A Novel type of High-Frequency Transformer Linked Soft-Switching PWM DC-DC Power Converter for Large Current Applications

Keiki Morimoto*, Nabil A. Ahmed†, Hyun-Woo Lee and Mutsuo Nakaoka****

Abstract - This paper presents a new circuit topology of DC busline switch and snubbing capacitor-assisted full-bridge soft-switching PWM inverter type DC-DC power converter with a high frequency link for low voltage large current applications as DC feeding systems, telecommunication power plants, automotive DC bus converters, plasma generator, electro plating plants, fuel cell interfaced power conditioner and arc welding power supplies. The proposed power converter circuit is based upon a voltage source-fed H type full-bridge high frequency PWM inverter with a high frequency transformer link. The conventional type high frequency inverter circuit is modified by adding a single power semiconductor switching device in series with DC rail and snubbing lossless capacitor in parallel with the inverter bridge legs. All the active power switches in the full-bridge inverter arms and DC busline can achieve ZVS/ZVT turn-off and ZCS turn-on commutation operation. Therefore, the total switching losses at turn-off and turn-on switching transitions of these power semiconductor devices can be reduced even in the high switching frequency bands ranging from 20 kHz to 100 kHz. The switching frequency of this DC-DC power converter using IGBT power modules is selected to be 60 kHz. It is proved experimentally by the power loss analysis that the more the switching frequency increases, the more the proposed DC-DC converter can achieve high performance, lighter in weight, lower power losses and miniaturization in size as compared to the conventional hard switching one. The principle of operation, operation modes, practical and inherent effectiveness of this novel DC-DC power converter topology is proved for a low voltage and large current DC-DC power supplies of arc welder applications in industry.

Keywords: DC-DC power converter, High frequency transformer link, Quasi-resonant soft-switching PWM, Active Snubber by DC rail switch and lossless capacitor, Low voltage large current DC power supply, Arc welding power supply

1. Introduction

Generally, the high performance isolated DC-DC power conditioning converter type semiconductor switching mode power supplies ranging from several kW to about 30 kW or more have been practically required for DC feeding systems, telecommunication power plants, automotive DC bus converters, plasma generator, electro plating plants as well as promising fuel cell interfaced power conditioner and the power supplies of TIG and MIG arc welding applications in industry. Many downsized arc welding high frequency switching mode high power supplies using power MOSFETs, IGBTs and SITs with the aid of transformer resonant, quasi-resonant and multi-resonant circuit topologies have been begun to be developed for large current applications and partially put into practice. However, high frequency resonant power converter topologies on the basis of series resonant, parallel resonant, series and parallel resonant circuits have been adopted for the low voltage and large current DC switch mode power supplies with DC output power rating not more than 10kW due to the effective cost and difficulty to condition the DC output voltage with high power conversion efficiency. Therefore, high frequency pulse width modulated switching mode DC-DC power converters with a high frequency transformer, which is based upon hard-switching PWM voltage source-fed full-bridge inverter circuit operating in the switching frequency of 10 kHz, have been considered widely for output power supplies designed for low voltage-large current applications as arc TIG/MIG welding machines in industry. Under this technological situation, high performance and high efficiency DC-DC power converter with an isolated transformer link should be practically developed for higher power arc welder more than 10 kW and high switching frequency bands ranging from 20 kHz to 100 kHz or more.

In recent years, saturable reactor assisted zero voltage

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switching (ZVS) PWM voltage source-fed full-bridge high-frequency inverter linked DC-DC power converter [1], lossless capacitors and transformer parasitic inductive components assisted soft-switching DC-DC power converter with phase-shifted modulation control scheme in secondary side of high frequency transformer [2]-[6] have been developed and evaluated from practical point of view. These power converter circuit topologies are more suitable and acceptable for handling output power more than about several kilo watts, especially for high voltage and low current DC output applications for new energy generation and storage devices related power supplies. However, the secondary magnetic switches or transformer secondary side active power semiconductor switching devices in these power converter circuit topologies cause large conduction loss when these power converters are adopted for low voltage and large DC output current applications as arc welding and electroplating power supplies. Thus, for the low voltage and large DC output current applications required high performance and high efficiency applications, an isolated voltage source-fed soft switching PWM DC-DC power converter with active power switches in the primary side of high frequency transformer has been considered more suitable and practical so far by the authors from the converter power losses and the overall efficiency [7].

This paper presents a novel circuit topology of voltage source-fed full-bridge type soft-switching PWM DC-DC power converter with specially-designed high frequency planar transformer, which is composed of conventional voltage source-fed full-bridge high frequency PWM inverter type [1]-[5] and an additional power semiconductor switching device; IGBT in series with DC busline and only single lossless capacitive snubber in parallel with two bridge legs of the high frequency inverter. In the proposed high frequency transformer link soft switching PWM DC-DC power converter, all the active power switches in four full-bridge arms and active power switch in series with DC busline can effectively achieve ZVS/ZVT turn-off soft switching commutation with the aid of the lossless capacitive snubber, and Zero current soft switching (ZCS) turn-on transition with the aid of the high frequency transformer leakage inductance as a lossless inductor.

The principle of operation and operation modes of the DC rail switch and lossless quasi-resonant capacitor snubber-assisted soft switching PWM DC-DC power converter with a thinner high frequency planar transformer link are described in details with its remarkable operating features. The experimental operation results as well as the simulation ones of this new voltage source soft switching PWM DC-DC high power converter topology using the latest IGBT power modules in which 60 kHz thinner high frequency planar transformer is used newly are illustrated and evaluated including power loss analysis as compared with those of high frequency transformer isolated link voltage source hard-switching PWM DC-DC power converter used commonly. The practical effectiveness of the proposed high frequency transformer link soft switching PWM DC-DC power converter designed for TIG and MIG arc welding applications which require low voltage of 32 V and large output current of 300 A are actually proved on the basis of simulation and experimental data in this paper.

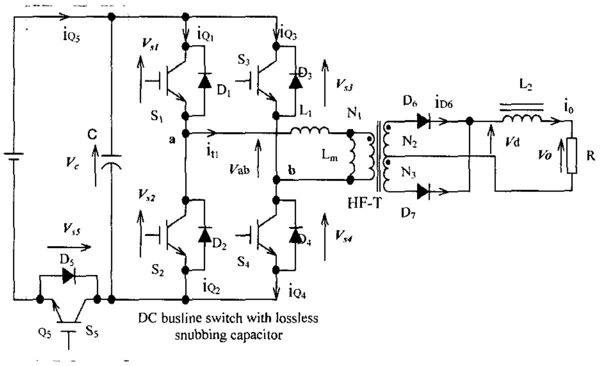


Fig. 1 A novel proposed soft-switching PWM DC-DC converter.

2. A Novel Soft Switching DC-DC Converter

The novel soft switching PWM DC-DC power converter using H-shaped voltage source single-phase full-bridge high frequency PWM IGBTs inverter circuit and a high frequency planar transformer link with secondary center taped winding, a single series switch in DC busline and a single lossless snubbing capacitor in parallel with DC busline is shown in Fig. 1. A single active PWM switch $Q_5(S_5/D_5)$; reverse conducting IGBT type (RC-IGBT); is additionally inserted in series with the DC power busline connecting the supply voltage source E to the H full-bridge type high frequency inverter and a single lossless snubbing capacitor C is also additionally inserted in parallel to the active PWM switch Q_5 and the H full-bridge type high frequency inverter. The main active power switches $Q_1(S_1/D_1)$ and $Q_4(S_4/D_4)$ in diagonal bridge arms or $Q_2(S_2/D_2)$ and $Q_3(S_3/D_3)$ in another diagonal bridge arms of the voltage source high frequency inverter section can be turned on and turned off in accordance with specifically modified PWM control processing circuit similar to conventional H full-bridge type hard-switching PWM inverter. Under the newly proposed soft switching DC-DC power converter, the active power switches Q_1~Q_4 in the full-bridge type inverter can perform ZVS turn-off transition due to the presence of the active PWM switch Q5 and the lossless snubbing capacitor C, which is completely discharged before the active power switches Q_1 and Q_4 or Q_2 and Q_3 in voltage source-fed full-bridge type inverter diagonal bridge arms are turned off simultaneously. In addition, the inverter bridge side switches can also perform ZCS at a turn-on switching transition with the aid of parasitic inductance L_l, observed as a parasitic leakage inductance of specially-designed high frequency type transformer HF-T.

As for the active PWM switch Q_5 inserted in series with the DC busline side, the PWM controlled switch can achieve ZVS/ZVT at a turn-off mode transition due to the presence of the single lossless snubbing capacitor C in parallel to the DC buline. This active PWM switch Q5 can also achieve ZVS at a turn-on mode transition due to the single lossless snubbing capacitor C as quasi-resonant snubber, which has been charged up to the same voltage as the source of DC power supply E by the energy storage in the leakage inductance L_l after the diagonal bridge arm switches are turned off.

With the newly proposed soft switching PWM DC-DC converter circuit, although the conduction power loss due to the additional power switch may make the total conduction power loss increase a little as whole DC-DC power converter system, its total turn-off switching losses can be substantially decreased with the optimum soft switching operation manner with aid of DC busline series active power switch Q_5 and the DC busline parallel lossless snubbing capacitor C.

3. Principle of Operation

3.1 New Pulse Pattern of Gate Voltage Timing Sequences

Fig. 2 shows the timing pattern sequences of switching gate driving voltage pulses. The gate voltage pulse signals for the switches Q_1 and Q_4 or Q_2 and Q_3 in the voltage source-fed full-bridge inverter arms are basically the same as PWM signal timing sequences with a small dead time of conventional full-bridge PWM inverter. The turn-on gating voltage pulse signal is synchronously applied to the DC busline series active switch Q_5 with the turn-on gating signals of the diagonal inverter switches Q_1 and Q_4 or Q_2 and Q_3. However, for safe soft switching operation the series switch Q_5 must be turned off before the turn-off signals are diagonally applied to the bridge arm inverter switches by a an enough time to allow the DC busline capacitor C to fully discharged. In other words, the turn-off pulse signals are diagonally applied to the switches Q_1 and Q_4 or Q_2 and Q_3 after the turn-off gate signal is supplied to the DC rail switch Q_5 with a predetermined length of time t_d. The time t_d plays the key factor of the soft switching operation.

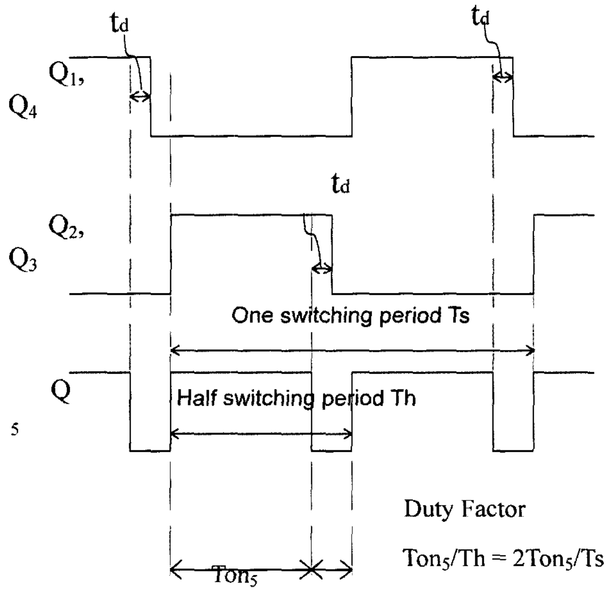


Fig. 2 Timing sequences of switching gate driving pulses.

3.2 Operation Modes and Switching Equivalent Circuits

Fig. 3 illustrates the relevant steady-state operating voltage and current waveforms during a complete switching period for the pulse pattern of gate drive timing sequences depicted in Fig. 2. The operation circuit modes are divided into eleven switching operation modes during each switching cycle. The first six switching modes in half switching cycle from mode 0 to mode 6 in accordance with an operational timing process from t_o to t_6 will be explained in details in this section. The other six switching modes are similar to these modes with the conduction transferred to the other active switches. The equivalent switching circuits corresponded to each switching mode transition are demonstrated in Fig. 4. The operation principle in each mode is described in the following,

Mode 0: ~ t_0

In this mode, the active power switches Q_1, Q_4 and Q_5 are assumed conducting simultaneously. The current i_{t1} flows through the primary winding of high frequency transformer HF-T, the current i_{s1} flows through the diagonal switches; Q_1, Q_4 and the current i_{s5} flows through the series switch Q_5. During this period, all the currents are equal and the voltage v_c across the lossless snubbing capacitor C is completely the same as the DC busline voltage E. The high speed diode D_6, in the rectifier circuit connected to the high frequency transformer secondary-side winding is turned on and it transfers the primary side energy conveniently to the load resistance R through the loop of rectifier diode D6, DC smoothing filter reactor L_2 and the secondary winding of high frequency transformer. Now, it is safe at any time to turn-ff the DC rail series switch Q_5 with ZVS.

Mode 1: $t_0 \sim t_1$

At time t_o, the turn-off gate pulse signal in Fig. 2 is applied to the DC rail series switch Q_5. At this time, this series switch Q_5 is efficiently turned-off with ZVS and the current i_{s5} through the series switch Q_5 is immediately transferred to the lossless snubbing capacitor C. The voltage v_c across the losses snubber capacitor C discharges gradually toward zero voltage.

In the circuit connected to the high frequency transformer secondary-side winding, the rectifier diode D6 is still conducting supplied the energy to the load.

Observing the equivalent circuit in mode1, the voltage v_c across the lossless snubber capacitor C is given by

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

From (1), the discharging time t_x of the lossless snubber capacitor C until the voltage v_c becomes zero is estimated as

$$t_x = CE/i_{t1} \qquad (2)$$

From (2), the more the current i_{t1} though the primary side winding of high frequency transformer HF-T is high, the more discharging time t_x for lossless snubber capacitor C is short. Under this newly-developed DC-DC power converter circuit, the delay time t_d indicated in Fig. 2 is designed as to be longer than the discharging time t_x under the condition of maximum output current i_{t1} to achieve complete ZVS turn-off switching mode commutation of the inverter switches Q_1 and Q_4 or Q_2 and Q_3.

Mode 2 : $t_1 \sim t_2$

When the voltage v_c across the lossless snubber capacitor C becomes zero at time t_1, mode 1 shifts to mode 2. In the interval from t_1 to t_2, the antiparallel diodes D_2 of Q_2 and D_3 of Q_3 become forward baising and are turned on. The current i_{t1} through the high frequency

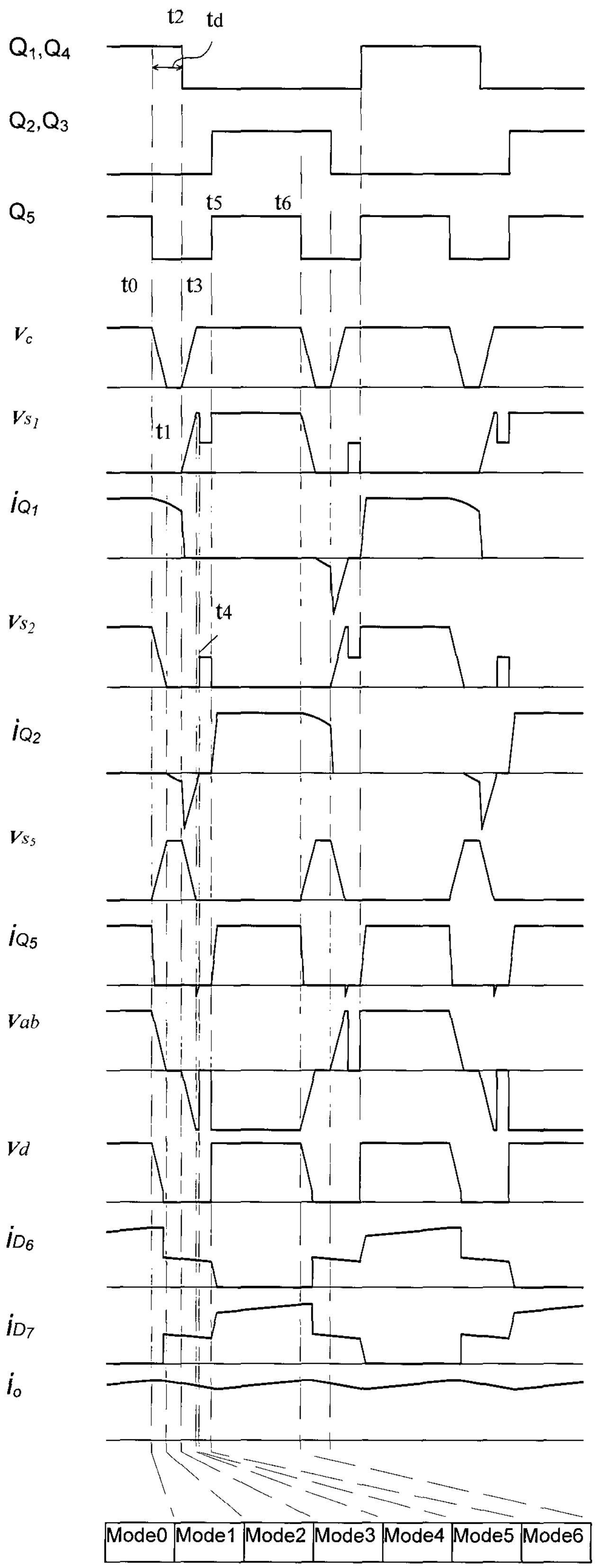


Fig. 3 Operating voltage and current waveforms during one half switching cycle.

transformer primary side winding flows through two circulating loops formed by L_1, D_3, S_1, L_1 and L_1, S_4, D_2, L_1 as shown in Fig. 4(c).

In the secondary circuit of the power converter, the diodeD$_7$ becomes forward biasing and turned-on and to share the load current with the diodes D_6.

Mode 3 : $t_2 \sim t_3$

At time t_2, the turn-off gate pulse signals are applied to the diagonal bridge arm switches Q_1 and Q_4. At this time, these active switches Q_1 and Q_4 can be turned off with ZVS because the voltage v_c has been already reached zero and the antiparallel diodes D_2 of Q_2 and D_3 of Q_3 are continue conducting. After this, the lossless snubbing capacitor C starts charging up to the same voltage as the DC busline voltage source E. In the power converter circuit connected to the high frequency transformer secondary side center tapped windings, the rectifier diodes D6 and D7 are still in conduction mode.

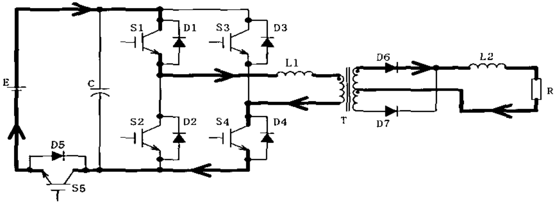
At this operating mode, the condition that the lossless snubbing capacitor C is just charged up to the same voltage as the DC busline voltage source E can be estimated as follows

$$(1/2)CE^2 = (1/2)L_1(i_{t1})^2 \qquad (3)$$

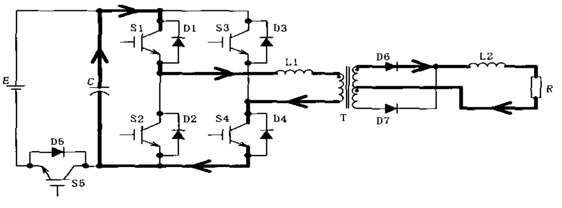
Therefore, the circuit parameters should be designed to meet the condition of *1/2)CE^2* $\leq$ *(1/2)L$_l$(i$_{tl}$)* in order to achieve ZVS soft commutation at turn-on switching transition of the DC rail series switch Q5.

When the snubbing capacitor voltage v_c is completely charged up to the DC busline voltage E, mode 3 shifts to mode 4.

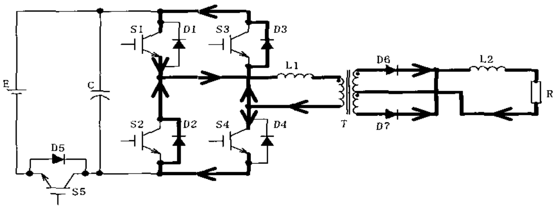
(a) Mode0 (~t_0); Energy transfer to secondary during turn-on of Q_1,Q_4 and Q_5.



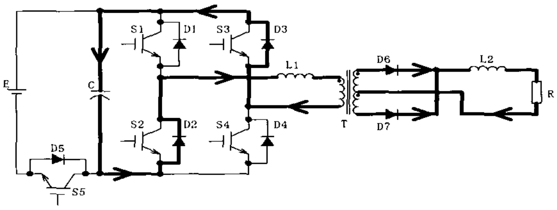
(b) Model (t_0\ ~ t_1); Discharge of C after Q_5 being turned off.



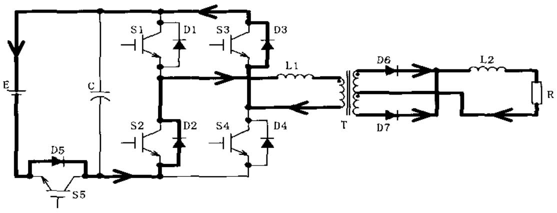
(c) Mode2 (t_1 ~ t_2); Current circulation after discharge of C.



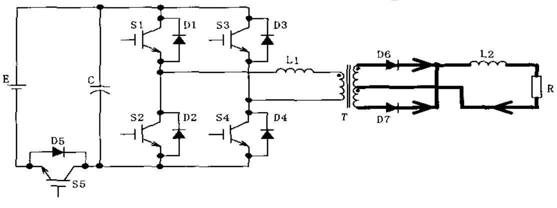
(d) Mode3 (t_2 ~ t_3); Charge of C after Q_1, Q_4 being turned off.



(e) Mode4 (t_3 ~ t_4); V_C being clamped by E.



(f) Mode5 (t_4 ~ t_5); No operation in primary circuit.



(g)Mode6 (t_5 ~ t_6); Energy transfer to secondary during turn-on of Q_2,Q_3 and Q_5.

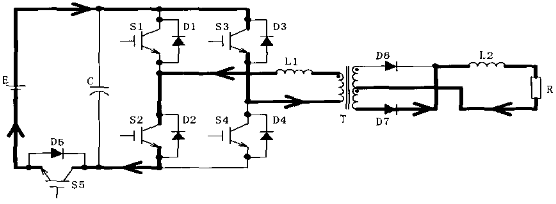


Fig. 4 Equivalent circuits during operation modes.

Mode 4 : $t_3 \sim t_4$

When the snubbing capacitor voltage v_c reaches the DC busline voltage E, it will be clamped to the E due to the conduction of the antiparallel diode D_5 of DC rail series switch Q_5, the energy stored in the leakage inductance L_1 of the high frequency transformer is returned back to the DC busline voltage source E. The rectifier diodes D6 and D7 are still conducting carrying the load in the power converter circuit connected to the high frequency transformer secondary side center-tapped windings.

Mode 5 : $t_4 \sim t_5$

This mode starts when the stored energy in the transformer leakage inductance is completely returned back to the supply. In this operating mode, all the switching mode operations are stopped in the circuit including primary side winding of the high frequency transformer, except the voltages across the diagonal power switches Q_1 and Q_4 decrease down to (1/2)E and the voltages across another diagonal power switches Q_2 and Q_3 increase up to (1/2)E due to the parasitic circuit parameters of the switches Q_1, Q_2, Q_3, and Q_4 in the inverter bridge arms. In the power converter circuit connected to the high frequency transformer secondary side center-tapped windings, the load current takes its pass through the rectifier diodes D_6 and D_7 which are still in conduction mode.

Mode 6 : $t_5 \sim t_6$

At time t_5, the turn-on gate pulse signal timing sequences indicated in Fig. 2 are applied to the active power switches Q_2, Q_3 and Q_5. At this time, the second diagonal switches Q_2 and Q_3 of the PWM inverter can be turned on with ZCS mode transition due to the parasitic leakage inductance L_l of the high frequency transformer HF-T. In this operation mode, the DC rail series switch Q_5 in the busline achieves complete soft switching commutation of ZVS/ZCS at turn-on switching transition, since the voltage v_c has the same value as the DC power busline voltage source E. In the secondary circuit, only the rectifier diode D_7 is conducting and the high frequency transformer primary side energy is supplied to the load resistance R through the loop of the rectifier diode D_7, DC smoothing filter reactor L_2, secondary side center-tapped windings of the high frequency transformer.

Thereafter, the operation processes for the second group switches Q_2, Q_3 and Q_5 become the same as that for the first group switches Q_1, Q_4 and Q_5, described before, and the operation processes will be continuously repeated in periodic sequence.

4. Experimental Results and Discussions

4.1 Experimental System Implementations

The experimental setup circuit of the proposed soft switching PWM DC-DC power converter with 60 kHz planar transformer with center-tapped windings is shown in Fig. 5. In the feasible setup implementation, the maximum output voltage and current ratings are 32 V, 300 A, respectively. The DC bus line voltage E is obtained from a three-phase controlled rectifier connected to three-phase ac supply. The design specifications and circuit parameters are indicated in Table. 1.

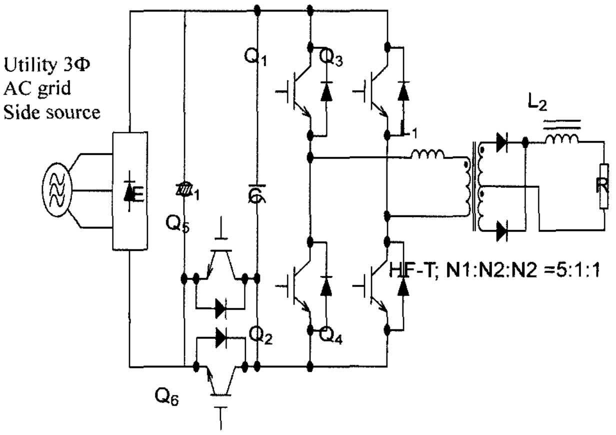


Fig. 5 Experimental setup circuit implementation.

Table 1 Design specifications and circuit parameters.

Item	Symbol	Value
DC Busline Voltage	E	280 [V]
Inverter Switching Frequency	F_s	60 [kHz]
Switching Period	T_s	16.7 [μs]
Leakage Inductance of HF-T	L_l	2.0 [μF]
Lossless Snubbing Capacitor	$C_2=C$	0.1 [μF]
Inductance of Filter Reactor	L_2	100 [μH]
Load Resistance	R	0.07 [Ω]
Rated Load Current	I_0	300 [A]
Rated Load Voltage	V_0	32 [V]
Turns Ratio of HF-T	N_1:N_2:N_2	5:1:1
Remarks		
IGBTs Doides	S1-S4 D1-D4	CM100DUS-12F Vces=600V,Ic=100A(Tc=25°C)
	S5-S6 D1-D4	CM75DU-12H Vces=600V,Ic=75A(Tc=25°C)

Two in one IGBT power modules CM100DUS-12Fs produced by Mitsubishi Electric Co. Ltd. are used for the active power switches $Q_1(S_1/D_1)$, $Q_2(S_2/D_2)$ and $Q_3(S_3/D_3)$, $Q_4(S_4/D_4)$ in the inverter bridge arms. In addition, a two in one IGBT power modules CM75DU-12Hs are actually used for two active PWM switches Q5(S5/D5) and Q6(S6/D6) (see Fig. 5) in series with DC busline. The DC rail switches Q_5 and Q_6 in parallel are effectively necessary for realizing the same operating frequency as the high frequency inverter operating frequency.

In the switching mode-based equivalent circuit shown in Fig. 5, the series power switch Q5 in DC rail is switched during the operation of the first diagonal switches Q1 and Q4 and the DC rail series switch Q6 is also switched during the operation of the second diagonal switches Q2 and Q3.

The whole appearance of experimental setup of TIG arc welding power supply using newly-developed soft switching PWM DC-DC power converter with a high frequency transformer is demonstrated in Fig. 6. The maximum output specifications of the experimental setup produced here is 32 V and 300 A. Under the TIG arc welding soft switching PWM power supply used in industry as shown in Fig. 6, the diametric size is substantially 50% less and its weight is actually 48% less than these of the conventional hard switching PWM power supply developed previously for TIG arc welder in industry.

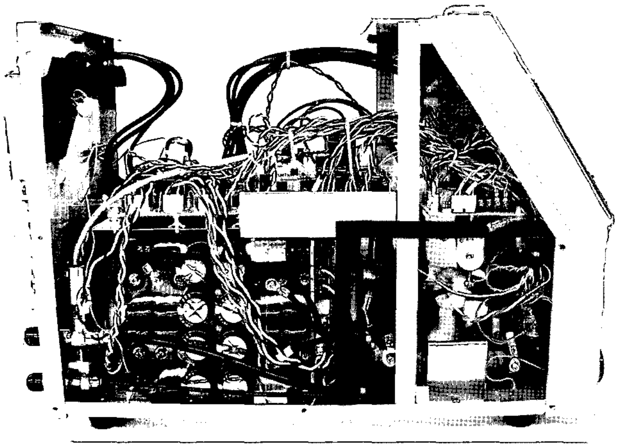


Fig. 6 Whole appearance of TIG arc welding power supply using newly-developed PWM DC-DC power converter.

Fig. 7 represents the appearance of assembled power converter printed circuit board in the primary side of the frequency transformer high frequency. Four IGBT modules are mounted on the heat sink with forced air cooling and connected by the printed circuit board on which the DC smoothing capacitors C1 and the lossless snubbing capacitor C are mounted on the printed board. Connecting IGBTs, the DC smoothing capacitor C1 and the lossless snubber capacitor C by the printed circuit board enables to minimize the stray inductance for laminated busbar assembled connections among IGBTs, C and C1.

Fig. 8 shows the exterior appearance for the planar type high frequency transformer used for TIG arc welding power supply in Fig. 7. This high frequency transformer is extremely small and very thin because of 60 kHz high switching frequency operation design and cupper foil winding, which punched through by molding design and manufactured specially for this type of high frequency transformer as its primary and secondary side center-tapped windings.

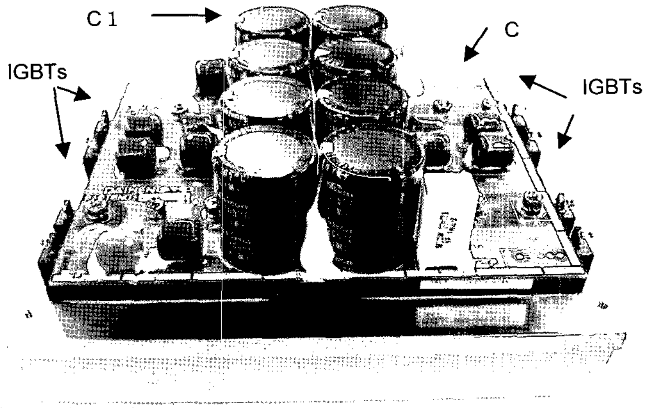


Fig. 7 Appearance of assembled component in high frequency transformer primary side circuit.

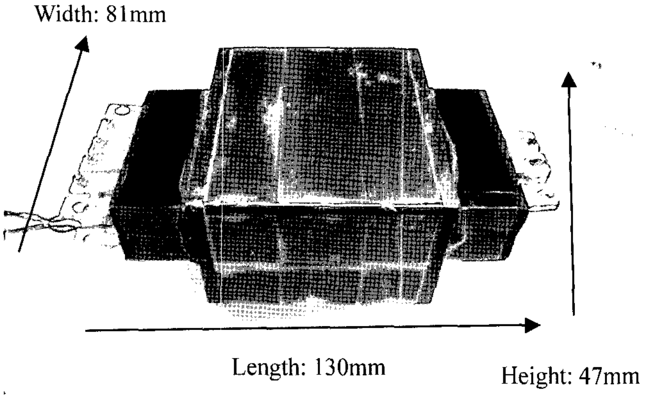
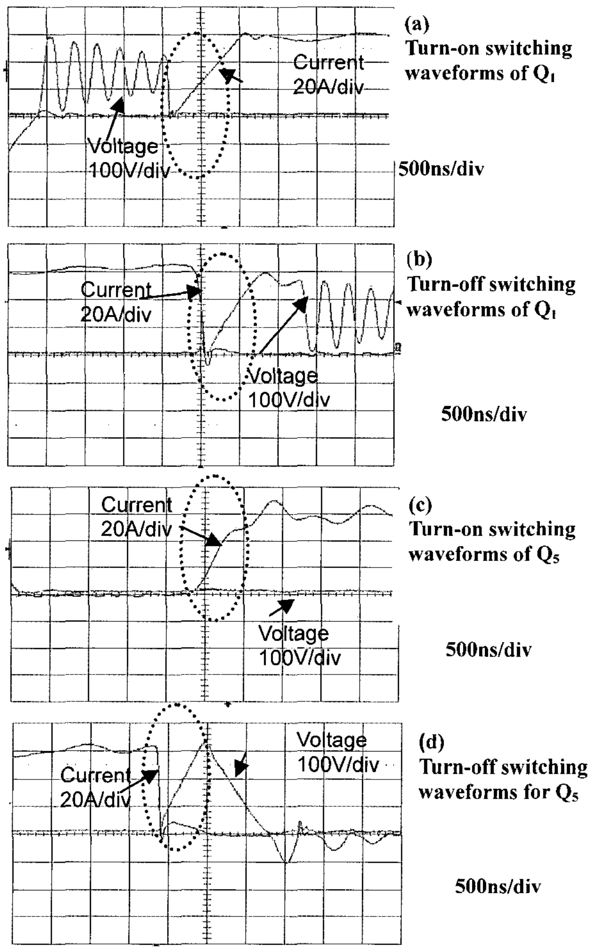


Fig. 8 Exterior appearance and size of planar type high frequency transformer.

4.2 Measured Voltage and Current Switching Waveforms and Converter Evaluations

The operating voltage and current switching waveforms of the proposed soft switching PWM DC-DC power converter are shown in Fig. 9 (a) and (b) when the inverter bridge arm switch Q1 is turned on and turned off, respectively. Observing these waveforms, the switch Q1 is turned on with ZCS and is completely turned off with ZVS. The operating voltage and current switching waveforms are shown respectively in Fig. 9 (c) and (d) when the DC rail switch Q5 is turned on and turned off. From the operating waveforms shown in Fig. 9 (c) and (d), the DC rail series switch Q5 is ideally turned on with ZVS/ZCT and is confirmly turned off with ZVS. However, at the turn-off switching transition for the switches Q1 and Q5, some power losses still exist due to inherent tail current characteristics of IGBT power modules.



(a) Turn-on switching waveforms of Q_1

(b) Turn-off switching waveforms of Q_1

(c) Turn-on switching waveforms of Q_5

(d) Turn-off switching waveforms for Q_5

Fig. 9 Measured switching voltage and current waveforms for active power switches Q_1 and Q_5.

4.3 Comparative Results on Power Loss Analysis

Fig. 10 shows the total power loss with the switching frequency of all the active power switches including the DC rail switches Q5 and Q6 in the newly-developed DC-DC power converter circuit is compared with the total power loss of all the switches in conventional hard-switching PWM inverter type. When the switching frequency is 10 kHz, the total power losses for both inverter type DC-DC power converter circuits are almost equal. The switching frequency of the proposed soft switching DC-DC converter is designed to be 60 kHz under the considerations of IGBTs characteristics; more than 18 kHz because of acoustic noise viewpoint. The more the switching frequency of full-bridge inverter stage increases, the more this newly-developed soft switching PWM DC-DC power converter circuit system can get unique advantages in the power conversion efficiency, power density and downsizing as compared with the conventional hard-switching PWM inverter type DC-DC power converter.

Thus, in case the switching frequency of inverter stage is selected to be 60 kHz, the total power loss in the proposed soft switching PWM DC-DC power converter circuit is estimated 280W and the power loss of the conventional hard-switching PWM inverter type DC-DC power converter circuit is 520W. Furthermore, the R-C snubber circuit to block the voltage and current switching surges is necessarily designed for the conventional hard-switching PWM DC-DC power converter. Therefore, the total system power loss for the conventional hard-switching PWM DC-DC power converter circuit including the power losses of snubber circuit components is actually estimated to be about 900W. This power loss in the hard switching power converter is three times more than the total power loss of newly-developed soft switching PWM DC-DC power converter circuit.

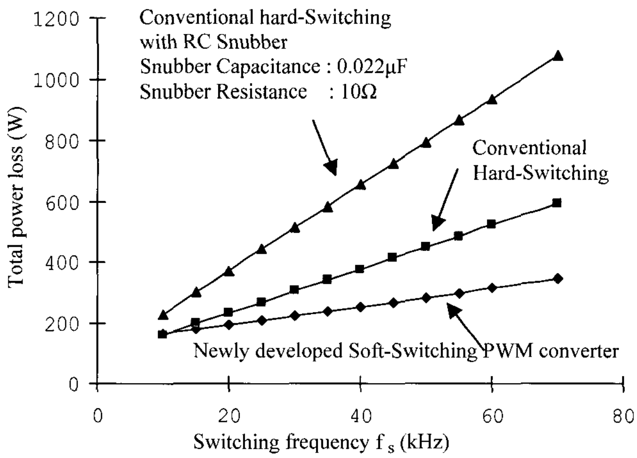


Fig. 10 Comparative power loss.

5. Conclusions

A novel circuit topology of soft-switching PWM DC-DC power converter with a high frequency planar transformer link has been presented in this paper for low voltage and large current of 32V and 300A output specifications as TIG arc welding equipment in industry. The practical effectiveness of the newly proposed DC-DC power converter operating under stable soft-switching PWM control scheme were substantially proved from a practical point of view. Based on the operated voltage and current waveforms, all active switching devices can achieve soft switching commutation of ZVS/ZVT turn-off and ZCS turn-on switching mode transitions. The power loss analysis of the proposed soft switching PWM DC-DC power has been evaluated and discussed as compared with the conventional hard-switching PWM DC-DC power converter with high frequency link. The more the switching frequency increases, the more the proposed power converter has remarkable advantageous points such as the high power conversion efficiency, high power density and high performances and energy saving as compared with the conventional hard-switching one. Therefore, downsized and lighter weighted TIG/MIG arc welding power supplies using this newly-developed power converter have been achieved and have already been put into the practical market in industry.

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