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Dual Utility AC Line Voltage Operated Voltage Source and Soft Switching PWM DC-DC Converter with High Frequency Transformer Link for Arc Welding Equipment

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Abstract - This paper presents two new circuit topologies of the dc busline side active resonant snubber assisted voltage source high frequency link soft switching PWM full-bridge dc-dc power converters acceptable for either utility ac 200V-rms or ac 400V-rms input grid. These high frequency switching dc-dc converters proposed in this paper are composed of a typical voltage source-fed full-bridge PWM inverter, high frequency transformer with center tap, high frequency diode rectifier with inductor input filter and dc busline side series switches with the aid of a dc busline parallel capacitive lossless snubber. All the active switches in the full-bridge arms as well as dc busline snubber can achieve ZCS turn-on and ZVS turn-off transition commutation with the aid of a transformer leakage inductive component and consequently the total switching power losses can be effectively reduced. So that, a high switching frequency operation of IGBTs in the voltage source full bridge inverter can be actually designed more than about 20 kHz. It is confirmed that the more the switching frequency of full-bridge soft switching inverter increases, the more soft switching PWM dc-dc converter with a high frequency transformer link has remarkable advantages for its power conversion efficiency and power density implementations as compared with the conventional hard switching PWM inverter type dc-dc power converter. The effectiveness of these new dc-dc power converter topologies can be proved to be more suitable for low voltage and large current dc-dc power supply as arc welding equipment from a practical point of view.

Keywords: Arc welding power supply, Dc-dc converter, Dc rail series switch assisted parallel capacitor snubber, High frequency transformer link, Soft switching PWM, Voltage-fed full-bridge topology

1. Introduction

For low voltage and large current applications as supplied by arc welding power, dc-dc converters using dc busline switch resonant snubber-assisted full-bridge soft switching PWM inverters with high frequency transformer links have been recently developed and put into practice in industrial equipment[1-4].

The utility ac 200V-rms or ac 220V-rms in industries is commonly used for the ac power distribution power mains in Japan, Korea and Taiwan. In contrast, the other countries in the world, China, Europe, United States and so forth, utility ac 380V-rms, ac 400V-rms or ac 460V-rms are widely used as the utility power distribution mains in the various industries. Thus, in case we export the industrial products incorporating the inverter type dc-dc power converter with high frequency transformer designed for utility ac 200V-rms input line to the region where the utility ac 400V-rms input line is used, the primary side inverter circuit of high frequency transformer winding in the dc-dc power converter must be completely re-designed. In actuality, this has been a significant problem needing resolution and has also been cost-consuming for designers and companies in case of spreading out their new products in the various world wide markets.

This paper presents the proposal of two novel circuit topologies on voltage source full-bridge type active snubber assisted soft switching PWM inverters suitable and adaptable for either utility ac 200V-rms or ac 400V-rms input lines. Under the newly-proposed soft switching PWM full-bridge dc-dc power converter circuits with high frequency transformer, all the active switches in the full-bridge arms and dc buslines side resonant snubber can actively achieve ZCS turn-on and ZVS turn-off transition

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commutation.

The steady state operating principles of the new soft switching high frequency linked PWM full-bridge dc-dc power converters tested here are described, along with its remarkable features. The experimental results of new prototypes of active resonant snubber assisted soft switching PWM full-bridge dc-dc power converters using IGBT power modules are also illustrated including power loss analysis as compared with those of the high frequency link hard switching PWM dc-dc power converter. The practical effectiveness of the proposed soft switching PWM full-bridge dc-dc power converters acceptable and suitable for high power applications which are designed for low voltage and large current output is substantially proved on the basis of experimental data of arc welding power supplies.

2. New DC-DC Converter Topology for Utility AC 200V

2.1 Circuit Description

Fig. 1 shows a high frequency transformer linked voltage source full-bridge soft switching PWM controlled dc-dc power converter circuit acceptable for utility ac 200V-rms, which is composed of a voltage source full-bridge high frequency PWM inverter with active switches in series with the dc busline and a single lossless snubbing capacitor in parallel with the dc busline, a high frequency transformer with secondary side center-tapped winding, dc reactor filter and dc load as arc welder. In the newly-developed dc-dc power converter circuit, the PWM controlled switches IGBTs; $Q_5(S_5/D_5)$ and $Q_6(S_6/D_6)$ and a lossless capacitor C are respectively added in series with the dc busline and in parallel with high and low side dc buslines of the voltage source full-bridge high frequency inverter composed of $Q_1(S_1/D_1)$, $Q_2(S_2/D_2)$, $Q_3(S_3/D_3)$ and $Q_4(S_4/D_4)$.

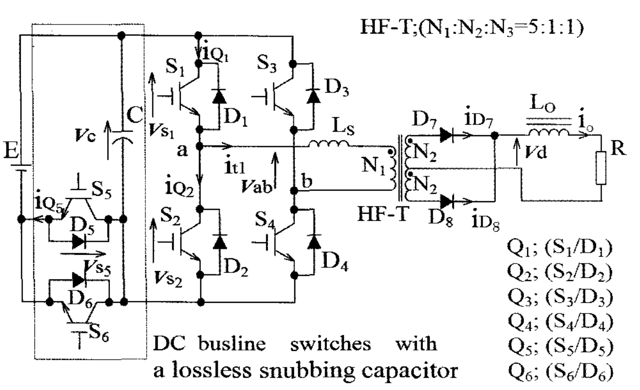


Fig. 1 novel type soft-switching PWM dc-dc converter with a center-tapped high frequency transformer for utility ac 200V-rms input source

2.1 Gate Pulse Timing Sequences

Fig. 2 depicts timing sequences of switching gate driving pulses to be provided to switches Q_1 - Q_4, Q_5 and Q_6. The gate voltage pulse signals with a certain dead time, which is delivered to Q_1 and Q_4 or Q_2 and Q_3 in the voltage source full-bridge inverter arms, just as in the case of the signal sequences of the conventional full-bridge inverter. Regarding the gate voltage pulse signals to the dc busline side series switches Q_5 or Q_6, the gate voltage pulse signals are synchronously applied to Q_5 or Q_6 at the same timing as the front edge gate voltage pulse signals to Q_1 and Q_4 or Q_2 and Q_3, respectively. As for the back edge gate voltage pulse signals to Q_5 or Q_6, the gate voltage pulses are delivered to Q_5 or Q_6 before the predetermined specific length of time t_δ to a certain time when the back edge gate voltage signals are respectively delivered to switches Q_1 and Q_4 or Q_2 and Q_3.

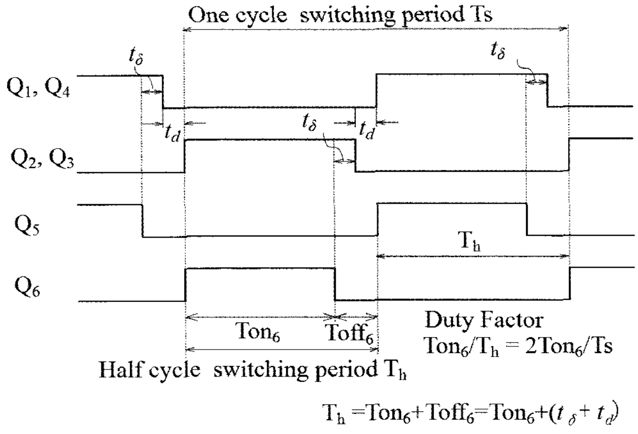


Fig. 2 Switching gate driving pulse

2.2 Circuit Operating Principle

Fig. 3 illustrates the relevant operating waveforms for the circuit with utility ac 200V-rms input during a complete switching period for the gate drive pulse timing sequences presented in Fig. 2. The operation modes in the half switching period T_h of this dc-dc converter circuit for the utility ac 200V-rms input are divided into seven operation sub-modes from mode 0 to mode 6 in accordance with operation timing transition points from t_0 to t_6. Its operation principle is described as follows for a steady state condition. The equivalent circuits corresponding to these sub-modes are indicated in Fig. 4.

1)Mode 0 : ~ t_0 Before time t_0, the switches Q_1, Q_4 and Q_5 are conducting. In this mode, the transformer primary side power is supplied to load R through its secondary circuit.

2)Mode 1 : t_0~ t_1 At time $t = t_0$, the series switch Q_5

in the dc busline side is to be turned off. At this time, the series switch Q_5 can turn off with ZVS because the current i_{S5} through Q_5 is immediately cut off with the aid of the lossless snubbing capacitor C. After time t_0, the voltage v_C across the lossless snubbing capacitor C begins to discharge toward zero voltage from E.

During this time, the voltage v_C across the lossless snubber capacitor C can be estimated as,

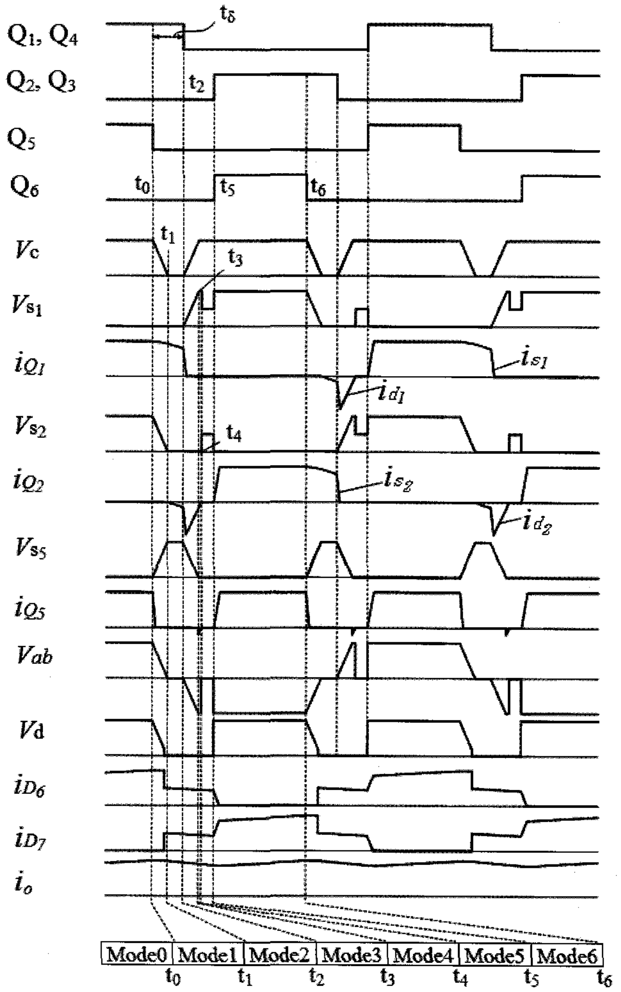
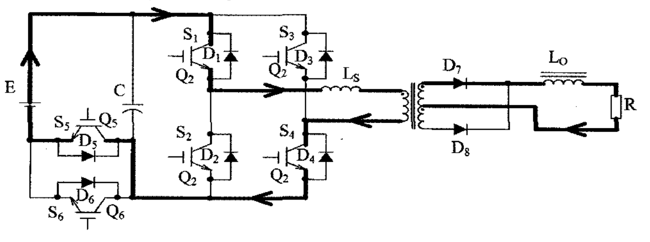
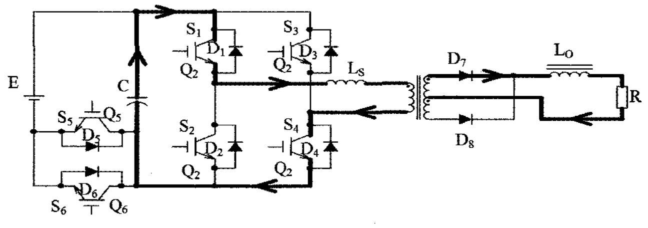


Fig. 3 Operating waveforms of dc-dc converter in Fig. 1 for 200V-rms ac utility grid during one cycle switching period

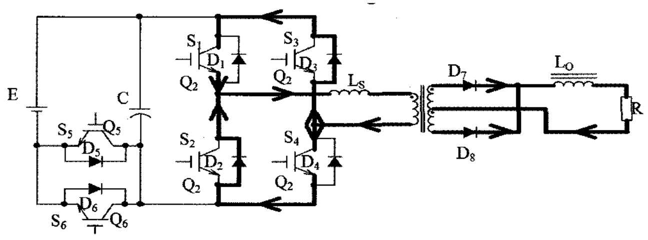
(a) Mode 0 ($\sim t_0$); Energy transferring mode to transformer secondary side during conduction period of Q_1,Q_4 and Q_5



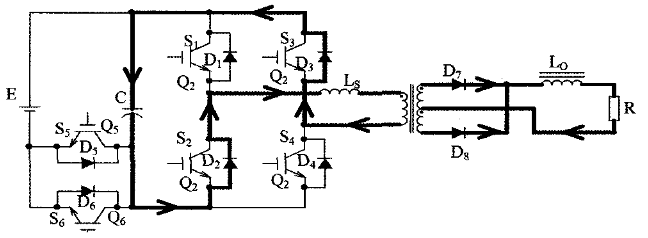
(b) Mode 1 ($t_0 \sim t_1$); Discharging mode of C when Q_5 is turned off



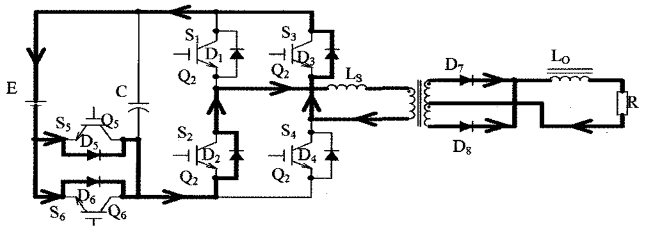
(c) Mode 2 ($t_1 \sim t_2$); Current circulation mode after discharge of C



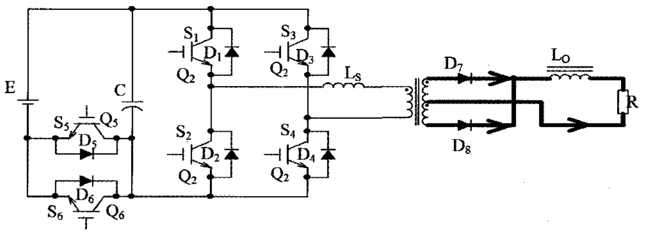
(d) Mode 3 ($t_2 \sim t_3$); Charging mode of C after Q_1 and Q_4 are turned off



(e) Mode 4 ($t_3 \sim t_4$); Capacitor voltage clamping mode in which *Vc* is kept to E



(f) Mode 5 ($t_4 \sim t_5$); No operation mode of transformer primary circuit



(g) Mode 6 ($t_5 \sim t_6$); Energy transferring mode delivered to transformer secondary side during a turn-on interval of Q_2, Q_3 and Q_6

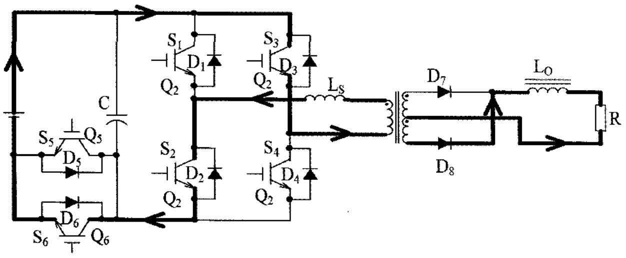


Fig. 4 Equivalent switching circuits for seven operation sub-modes in case of utility ac 200V-rms input

$$v_c(t) = E - (\, i_{t1}(t_o) / C \,)\, t \tag{1}$$

where, $i_{t1}(t_o)$ is a primary winding current of high frequency transformer at time $t = t_0$ and $i_{t1}(t_o)$ is approximately assumed as a constant value. From Eq. (1), the discharging time t_{dc} of current through the capacitor C until the voltage v_C becomes zero is given by,

$$t_{dc} = CE / \, i_{t1}(t_o). \tag{2}$$

For this newly-developed dc-dc converter circuit, an appropriate delay time t_δ indicated in Fig. 2 is designed so as to be a little longer than a certain time calculated from Eq. (2) under a condition of the maximum $i_{t1}(t_o)$. In this case, the switches Q$_1$ and Q$_4$ or Q$_2$ and Q$_3$ can completely achieve ZVS at a turn-off transition. If we need to widen complete ZVS operation range at the turn-off commutation for the switches Q$_1$ and Q$_4$ or Q$_2$ and Q$_3$, the optimum delay time t_δ should be varied in accordance with the value of the transformer primary current $i_{t1}(t_o)$. It is more effective to make use of a little small magnetizing inductance of the high frequency transformer.

3) *Mode 2 : t_1~ t_2* At time $t = t_1$, the voltage v_C is completely discharged to zero. In the interval from t_1 to t_2, the diodes D$_2$ of Q$_2$ and D$_3$ of Q$_3$ are naturally turned on. As a result, the current i_{t1} through the high frequency transformer primary winding flows through two circulation loops; L$_S$→D$_3$→S$_1$→L$_S$ and L$_S$→S$_4$→D$_2$→L$_S$.

4) *Mode 3 : t_2~ t_3* At time $t = t_2$, the switches Q$_1$ and Q$_4$ are turned-off simultaneously. At this time, the active switches Q$_1$ and Q$_4$ can be turned off with ZVS, because the voltage v_C across the lossless snubber capacitor has been already equal to zero and the diodes D$_2$ of Q$_2$ and D$_3$ of Q$_3$ as passive switches immediately begin to conduct.

At this mode, the condition of the capacitor C has been just charged up to be the same voltage as dc busline voltage E and can be estimated by Eq. (3), namely,

$$(1/2)CE^2 = (1/2)\, L_S\, (i_{t1}(t_o))^2. \tag{3}$$

However, as described in mode 6, the circuit parameters should be designed to meet a soft switching condition of $(1/2)CE^2 \leqq (1/2)L_S(i_{t1}(t_o))^2$ in order to achieve ZVS commutation at the turn-on transition of switch Q$_6$.

5) *Mode 4 : t_3~ t_4* Under a condition of $(1/2)CE^2 < (1/2)L_S(i_{t1}(t_o))^2$, the voltage v_C across the lossless snubber capacitor C is clamped to dc busline voltage E after the voltage v_C reaches the dc busline voltage E, because the diodes D$_5$ of Q$_5$ and D$_6$ of Q$_6$ are turned on and the energy stored in leakage inductance L$_S$ is returned back to the dc busline voltage source side.

6) *Mode 5 : t_4~ t_5* In this mode, all the operations in the primary side circuit of the high frequency transformer are stopped, except the voltages across the switches Q$_1$ and Q$_4$ decrease down to (1/2)E from the dc busline voltage E and the voltages across the switches Q$_2$ and Q$_3$ increase up to (1/2)E from zero due to parasitic parameters of the switches Q$_1$,Q$_2$, Q$_3$ and Q$_4$.

7) *Mode 6 : t_5~ t_6* At time $t = t_5$, the switches Q$_2$, Q$_3$ and Q$_6$ are turned on respectively. At this time, the switches Q$_2$, Q$_3$ and Q$_6$ can be turned on with ZCS because of a parasitic leakage inductance L$_S$ of the high frequency transformer. Especially, the switch Q$_6$ achieves ZVS/ZCS commutation at a turn-on transition because the voltage v_C is the same value as the dc busline voltage.

Thereafter, the aforementioned same operating processes are repeated during next half switching cycle T$_h$.

3. New DC-DC Converter Topology for Utility AC 400V

3.1 Circuit Description

Fig. 5 shows a high frequency transformer linked soft switching PWM dc-dc converter topology acceptable for utility ac 400V-rms input utilization. Under the dc-dc converter circuit used for utility ac 400V-rms input, the dc busline voltage source can be selected by the divided voltage sources E$_1$ or E$_2$, which are designed so as to be equal to E (E$_1$=E$_2$=E). The switch Q$_5$ in Fig. 1 is moved to the high side of the dc busline in Fig. 5. On the other hand, the switch Q$_6$ in Fig. 1 remains at the low side of the dc busline. The additional diodes, namely, D_9 and D_{10} with the mid point as shown in Fig. 5 are also inserted in parallel with the dc busline (E_1+E_2) between Q_5 or Q_6 and full-bridge inverter arms. And the center point between E_1 and E_2 is directly connected to the mid point between the diodes D_9 and D_{10}.

3.2 Operating Principle

The timing pattern sequences of switching gate driving pulses for utility ac 400V-rms input are exactly the same as that shown in Fig. 2 for the utility ac 200V-rms input.

Under the newly-developed dc-dc converter (see Fig. 5) suitable for the utility ac 400V-rms input, when the switches Q_5 or Q_6 are turned on and off alternately, half voltage E of dc busline voltage 2E is applied to the lossless snubbing capacitor C and full-bridge inverter arms. Therefore, the same IGBTs voltage rating as IGBTs in the dc-dc converter circuit (see Fig. 1) for utility ac 200V-rms input can be used even in the circuit for the utility ac 400V-rms input mains.

In addition to this remarkable feature, all the switches Q_1 - Q_4, Q_5 and Q_6 in the dc-dc converter circuit used for the utility ac 400V-rms input can also perform ZCS or ZVS/ZCS commutation at their turn-on transitions and perform ZVS commutation at turn-off transition as all the switches in the dc-dc converter circuit used for the utility ac 200V-rms input can achieve soft commutation.

The main difference between circuit operation with utility ac 200V input and circuit operation with utility ac 400V input is to be noted that the voltage v_C across the lossless snubbing capacitor C is not clamped to dc busline voltage 2E in case of the converter circuit for utility ac 400V-rms input mains.

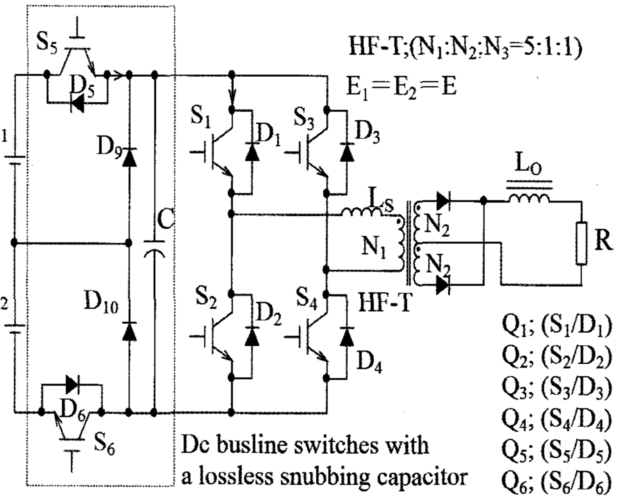


Fig. 5 A novel type soft switching PWM dc-dc converter with a center-tapped high frequency transformer for utility ac 400V-rms input source

4. Experimental Results and Discussions

4.1 Feasible System Implementations

The experimental setups for two types of soft switching PWM dc-dc converter circuits (see Fig. 1 and Fig. 5) with the high frequency transformer link for either the utility ac 200V-rms or ac 400V-rms input mains are implemented in Fig. 6 and Fig. 7, respectively.

In Table 1, the design specification and circuit parameters are listed respectively. Under both dc-dc converter circuits shown in Fig. 6 and Fig. 7, the 2 in 1 IGBT power modules 2MBI150TA-060 (I_C=150A, V_{CES}=600V) produced by Fuji Electric Device Technology Co. Ltd are used for all the active switches.

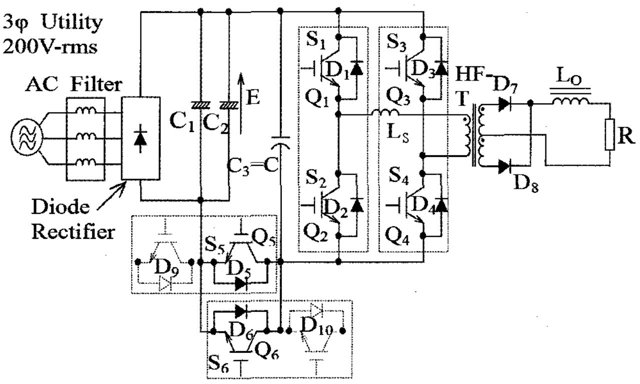


Fig. 6 Experimental setup for utility ac 200V-rms input

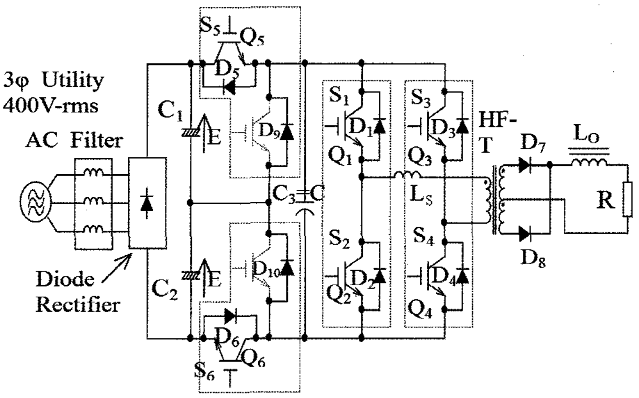


Fig. 7 Experimental setup for utility ac 400V-rms input

In Fig. 6, each IGBT with reverse conducting diode in the 2 in 1 IGBT power modules is used for the switches $Q_5(S_5/D_5)$ and $Q_6(S_6/D_6)$ and another IGBT with reverse conducting diode in the 2 in 1 IGBT power modules is not in use. In Fig. 7, each IGBT with reverse conducting diode and one reverse conducting diode in the 2 in 1 IGBT power modules are used for the active PWM switches $Q_5(S_5/D_5)$, D_9 and $Q_6(S_6/D_6)$, D_{10}. Observing Table 1, it is noted that all the components used in Fig. 6 and Fig. 7 are completely the same constants.

Table 1 Design specifications and circuit parameters

Item	Symbol	Value
Switching Frequency	f_S	40[kHz]
Leakage Inductance of High Frequency Transformer	L_S	2[μH]
Capacitance of Smoothing	C_1	1880[μH]
Capacitance of Smoothing	C_2	1880[μH]
Capacitance of Quasi Resonace Capacitor	C_3	0.1[μF]
Inductance of DC Reactor in Load Side	L_2	100[μH]
Load Resistance (Arc Welder)	R	0.1[Ω]
Maximum Load Current	I_o	350[A]
Turns Ratio of High Frequency Transformer Windings (Magnetizing Inductance L_m » Leakage Inductance Ls)	N_1: N_2:N_2	5:1:1

Fig. 8 demonstrates the exterior appearance of the experimental setup using CO_2/MAG arc welding power supply for both utility ac 200V-rms and ac 400V-rms input. The maximum output rating of this experimental setup is 36V, 350A (12.6kW).

Fig. 9 represents the assembled component appearance in the primary side high frequency inverter of soft switching PWM dc-dc converter circuit used in the experimental setup in Fig. 6. The only difference on the assembled components in the primary side high frequency inverter of dc-dc converter circuit between the experimental setups in Fig. 6 and in Fig. 7 should be the printed circuit board designed for the selective circuit connections.

The IGBT modules are mounted on the heat sink and connected by the printed circuit board on which the capacitors C_1, C_2 and C_3 =C are mounted, respectively. Connecting IGBTs, the capacitors C_1, C_2 and C_3 =C by the printed circuit board enables the minimization of the stray inductance at wiring connections among IGBTs, C_1, C_2 and C_3 =C. Actually, the minimum leakage inductance assembled by the printed circuit board connections is particularly an important factor on this newly-developed soft-switching PWM dc-dc converter with a high frequency link, because spike voltage across collector and emitter of IGBTs easily appears at a turn off switching dynamic transition if wiring stray inductances exists between the lossless snubbing capacitor C_3 =C and the IGBT switches in full-bridge high frequency inverter arms and dc busline active snubber.

4.2 Measured Switching Waveforms and Discussions

In experimental implementation, the measured switching operating waveforms for voltage and current under maximum output power specifications (36V, 350A) and circuit constants in Table 1 for utility ac 400V-rms input are depicted in Fig. 10 (a), (b), (c) and (d), respectively, when the switches Q_1 and Q_5 are turned on and turned off. Observing these waveforms in Fig. 10, the switches Q_1 and Q_5 are turned on with ZCS and turned off with ZVS. Especially, the switch Q_5 can be turned on with a complete soft switching commutation of ZVS/ZCS. However, at the turn-off mode transition processing for the switches Q_1 and Q_5, some power losses still exist due to the inherent tail current characteristic of the used IGBTs. These power losses depend upon the capacitance of lossless snubbing capacitors and selected IGBTs.

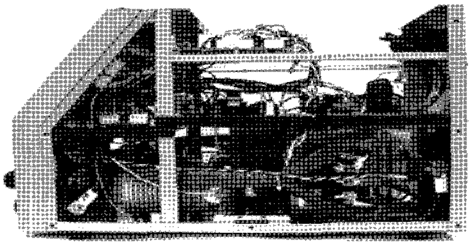


Fig. 8 Exterior appearance of experimental setup using CO2/MAG arc welding power supply

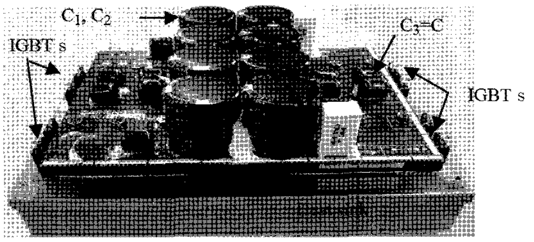
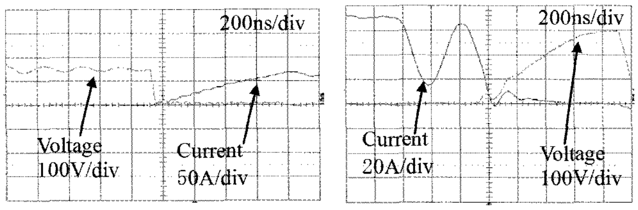
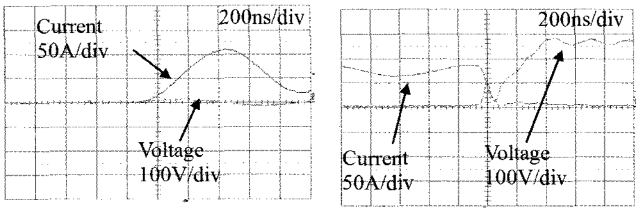


Fig. 9 Assembled component appearance in the transformer primary side high frequency inverter of soft switching PWM dc-dc converter circuit



(a) Turn-on switching waveforms for Q_1

(b) Turn-off switching waveforms for Q_1



(c) Turn-on switching waveforms for Q_5

(d) Turn-off switching waveforms for Q_5

Fig. 10 Measured switching voltage and current waveforms for the switches Q_1, Q_5 under new dc-dc converter circuit for utility ac 400V-rms input

4.3 Power Loss Analysis

Considering power loss analysis in Fig. 11, the total power losses of all the active switches in the full-bridge high frequency inverter arms including the switches Q_5 and Q_6 in series with dc busline for two types of newly-developed soft switching PWM dc-dc power converter circuits shown in Fig. 6 and Fig. 7 for utility ac 200V-rms and ac 400V-rms input mains are compared with those of all the switches with RC snubber for surge suppressing in the conventional hard switching PWM inverter type dc-dc power converters. When the switching frequency is designed for about 20 kHz, the total power losses for the soft switching PWM inverter type dc-dc converter and the hard switching PWM inverter type dc-dc converter are almost equal. When the switching frequency of the full-bridge high frequency inverter power stage using IGBTs is designed so as to be more than about 20 kHz, the more the switching frequency of the full-bridge inverter increases, the more this newly-developed dc-dc converter circuits can have remarkable advantages from the view points of power conversion efficiency and power density as compared with those of the conventional hard switching inverter type dc-dc converters.

In case the switching frequency is designed for 40 kHz or the dc current ripple frequency for 80 kHz, the total power losses for all the switches in two newly-developed soft switching PWM dc-dc converter circuits are estimated as 405 W in case of utility ac 200V-rms input and 465 W in case of ac 400V-rms input, respectively. Conversely, those of the conventional hard switching PWM inverter type dc-dc power converters are estimated as 785 W and 1100 W, respectively. These two types of power losses are about two times more power loss than the total power loss of newly-developed converter circuits in case of ac 200V-rms input mains as well as two times more power loss than that in case of ac 400V-rms input mains.

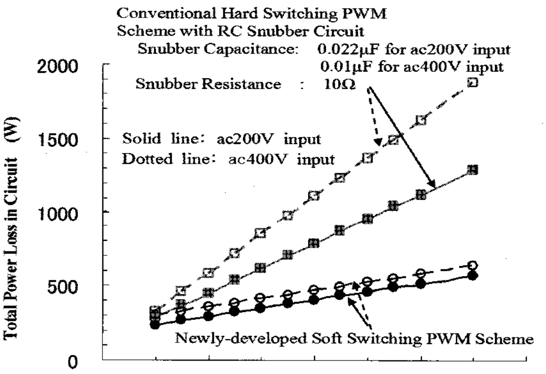


Fig. 11 Comparative power loss analysis between newly-developed soft switching PWM and conventional hard switching PWM dc-dc converters

4.4 Arc Welding Equipments

Under the experimental setup implementation of CO_2/MAG arc welding power supply shown in Fig. 8 using the two proposed types of dc-dc power converters, the volumetric size can be achieved as 59% less and its weight can be achieved as 47% less than those of the conventional CO_2/MAG arc welding power supply using hard switching PWM inverter type dc-dc power converters, because two newly-developed soft switching PWM full-bridge dc-dc power converter circuits enable the switch of IGBT power modules at 40 kHz frequency for the new generation CO_2/MAG arc welding power supply without increasing the power loss of all the active switches, while the inverter switching frequency of conventional arc welding power supply is designed so as to be 13 kHz for hard switching PWM operation. In addition to this, the arc welding dynamic performance can be much improved by high control responses in accordance with the high switching frequency operation.

5. Conclusions

In this paper, two new circuit topologies of voltage-fed active resonant snubber assisted soft switching PWM dc-dc power converters with leakage high frequency transformer links suitable and acceptable for utility ac 200V-rms or 400V-rms dual voltage input mains were presented originally along with their operating principles and experimental verifications. These converter topologies are composed of voltage source-fed full-bridge high frequency PWM inverters with additional series PWM switches in dc busline and a parallel lossless capacitive snubber between dc busline ports, a high frequency transformer with its center- tapped configuration at secondary side winding, a full-wave diode rectifier and a dc reactor in series with the load.

The main unique features of two newly-developed soft switching PWM dc-dc power converters can be summarized as follows;

(i) By adding a simple active resonant snubber circuit of additional switching devices in series with dc rail and a passive snubbing capacitor in parallel with dc rail assisted by high frequency transformer leakage component to the conventional full-bridge hard switching PWM inverter, all the semiconductor switching devices could achieve ZVS turn-off and ZCS turn-on soft commutation. The total power losses for all the active switching devices for two new soft switching PWM dc-dc power converters using IGBT power modules could be decreased when the switching frequency of the high frequency inverter power stage is selected so as to be more than 20 kHz.

(ii) Two newly-developed dc-dc power converters could be used for both utility ac 200V-rms and ac 400V-rms dual voltage input line mains without replacing any power semiconductor switching devices and high frequency transformers by means of changing lead wiring connections only. Thus, two newly-developed soft-switching PWM dc-dc converters with a high frequency transformer have a cost effective applicability and flexibility for the utility ac 200V/400V input voltage.

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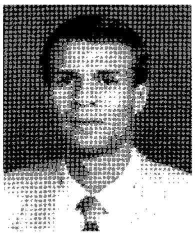

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