A Novel Prototype of Duty Cycle Controlled Soft-Switching Half-Bridge DC-DC Converter with Input DC Rail Active Quasi Resonant Snubbers Assisted by High Frequency Planar Transformer

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Abstract - This paper presents a new circuit topology of active edge resonant snubbers assisted half-bridge soft switching PWM inverter type DC-DC high power converter for DC bus feeding power plants. The proposed DC-DC power converter is composed of a typical voltage source-fed half-bridge high frequency PWM inverter with a high frequency planar transformer link in addition to input DC busline side power semiconductor switching devices for PWM control scheme and parallel capacitive lossless snubbers. The operating principle of the new DC-DC converter treated here is described by using switching mode equivalent circuits, together with its unique features. All the active power switches in the half-bridge arms and input DC buslines can achieve ZCS turn-on and ZVS turn-off commutation transitions. The total turn-off switching losses of the power switches can be significantly reduced. As a result, a high switching frequency IGBTs can be actually selected in the frequency range of 60 kHz under the principle of soft switching. The performance evaluations of the experimental setup are illustrated practically. The effectiveness of this new converter topology is proved for such low voltage and large current DC-DC power supplies as DC bus feeding from a practical point of view.

Keywords: Arc welding machine, DC-DC power converter, DC rail active quasi-resonant snubbers, Divided voltage source type, High frequency transformer link, Soft switching PWM

1. Introduction

1.1 Research Background

Recently, a saturable inductor assisted ZVS-PWM full-bridge high-frequency inverter link DC-DC power converter [1], and 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 [2-4] have been developed and evaluated. These power converter circuit topologies are suitable for handling high output power of more than about several kW, especially for high voltage and low current applications as new energy related power supplies. However, secondary magnetic switches or transformer secondary side semiconductor switching devices in these converter circuit topologies may cause large conduction loss when these power circuit topologies are adopted for low voltage and large current applications such as arc welding power supplies. Therefore, for the low voltage and large current application required for arc welding power supplies, a soft switching DC-DC power converter with active switches in the primary side of the high frequency transformer is considered to be more suitable and acceptable. As a circuit topology to meet this requirement for the arc welder, the authors developed the novel circuit topology of voltage source full-bridge type soft switching PWM inverter in which all the active switches can actively achieve ZCS turn-on and ZVS turn-off commutation operation [6-7].

1.2 Research Objectives

This paper presents a novel circuit topology of the voltage source half-bridge type soft switching PWM inverter. Under the newly-proposed high frequency inverter link DC-DC power circuit, all the active switches in the half-bridge arm and dc bus lines can actively achieve ZCS turn-on and ZVS turn-off commutation operation.

The steady state operating principle of the proposed soft switching PWM DC-DC power converter is described with its remarkable features. The experimental operation results of this new type of soft switching PWM DC-DC power converter using IGBT power modules are illustrated including power loss analysis as compared with that of the

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hard switching PWM DC-DC power converter. The practical effectiveness of the proposed high frequency transformer link DC-DC power converter acceptable and suitable for high power applications that is designed for low voltage and large current output is actually proved on the basis of experimental data.

2. New Soft Switching DC-DC Converter Topology

Fig. 1 shows the proposed soft switching PWM DC-DC converter circuit using a novel type half-bridge soft switching PWM inverter with high frequency transformer link. The proposed converter is composed of a typical voltage source half-bridge inverter with an active PWM switch $Q_3(S_3/D_3)$ in the positive dc bus line, an active PWM switch $Q_4(S_3/D_3)$ in the negative dc bus line, two lossless snubbing capacitors C_1, C_2 and two diodes D_5, D_6. Two centre points of two capacitors C_1, C_2 and two diodes D_5, D_6 are connected to a mid point of two voltage sources E_1, E_2 and one of the primary winding terminals of the high frequency transformer. The voltage of the two voltage sources E_1, E_2 and capacitance of capacitors C_1, C_2 are designed so as to be equal ($E_1=E_2=E$, $C_1=C_2=C$). The main active switches $Q_1(S_1/D_1)$ or $Q_2(S_2/D_2)$ can be turned on and turned off in accordance with the modified PWM control circuit similar to the conventional half-bridge type hard switching PWM inverter.

Under the proposed soft switching DC-DC converter, the switches in the half-bridge type inverter can perform ZVS turn-off transition due to the presence of the active PWM switches Q_3 or Q_4, which are turned off and the snubbing capacitors C_1 or C_2, which are completely discharged before the active switches Q_1 or Q_2. In the case of half-bridge type inverter, arms are turned off. In addition, the inverter switches can also perform ZCS at a turn-on transition with the aid of inductance L_S, as a parasitic leakage inductance of the high frequency transformer.

As for the active PWM switches Q_3 or Q_4 in series with the dc bus line side, the PWM controlled switches can achieve ZVS at turn-off mode transition due to the lossless snubbing capacitors C_1 or C_2. These active PWM switches Q_3 or Q_4 can also achieve ZVS/ZCS at turn-on mode transition due to the lossless snubbing capacitors C_1 or C_2, which have been charged up to the same voltage as the half voltage E_1or E_2 of dc power bus line voltage source by the energy storage in the leakage inductance L_S after the half-bridge type inverter switches are turned off completely.

Although the conduction power loss of the additional switches may increase the total power loss a little, the total turn-off switching loss of the half-bridge type PWM inverter can be significantly decreased with the optimum aid of dc bus line series switches Q_3 or Q_4 and the lossless snubbing capacitors C_1 or C_2.

3. Principle of Operation

3.1 Gate Voltage Pulse Timing Sequences

Fig. 2 shows timing pattern sequences of switching gate driving pulses. The gate voltage pulse signals for the inverter switches Q_1 or Q_2 in voltage source half-bridge inverter arms are the same as PWM signal sequences of the conventional half-bridge inverter. Regarding the turn-on gate voltage pulse signals to the dc bus line side series switches Q_3 or Q_4, the signals are applied to Q_3 or Q_4 at the same timing as the turn-on signals to Q_1 or Q_2, respectively. As for the turn-off signals to Q_3 or Q_4, the signals are delivered to Q_3 or Q_4 before the predetermined length of time t_d on the basis of the time when the turn-off signals are applied to Q_1 or Q_2. In other words, the turn-off pulse signals are applied to Q_1 or Q_2 after the turn-off gate signals are supplied to Q_3 or Q_4 by a time t_d.

3.2 Switching operation modes and equivalent circuits

Figure 3 illustrates the relevant operating waveforms during a complete switching period for the pattern of gate drive pulse timing sequences shown in Fig. 2. The switching operation modes of this DC-DC power converter are divided into twelve operation modes from mode 1 to mode 12 in accordance with operating timing sequences, from t_1 to t_{12}. The operation principle is described in the following paragraph. The equivalent circuits corresponding to respective operation mode are shown in Fig. 4.

1) Mode 1(~t_1): Before time t_0, the switches Q_1 and Q_3 are turned on. At this time, i_{t1} flows through the primary winding of high frequency transformer HF-T. i_{s1} flows through Q_1 and i_{S3} flows through Q_3. In this period, all currents i_{t1}, i_{s1} and i_{s3} are equal and the voltage v_{C1} across C_1 is the same as the DC busline voltage E_1.
2) Mode 2(t_1 ~ t_2): At time t_0, the turn-off pulse signal is applied to Q_3. At this time, the high side series switch Q_3 in the DC busline can be turned off with ZVS because the current i_{s3} through Q_3 is immediately cut off due to the lossless snubbing capacitor C_1. After time t_1, the voltage v_{C1} across the capacitor C_1 discharges constantly toward zero voltage from $E1=E$. At this time, the voltage $^{V}{}_{C1}$ across the lossless snubber capacitor C_1 is estimated by,

$$v_{C1}(t) = E - (i_{t2}/C)t \qquad (1)$$

where, i_{t1} is a primary current of the high frequency transformer. From Eq. (1), until this voltage v_{C1} becomes zero, the discharging time t_x of the capacitor C_1 is given by;

$$t_x = CE / i_{t2} \quad (2)$$

From Eq. (2), the larger the current i_{t1} though the primary winding of high frequency transformer HF-T, the shorter the discharging time for capacitor C_1. On the other hand, the smaller the current i_{t1}, the longer the discharging time t_x.. Under this newly-developed DC-DC power converter circuit (see Fig. 1(a)), the delay time t_d indicated in Fig. 2 is designed so as to be longer than the time calculated from Eq. (2) under the condition of the maximum i_{t1} or the maximum output current. In this case, the switches Q_1 or Q_2 can achieve ZVS turn-off transition completely. To enlarge the complete ZVS operation range at the turn-off commutation for the switches Q_1 or Q_{2i} , the delay time t_d should be varied according to the value of current i_{t1}.

3) Mode 3(t_2~t_3): At time t_1, the voltage v_{C1} becomes zero. In the interval from t_1 to t_2, the diodes D_5 is turned on and the current i_{t1} through high frequency transformer primary winding flows through the circulation loop; $L_S \rightarrow D_5 \rightarrow S_1 \rightarrow L_S$.

4) Mode 4(t_3~t_4): At time t_2, the turn-off gate pulse signal (see Fig. 2) is applied to Q_1. At this time, the switch Q_1 can be turned off with ZVS because the voltage v_{C2} across C2 was already zero during the next half operation cycle and the diodes D_2 of Q_2 are immediately turned on. After that, the capacitor C_2 is charged up to the same voltage as dc busline voltage E_2.

At this mode, the condition in which the capacitor C_2 is charged up to the same voltage as DC bus line voltage E_2 can be estimated by Eq. (3).

$$(1/2)CE^2 = (1/2)L_s i_{t2}^2 \quad (3)$$

where $C1=C2=C$

However, as described later in mode 6, circuit parameters should be designed to meet the condition of;

$$(1/2)CE^2 \le (1/2)L_s i_{t2}^2 \quad (4)$$

in order to achieve ZVS, a turn-on transition of Q_4.

5) Mode 5(t_4~t_5): Under a condition of Equation (4), after the voltage v_{C2} reaches the DC busline voltage E_2, the voltage v_{C2} across the snubber capacitor C_2 is clamped to dc bus line voltage E_2 because the diode D_4 of Q_4 is turned on and the energy stored into the inductor with leakage inductance L_S is back to DC busline voltage source E_2.

6) Mode 6(t_5~t_6): In this mode, all operations are stopped in the primary circuit of the high frequency transformer.

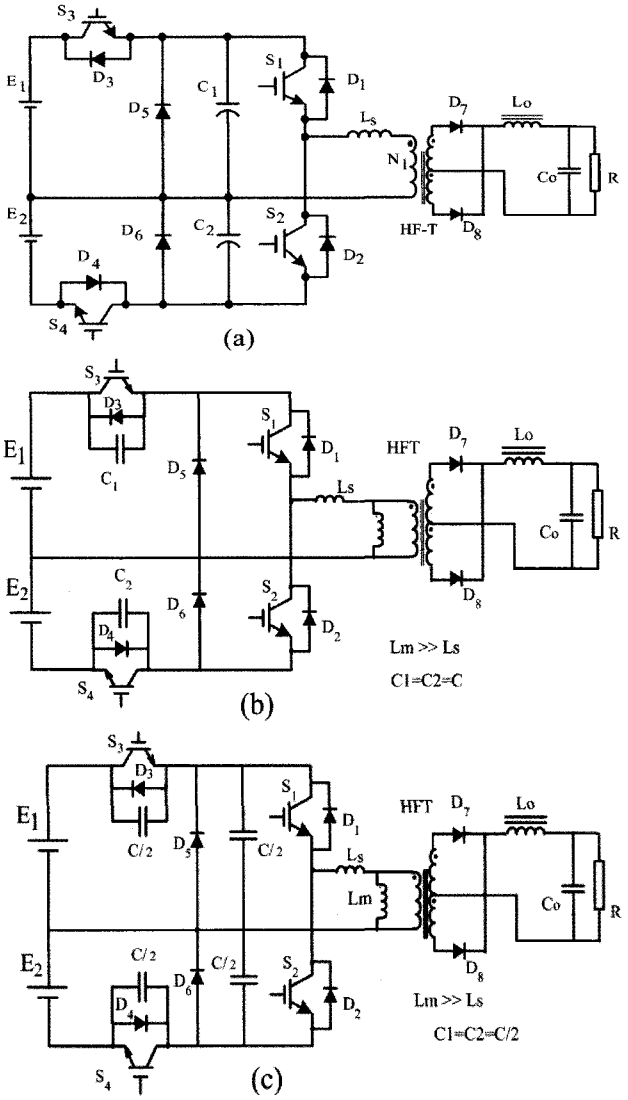


Fig. 1. A novel type half-bridge soft-switching PWM DC-DC power converter.

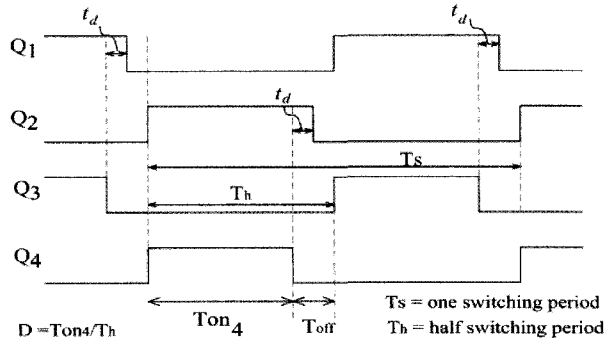


Fig. 2. Timing Pattern sequences of switching gate driving pulses.

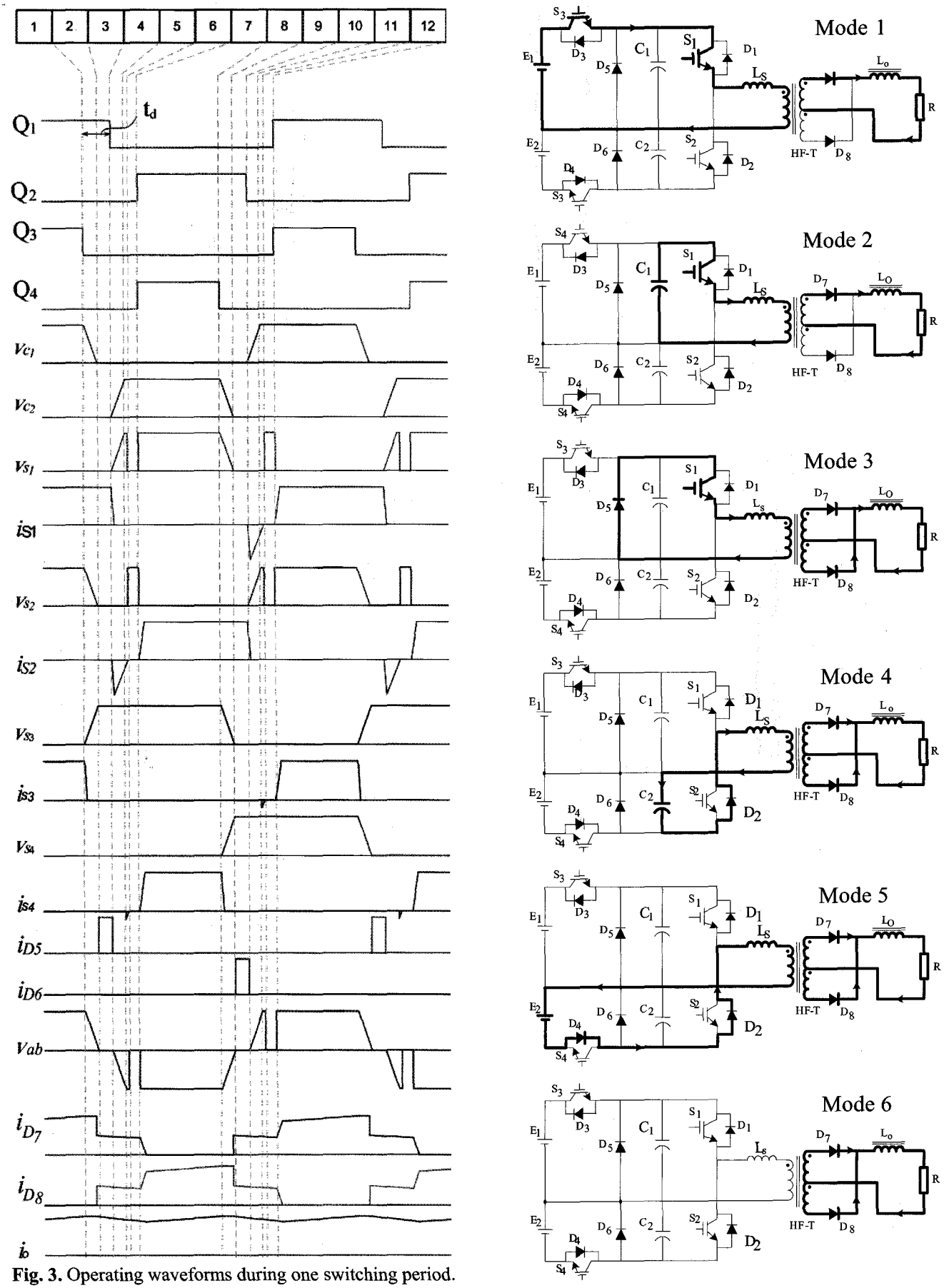


Fig. 3. Operating waveforms during one switching period.

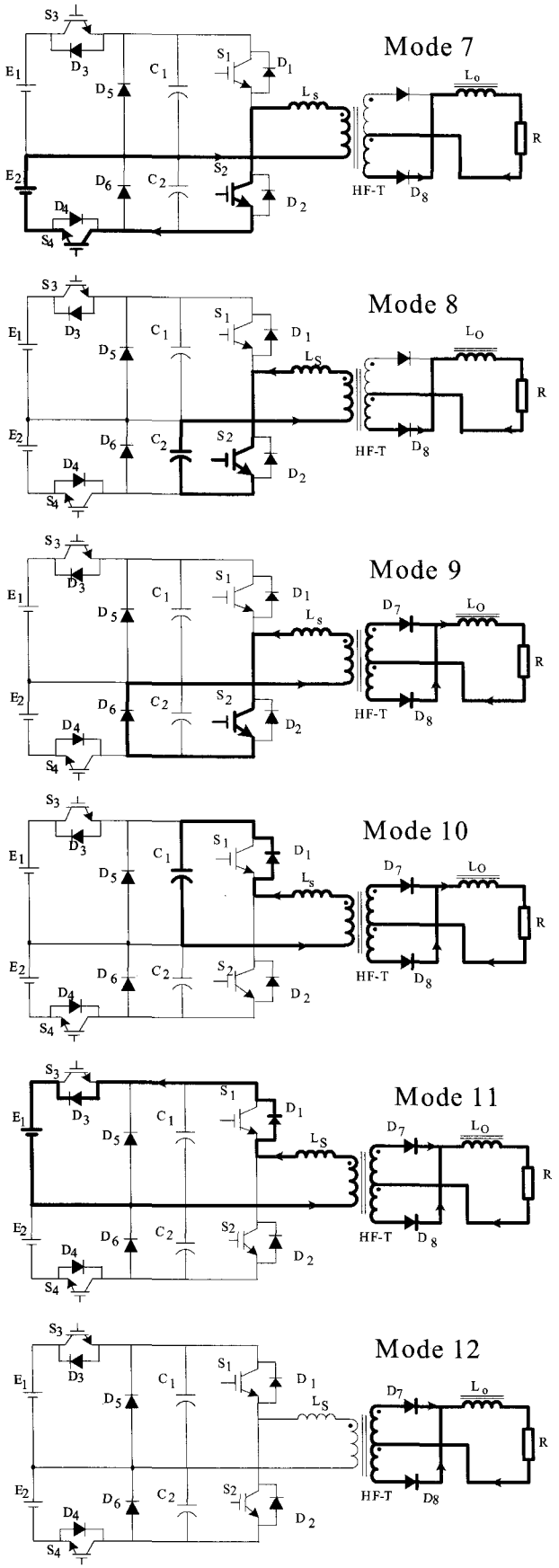


Fig. 4. Equivalent circuits and operational modes for one switching cycle.

7) Mode 7(t_6~t_7): At time t_5, the turn-on gate pulse signals are applied to the switches Q_2 and Q_4. At this time, the switch Q_2 can be turned on with ZCS due to the primary-side lumped parasitic inductance L_S of the high frequency transformer. Furthermore, the series switch Q_4 in the bus line achieves a complete soft-switching ZVS/ZCS at turn-on transition because the voltage v_{C2} is the same voltage as DC busline voltage E_2.
8) Mode 8(t_7~t_8): The turn-off signal is applied to Q_4. At this time, the series switch Q_4 in dc the busline can be turned off with ZVS because the current i_{s4} through Q_4 is immediately cut off due to the lossless snubbing capacitor C_2. The voltage v_{C2} across the capacitor C_2 discharges constantly toward zero.
9) Mode 9(t_8~t_9): The voltage v_{C2} becomes zero, the diodes D_6 are turned on and the current i_{t1} through transformer primary winding flows through the loop; $L_S \rightarrow S_2 \rightarrow D_6 \rightarrow L_S$.
10) Mode 10(t_9~t_{10}): The turn-off gate pulse signal is applied to Q_2. At this time, the switch Q_2 can be turned off with ZVS because the voltage v_{C2} was already zero during the last half operation cycle and the diodes D_1 of Q_1 are immediately turned on. After that, the capacitor C_1 is charged up to the same voltage as dc busline voltage E_1.
11) Mode 11(t_{10}~t_{11}): After the voltage v_{C1} across the snubber capacitor C_1 reaches the dc busline voltage E_1, it is clamped to dc busline voltage E_1 because the diode D_3 of Q_3 is turned on and the energy stored into leakage inductance L_S is back to dc busline voltage source E_1.
12) Mode 12(t_{11}~t_{12}): At this mode, all operations are stopped in the primary circuit.

Thereafter, the operation processes for Q_1, Q_3 and Q_2, Q_4 will be repeated in sequence continuously from mode 1 to mode 12 as in Fig. 4.

4. Experimental Results and Discussions

4.1. Total System Implementations

The experimental DC-DC converter circuit setup treated here is shown in Figure 5. In the DC-DC converter setup implementation, the maximum output voltage and current are designed for 36V, 400A, respectively. The design specifications and circuit parameters are described in Table 1.

The complete appearance of experimental setup using low voltage large current arc welding power supply is presented in Figure 6. The maximum DC output power of this experimental power supply setup is designed for 14.4

kW. Figure 7 represents the assembled component appearance on the printed circuit board (PCB) in the primary main circuit. Figure 8 shows the exterior appearance of the high frequency transformer in the proposed soft switching PWM DC-DC converter. The IGBT power modules are mounted on the heat sink and connected by the printed circuit board in which the capacitors C_1 and C_2 are mounted on the PCB and the capacitors C_3 and C_4 are directly connected to the output of the three phase rectifier. Connecting IGBTs and capacitor C_1, C_2, C_3 and C_4 by the printed circuit board enables minimization of the stray line inductance with optimum connections among IGBTs, C_1, C_2, C_3 and C_4. Actually, the minimum leakage inductance of the high frequency transformer is particularly important on this new soft-switching PWM DC-DC converter, because spike voltage across collector and emitter of IGBTs easily appears at a turn off transition if there is wiring stray inductance between snubbing capacitors and the IGBT switches.

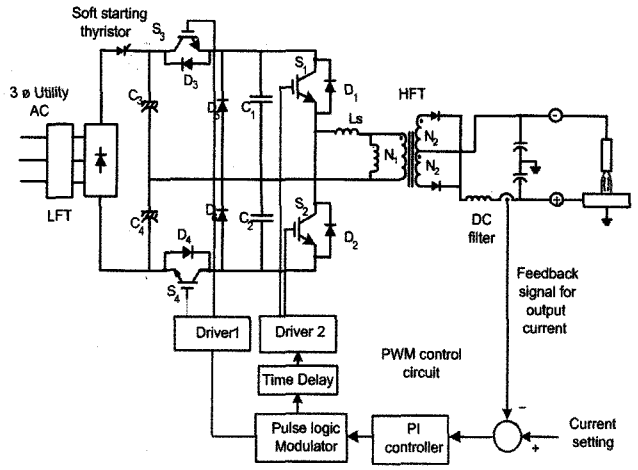


Fig. 5. Experimental setup circuit implementation.

Table 1. Design specifications and circuit parameters.

Item	Symbol	Value
Utility AC Input Voltage		AC400[V]
Inverter Switching Frequency	*fs*	40 [kHz]
Switching Period	*Ts*	25 [μs]
Primary Side Lumped Leakage Inductance of High Frequency Transformer	*Ls*	2 [μH]
Capacitance of Quasi Resonant Capacitors	C_1, C_2	0.235[μF]
Capacitance of DC Smoothing Filter Capacitor	C_3, C_4	2200[μF]
Inductance of DC Reactor in Load Side	*Lo*	60[μH]
Equivalent Load Resistance (Stable Arc Welding Load)	*R*	0.09 [Ω]
Maximum Load Current	*Io*	400 [A]
Turns Ratio of HFT	N_1:N_2:N_3	4:1:1
Remarks; *Lm* >> *Ls*		

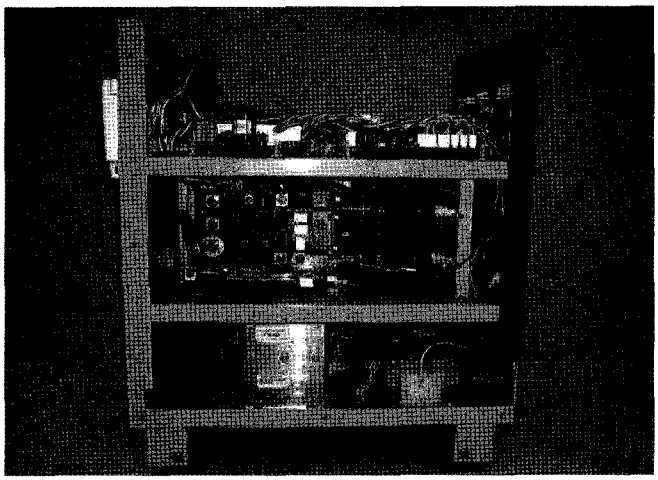


Fig. 6. Complete appearance of stick arc welding power supply using newly-developed soft switching DC-DC converter.

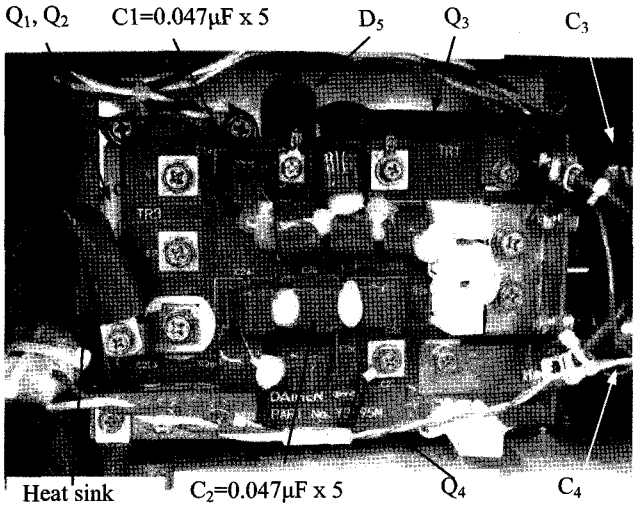
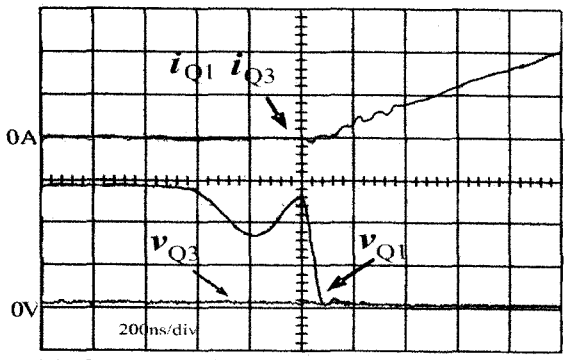


Fig. 7. Assembled component appearance in high frequency transformer primary side circuit.

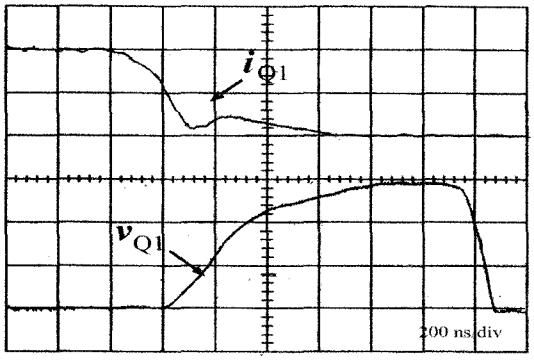
Fig. 8. Exterior appearance of high frequency transformer in the proposed soft switching PWM DC-DC converter.

4.2. Measured Voltage and Current Switching Waveforms

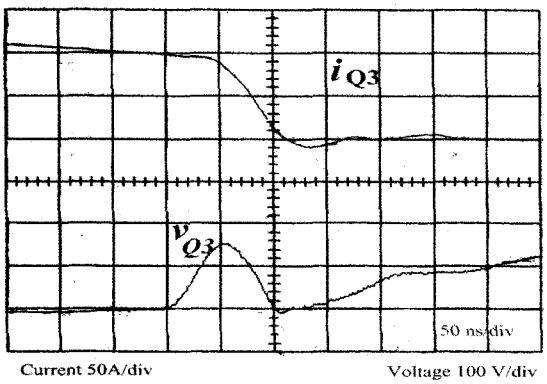
The switching operating waveforms for voltage and current when the switch Q_1 is turned on and turned off are shown in Fig. 9 (a) and (b). Observing these operating waveforms, the switch Q_1 is turned on with ZCS and also turned off with ZVS. The switching waveforms for voltage and current when the switch Q_3 is turned on and turned off are shown respectively in Fig 9 (a) and (c). Observing the operating waveforms, the switch Q_3 is turned on with ZVS/ZCS and is turned off with ZVS. However, at the turn-off transition for Q_1 and Q_3, only a few switching power losses still exist due to the inherent tail current characteristic of IGBTs.



(a) Turn on switching waveforms for Q1,Q3



(b) Turn off switching waveforms for the switch Q1



(c) Turn off switching waveforms for the switch Q3

Fig. 9. Measured switching waveforms for active power switches Q_1 and Q_3

4.3. Comparative Results of Power Loss Analysis

In the power loss analysis and evaluations presented in Fig. 9, the total power loss of all the switches including Q_3 and Q_4 in the newly-developed DC-DC power converter circuit is compared with that of all the switches in the 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 to each other. Furthermore, the switching frequency of the high frequency inverter power stage using IGBTs is designed for more than about 10 kHz. The more the switching frequency of the inverter increases, the more this newly-developed DC-DC power converter circuit has remarkable advantages relating to the power conversion efficiency and power density as compared with the conventional hard switching inverter type DC-DC power converter.

In case the switching frequency is designed for 40 kHz, the total power loss for the switches in newly-developed DC-DC power converter circuits is 445W and that of the conventional hard-switching PWM inverter is 865W. Furthermore, the snubber circuit is necessary for the conventional hard switching PWM DC-DC power converter circuit. Therefore, the total power loss for the conventional hard switching converter circuit including the power loss of the snubber circuit is estimated to be about 1370W. This loss is three times more than the total power loss of the newly-developed converter circuit.

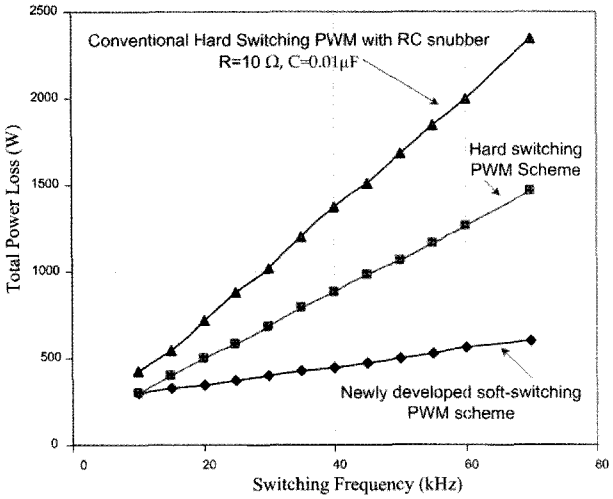


Fig. 10. Comparative power loss analysis between newly developed and conventional hard switching converters.

5. Conclusions

In this paper, the novel circuit topology of the voltage

source modified half-bridge soft switching PWM DC-DC power converter with a high frequency planar transformer link was presented. The operating principle, switching pattern and control strategy of the half-bridge soft switching PWM DC-DC power converter designed for inverter switching frequency 40 kHz, 36V and 400A output specifications were illustrated and discussed for low voltage and large current output applications such as telecommunication and automotive applications as well as arc welding power supply applications. The power loss analysis of the proposed soft switching DC-DC power converter was discussed and evaluated as compared with the hard switching PWM DC-DC power converter with a high frequency transformer link. The practical effectiveness of the proposed DC-DC power converter operation under a soft switching PWM scheme was actually proved from a practical point of view and the high efficiency and power density of this converter could be achieved on the basis of experimental results for low voltage and large current power supplies.

Under the simple circuit, which has two additional power semiconductor switching devices and two passive circuit components compared to the typical half-bridge inverter circuit, all the active switching devices incorporated into half bridge inverter arms and DC busline input achieve ZVS turn-off and ZCS turn-on commutation. When the switching frequency of the high frequency inverter using IGBTs is selected more than about 10 kHz, the more the switching frequency of inverter increases, the more this proposed PWM DC-DC power converter has remarkable advantage in relation to the power conversion efficiency and power density as compared with the conventional hard switching inverter type DC-DC power converter.

The downsizing and light-weighted power supply using this newly-developed soft switching DC-DC power converter circuit was developed and put into the practical market in industry.

In the future, in order to improve the power conversion efficiency and reduce the electromagnetic noise, SiC-SBD or GaN-SBD as the passive power switches and SiC-JFET/SIT as the active power switches should be introduced and evaluated for the proposed soft switching DC-DC converter with high frequency transformer link.

Acknowledgment

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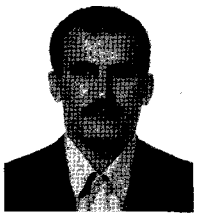

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