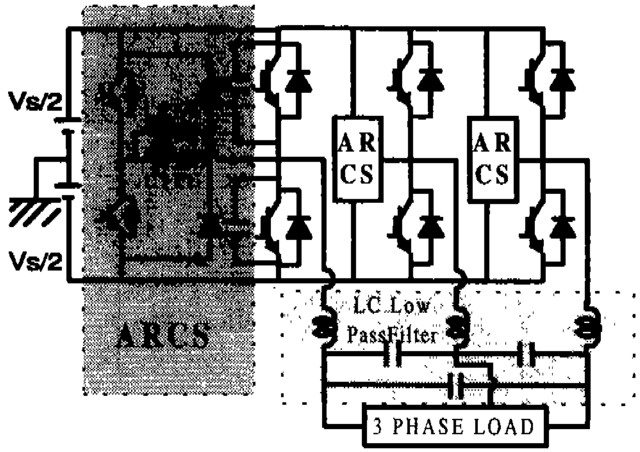

Fig.6 Three-phase voltage-source type soft switching inverter

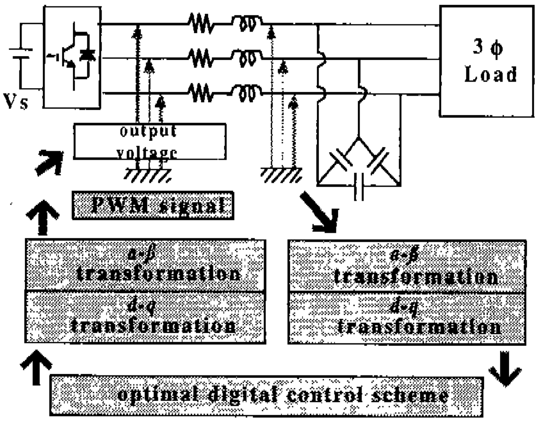

Fig.7 Schematic control system of three phase inverter

4. SYSTEM EVALUATIONS AND THEIR DISCUSSION

Simulation Method

This simulation was written by ANCI-C Language and this simulation is not affected by a computer system and compiler. The simulation results are achieved from the following steps.

The operation of auxiliary circuit in every operating mode is classified.

Each different mode equation for every mode circuit is described.

These equations are solved by using the 4th order RUNGE-KUTTA method and circuit operations is evaluated.

Using the 4th order RUNGE-KUTTA method, it is possible to keep the error as lower as possible in comparison with another numerical analysis method; Euler method

Design Specifications

Please note that in this case, a maximum output power of this inverter is designed for 50kVA. The results of this simulation analysis under circuit parameters in Table 1 and Table 2 are shown in Fig.8 and Fig.9

Table.1 Design Specifications

DC Voltage	800[V]
Sampling Frequency	12[kHz]
output Voltage	400[V]
Filter Inductor	848.8[μ]
Filter Registance	0.228[Ω]
Filter Capacitor	19.95[μF]
Primary Inductor	1.9[mH]
Secondary Inductor	7.9[mH]
Mutual Inductor	3.8[mH]
Primary Resistance	0.125[Ω]
Secondary Resistance	0.25[Ω]
Coupling Co-efficient	0.999
Turn Ratio	2.0
Boost Current1	15[A]
Boost Current2	13[A]

Table.2 Load parameters (Inductive load with Y-connection)

Load Resistance	2.56[Ω]
Load Inductor	5.09[mH]
Power-Factor	0.8

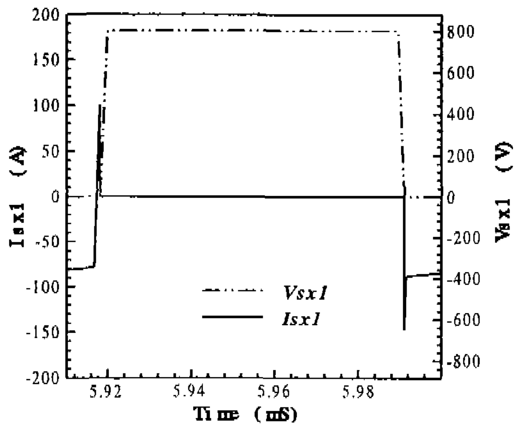

Fig.8 (a) Voltage and current waveforms of high side main switch in U phase

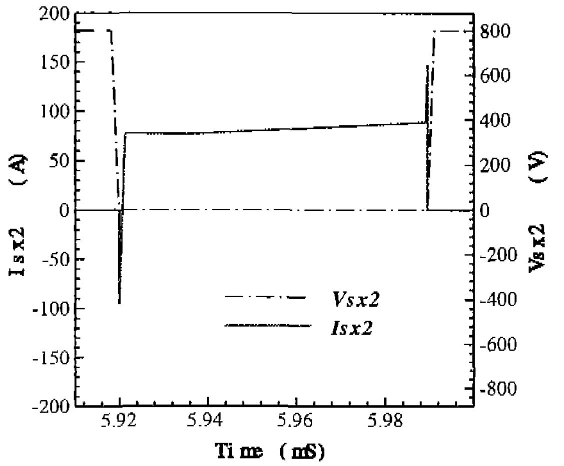

Fig.8 (b) Voltage and current waveforms of low side main switch in U phase

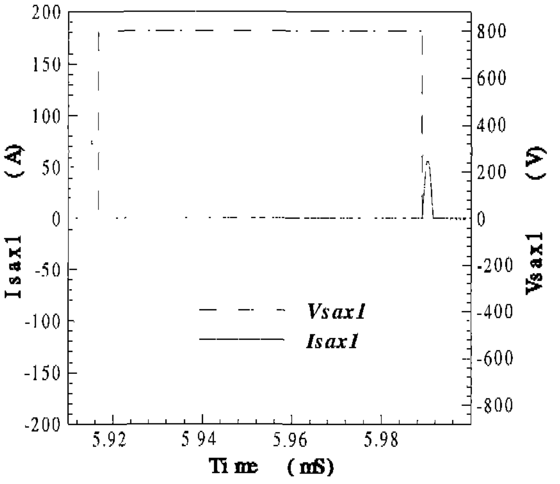

Fig.8 (c) Voltage and current waveforms of high side auxiliary switch in U phase

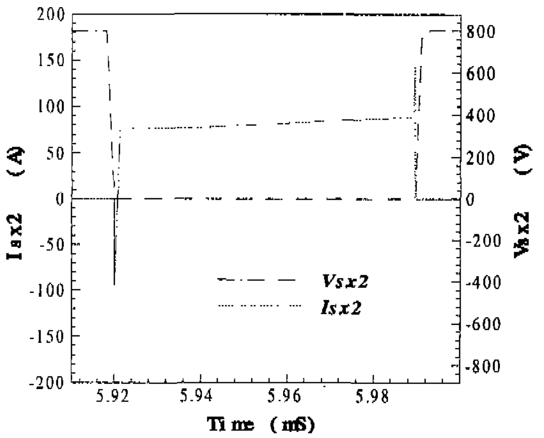

Fig.8 (d) Voltage and current waveforms of low side auxiliary switch in U phase

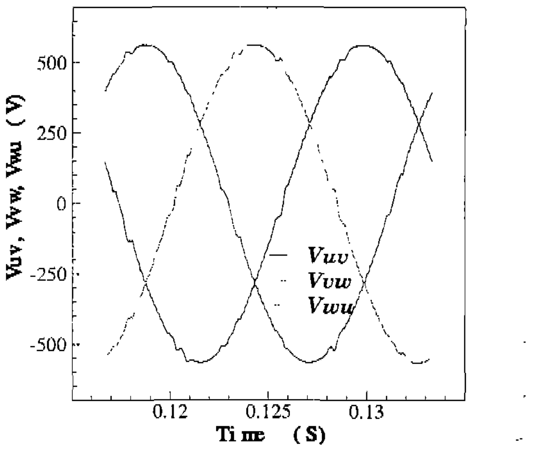

Fig.9 (a) Steady-state output AC voltage waveforms

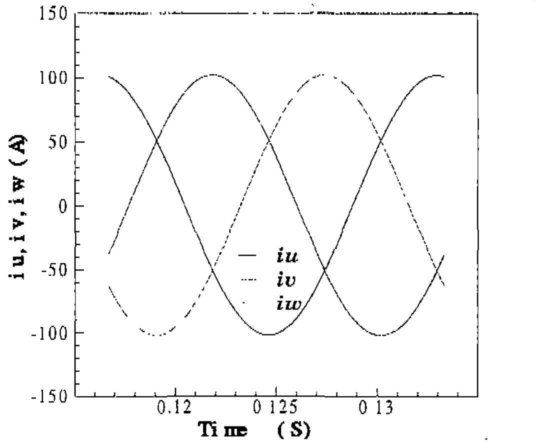

Fig.9 (b) Steady –state AC load current waveforms

Results and Discussion

Fig.8 (a) and (b) show the voltage and current waveforms of main active switch in U phase, and Fig.8 (c) and (d) show the voltage and current waveforms of auxiliary active switch in U phase. Fig.8 (a) and (b) indicate that main active switch is completely turned off under a ZVS condition and is also completely turned on under ZVS and ZCS conditions. Moreover, the auxiliary active switch is completely turned on under a ZCS condition. In addition, the peak current of auxiliary active switch is a little smaller than the main active switch. Fig.9 (a) illustrates the steady-state output AC voltage waveforms and Fig.9 (b) illustrates the steady-state AC load current waveforms in three phase voltage-fed soft-switching inverter.

Finally, each RMS current and conducting loss of each part active switch in this inverter and Mr.Dedonker's ARCP inverter is shown in Table 3. This table shows that the RMS current and conducting losses of the auxiliary active switch of this inverter type is decreased in comparison with ARCP inverter.

U defined as the conduction loss which is one of the main active switch of this type of inverter.

Table 3 RMS current and conduction loss of each switch

Inverter Type	Switch Type	RMS Current	Conduction Loss
ARCS with HF-TR	Main	48.2[A]	U
	Auxiliary	9.6[A]	0.039U
Dedonker's ARCP Imverter	Main	48.2[A]	1.0U
	Auxiliary	27.0[A]	0.21U

5. CONCLUSIONS

In this paper, the auxiliary resonant commutated snubber circuit with a high-frequency transformer power regeneration loop has been proposed as a convention of auxiliary resonant commutated snubber circuit. New soft switching circuit topology is described, in which the RMS current and conduction loss of auxiliary active switches could be considerably reduced. The operating principle of this resonant snubber was presented on the basis of the computer-aided simulation including the practical design method of this ARCS. In addition to this, in this paper, the three-phase voltage-fed type soft-switching inverter with ARCS treated here has been presented which was designed so as to operate in the basis of the optimum digital type 1 servo control theory. The performance evaluations of this inverter were represented. It was proved that the effectiveness of this soft-switched PWM inverter was more suitable for high-power applications.

REFERENCES

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[2] R.W.De Doncker:"The Auxiliary Resonant Commutated Pole Cnverter" IEEE IAS Records, pp.829-834, October 1989