Three-Phase Soft Switching Sinewave Inverter with Bridge PowerModule Package Configurated Auxiliary Resonant AC Link Snubber

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Abstract: This paper presents a novel prototype of the three-phase bridge power block module type auxiliary resonant AC link snubber circuit, which is effectively used for the three-phase voltage source type sinwave soft switching PWM inverter using IGBTs. Its operating principle is described for current source load model, along with its practical design approach based on the simulation data. The performance evaluations of the three-phase voltage source type sinewave soft switching PWM inverter incorporating a single three-phase bridge module of active auxiliary resonant AC link snubber treated here is illustrated, which is concerned with power quality efficiency power loss analysis. This inverter is discussed as compared with those of the three-phase voltage source type sinewave hard switching PWM inverter. The power loss analysis of this soft switching PWM inverter using IGBT power modules is evaluated on the basis of the measured v-i characteristics and switching power losses of IGBT, and antiparallel diodes. The practical effectiveness of this inverter is proven by the power loss analysis for distributed power supply.

Keywords ; Bridge block module type auxiliary resonant AC link snubber, Soft switching, Three-phase sinewave inverter, Power loss analysis

1. INTRODUCTION

In recent years, the research and development of the high frequency carrier-based soft switching sinewave PWM processing circuit technology to implement high performances of a three-phase voltage source type sinewave PWM inverter, the three-phase PFC rectifier with sinewave input current shaping and unity power factor, UPS, and a bi-directional converter. High frequency soft switching PWM power conversion circuit topologies (inverter, rectifier) using active auxiliary resonant snubber for utility interactive power supply are generally divided into four categories; an auxiliary resonant DC link, an auxiliary resonant AC link and an auxiliary resonant bridge leg commutation link, and an auxiliary resonant arm link. The power conditioning converter circuit using IPM (Intelligent Power Module) and processing PWM are substantially suitable and acceptable for the auxiliary resonant DC link and auxiliary resonant AC link snubber schemes. Especially, the auxiliary resonant AC link snubber circuit is suitable for medium power capacity and large power capacity applications, such as UPS, distributed power supply, active rectifier secondary battery and energy storage system. The authors has done performance evaluation of the three-phase inverters and converters on the star connected type resonant AC link snubber scheme so far as well as delta connected type resonant AC link snubber scheme based on a bi-directional switch type resonant AC link scheme discussed by J. Lai, et. al. and the single resonant inductor type resonant AC link snubber scheme developed by M. Yoshida et. al. This paper proposes the bridge power block module type resonant AC link snubber-assisted three-phase voltage type soft switching sinewave PWM inverter scheme, which is based on a bi-directional switch type resonant AC link scheme, and the principle of this circuit operation is described, the comparative evaluations of the power loss analysis is carried out for three type topological of the resonant AC link assisted three-phase voltage source type soft switching PWM inverter using IGBTs, and its practical effectiveness is verified on the basis of the computer-aided simulation data.

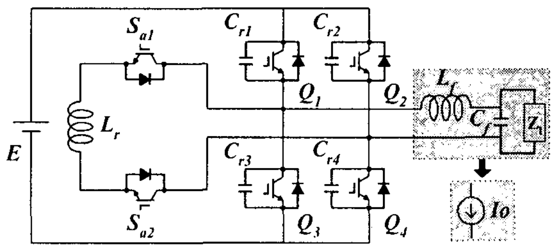

Fig.1: An auxiliary resonant AC link snubber with bi-directional switch circuit diagram

2. RESONANT AC LINK SNUBBER CIRCUIT

The main circuit configuration of the single-phase voltage source-fed inverter using a single auxiliary three-phase bridge power block module type resonant AC link snubber circuit is shown in Fig.1. The LC lowpass filter in Fig.1 is in the output side of the voltage source type inverter using IGBTs and is connected to the AC load or utility grid AC power source. The simplest auxiliary resonant snubber circuit shown in Fig.1 which operates under a principle of zero current soft switching (ZCS) is represented by using the equivalent current source, because the load current seems to be kept constant during one sampling operation period in high frequency carrier sinewave PWM strategy. This soft switching inverter operating under ZVS has lossless snubber capacitors *Cr1-Cr4* in parallel with the main active power switches *Q1-Q4* in each bridge arm. In the output load side, output edge resonant pulse commutation circuit is connected in parallel with the load, which consists of the resonant inductor Lr and auxiliary bi-directional power switches $Qa1$ and $Qa2$, including the lossless snubbing capacitors C_{r1}-C_{r4}. The main power switch can achieve zero voltage soft switching commutation in terms of operating the active auxiliary edge resonant pulse commutation circuit. The lossless capacitive snubber in parallel with the main power switch to be turned off has to be charged up from zero to the supply voltage Vs. As a result, the main power switch can achieve ZVS for turn off transition. On the other hand, the lossless capacitive snubber in parallel with the main power switch to be turned on has to be discharged down from Vs to zero during the dead time interval. The current through the main power switch commutates naturally to the antiparallel diode of IGBT. In this case, the main power switch can completely achieve ZVS and ZCS hybrid mode for a turn off transition. And then, the auxiliary switches $Qa1$ and $Qa2$ can achieve ZCS for turn on and turn off mode transitions with the aid of the resonant inductor Lr and the resonant capacitor $C_r=(C_{r1} \sim C_{r4})$.

3. PARAMETER DESIGN METHOD OF RESONANT SNUBBER CIRCUIT

3.1 Circuit Design of Basic Resonant AC Link Snubber

The circuit parameter design procedure of an active auxiliary resonant AC link snubber treated here should be sufficiently explained. The design specifications are given by switching frequency fs=20[kHz], DC power source voltage Vs=200[V], output voltage Vo=100[Vrms], output power rating Po=2[kW] for the resistive load. The required design conditions of this resonant snubber circuit respectively are specified as follows.

(a) The commutation operation period is to be designed so as to be 1/10 (5.0[ms]) of one switching period Ts.

(b) Peak stress across the power semiconductor device (IGBTs) is to be selected as low as possible.

When the load current Io is a maximum value; Io=30[A], the time Δtb required for the initial starting current stored into the quasi-resonant inductor under its various inductance variations is about one third of its commutation time. In this case, if this Δtb is specified to 1.6[μs], the resonant inductor inductance Lr is designed for 8.3[μH].

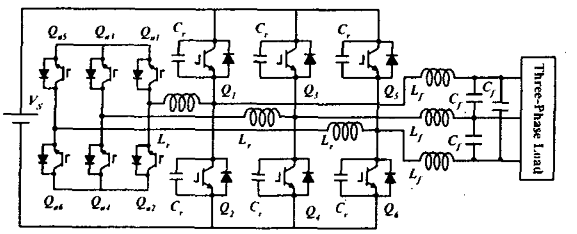

Fig.2: Power module bridge package type auxiliary AC resonant assisted three-phase voltage source inverter

Next, if Lr is set to 8.3[μH] and Δtr as edge resonant operating time in case of varying the lossless capacitor capacitance Cr is suppressed to a dead time td=1.5[μs], the lossless capacitor capacitance Cr is determined as Cr=73.3[nF].

The circuit design specifications and circuit parameters are indicated in Table.1 for the single-phase voltage source type full bridge soft switching inverter using IGBTs shown in Fig.1, which is incorporates the auxiliary resonant AC link snubber.

Table.1 Design specifications of resonant AC link snubber and the circuit parameters

Parameter		Value
DC Source Voltage	Vs	200[V]
Switching Frequency	fs	20[kHz]
Resonant Inductor	Lar	8.0[μH]
Lossless Snubber Capacitor	Cr	70.0[nF]

3.2 Circuit Parameters of Low Pass Filter in Inverter Output

The LC parameters of the low pass filter in the inverter output side are designed on the basis of % impedance =7%. The specification condition is provided to be the output voltage Vo=100[Vrms], the maximum output current Io_max=20[A], the output voltage frequency fo=60[Hz], the cut off frequency fc=2.0[kHz] of low pass filter. The inductance of the filter inductor is designed for L_f=928.4[μH] and the value of the filter capacitor designed for is C_f=6.82[μF]. The circuit parameters of this soft switching inverter are shown in Table.2.

Table.2 Design inverter specifications and its circuit parameters

Item		Value
Output Voltage(rms)	Vo	100[V]
Output Voltage Frequency	fo	60[Hz]
Filter Inductor Inductance	L_f	928.4[μH]
Filter Capacitor Capacitance	C_f	6.82[μF]
Resistive Load	R_l	5.0[Ω]
Inductive Load	R_l	4.0[Ω]
	L_l	7.96[mH]

4. THREE-PHASE VOLTAGE SOURCE TYPE SOFT SWITCHIG INVERTER USING IGBTs

A bi-directional switch type auxiliary resonant AC link snubber-assisted soft switching inverter using IGBTs in Fig.1 is developed as a three-phase output voltage inverter. The star connected type resonant AC link snubber and delta connected type resonant AC link snubber and single resonant inductor type resonant AC link snubber are considered for the resonant snubber. In addition, the newly proposed three-phase bridge power module switching type auxiliary resonant AC link snubber. The three-phase bridge power block module type resonant AC link snubber-assisted three-phase voltage type soft switching inverter with instantaneous space voltage vector modul action scheme is represented in Fig.2.

The main schematic feature of this topology has simple circuit configuration capable of using three-phase power block module snubber as well as three-phase power block module inverter. In addition, the total numbers of power devices conducting in series connection can be reduced for the edge resonant snubber switching operation. Moreover, the power semiconductor modules of 2 in 1 and 6 in 1 type can be conveniently used for this soft switching topology.

5. SIMULATION RESULTS AND EVALUATIONS

In case of operating as the three-phase bridge switching type auxiliary resonant AC link snubber-assisted three-phase voltage type sinewave soft switching PWM inverter using IGBTs, the output voltage and the output current operating waveforms are illustrated in Fig.3. This analytical software of the inverter treated here is automatically designed so as to stop the simulation processing in case of operating the hard switching PWM mode in three-phase inverter. The range to obtain the operation waveforms is considered by making use of the simulation for soft switching in all the power switches. All the main power switches and the auxiliary power switches can provide the sinewave voltage under the conditions of the soft switching operation. Switching frequency (sampling frequency) is to be determined by fs=20[kHz] from an acoustic noise point of view. A dead time is specified to t_d=1.5[ms] in design. The hard switching simulation of the three-phase sinewave PWM inverter also similarly carried out as compared with the three-phase soft switching sinewave PWM inverter. The waveform total distortion factor (THD) of the output voltage waveform in simulation is represented in Table.3 for balanced resistive and inductive loads. It is noted that the design specifications of the new type inverter treated here are actually set so as to meet the operating condition.

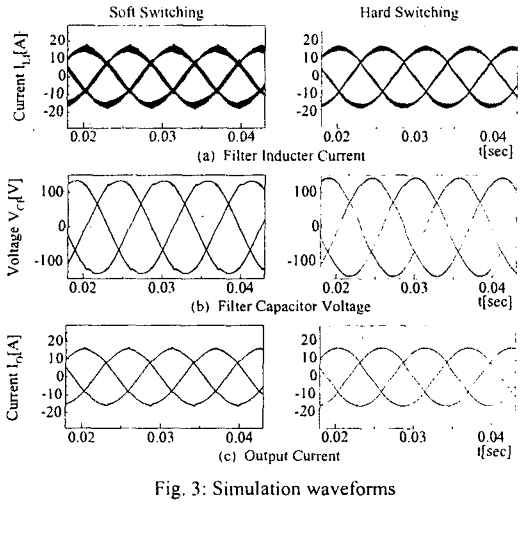

Fig. 3: Simulation waveforms

Table.3 Camparisons between THD in H-SW and S-SW PWM inverters

Load Profile	Switching Strategy	THD[%]
Resistive Loads	H-SW	1.77
	S-SW	2.56
Inductive Loads	H-SW	2.03
	S-SW	3.54

Note : Hard Switching H-SW ; Soft Switching S-SW

6. EFFICIENCY EVALUATION UNDER MEASURED CHARACTERISTIC DATA

6.1 Experimental Data-Based Power Devices

In general, the power losses generation by the three-phase sinewave soft switching PWM inverter circuit with a single three-phase bridge block module is characterized as follows,

(a) Conduction loss-based the internal resistance component of the resonant inductor
(b) Conduction loss by all the power semiconductor devices of the active power switches; IGBTs and the passive power switches; Antiparallel diodes
(c) The switching power loss in the switching transient state for the power semiconductor devices; IGBTs and Diodes.
(d) The conduction power loss by the LC low pass filter of three-phase voltage source type sinewave PWM inverter

The power losses by the resistance component of the inductor of (a) and (d) are required for the effective internal effective resistance of the inductor. The both conditions of (b) and (c) are based on the measured data in experiment. IGBTs and diodes in the three-phase inverter and three-phase power module-assisted auxiliary resonant AC link snubber are assumed to be the same characteristics.

The IGBTs uses the measured data of CM100DU-12F v-i characteristics. Then, the approximation described here is included in the simulation program, and conduction losses of the power semiconductor devices are required.

Each antipararellel diode uses the measured data of TOSHIBA 30JL2c41 on its v-i characteristics. Then, this approximation is included in the power electronic simulation program implemented by the authors, and the conduction losses of the passive switching power device are required for the power loss and efficiency estimation.

Once the diode turns on, and then, collector current of the IGBTs flows through IGBTs. Therefore, the turn-on loss does not exist almost practically. The turn off power losses are based on the switching power losses in the turn off related the IGBT transient current. The new simulation software offers an algorithm to calculate the switching loss in every turn-off.

6.2 Efficiency Evaluation

Fig.4 represents the results of the power loss analysis, which is based on the measured power loss data (v-i characteristics, switching characteristics) of IGBTs and diodes into the computer simulation program. The main power losses of a three-phase voltage type sinewave hard switching PWM inverter are the conduction loss of the main power switches, the conduction loss of a low pass filter, and the switching loss of the main power switch. Although, the switching losses of the main power switches in three phase voltage type sinewave soft switching PWM inverter with three-phase bridge module-assisted resonant AC link snubber could reduce over 50% as compared with those of three-phase hard switching inverter. But the total power loss in three-phase voltage type sinewave soft switching PWM inverter using IGBTs is larger than power loss of total power loss in three-phase hard switching inverter, because three-phase soft switching inverter have power losses (conduction loss of an auxiliary power switch, switching loss of an auxiliary power switch, conduction loss of resonant inductor) in an auxiliary resonant AC link snubber circuit composed of three-phase bridge power block module. The efficiency of a three-phase hard switching inverter is 94.29 [%]. And the actual efficiency of the three-phase soft switching inverter is 94.05 [%]. Therefore, three-phase soft switching inverter could be put into practice. The power rating is specified to 2kW in the laboratory power level. When a rating output power is 10kW or more, power loss of the main circuit component is larger than power loss of an auxiliary resonant AC link snubber circuit portion. Therefore, if the output power becomes high, the efficiency of the soft switching inverter effectively becomes higher than the efficiency of hard switching inverter.

7. CONCLUSIONS

In this paper, the operation principle of a bi-directional switch type resonant AC link snubber circuit was described for three-phase voltage source inverter, together with the practical design procedure. The novel type resonant AC link snubber assisted three-phase voltage type sinewave soft switching PWM inverter using IGBTs was demonstrated herein. It was verified that both the auxiliary power switches in this auxiliary resonant AC link snubber circuit and the main power switches commutate under the condition of soft switching operation. Moreover, It was shown that the output THD of three-phase voltage type sinewave soft switching PWM inverter is accuracy as compared with the output THD of thrre-phase hard switching inverter. It was illustrated and discussed that power loss analysis of three-phase soft switching inverter with a three-phase bride block module resonant AC link snubber circuit can be performed from a practical point of view. It was proven that a soft switching PWM inverter was made to high efficiency. In addition, which the power losses of the new inverter treated here were analyzed by implementing the experimented data of the IGBT and diode v-i characteristics and switching loss characteristics into our original computer simulation software. Then, three-phase voltage type sinewave soft switching PWM inverter was high efficiency. Finally, three-phase soft switching inverter using IGBTs could be put into practice as compared with hard switching PWM inverter with soft switching inverter.

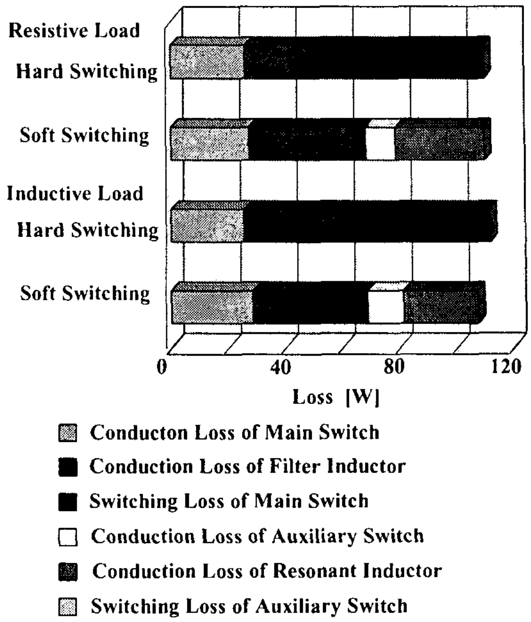

Fig.4: Power loss analysis

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