Three-Level Phase Shift ZVS-PWM DC-DC Converter with Neutral Point Clamping Diodes and Flying Capacitor for Gas Metal Arc Welding

Hisayuki Sugimura(1), Srawouth Chandhaket(2), Sang-Pil Mun(1), Soon-Kurl Kwon(1), Toshimitsu Doi(3), Mutsuo Nakaoka(1)(4)

(1) Kyungnam University, Masan, Republic of Korea
(2) Dept. of Electrical Eng., Walailak University, Thailand
(3) Yamaguchi University, Yamaguchi, Japan
(4) Welding & Mechatronics Company, Daihen Corporation, Kobe, Japan

Abstract— This paper is concerned with some experimental results and practical evaluations of a three-level phase shifted ZVS-PWM DC-DC converter with neutral point clamping diodes and flying capacitor for a variety of gas metal arc welding machines. This new DC-DC converter suitable for high power applications is implemented by modifying the high-frequency-linked half bridge soft switching PWM DC-DC converter with two active edge resonant cells in high side and low side DC rails, which is previously-developed put into practice by the authors. The operating principle of the three-level phase-shift ZVS-PWM DC-DC converter and its experimental and simulation results including power regulation characteristics vs. phase-shifted angle and power conversion efficiency characteristics in addition to power loss analysis are illustrated and evaluated comparatively from a practical point of view, along with the remarkable advantageous features as compared with previously-developed one.

Keywords-DC-DC power converter, neutral point clamping diodes and flying capacitor hybrid topology, Three-level half bridge, high frequency transformer link, primary side phase-shift PWM, Soft switching commutation, Gas metal arc welding

I. INTRODUCTION

In, recent years, the authors have demonstrated the half-bridge and full-bridge prototype of the high frequency transformer-linked soft-switching PWM DC-DC converters with simple active edge resonant cells (AERCs) in the input buslines of high side and low side rails for gas metal arc welding. These DC-DC converter topologies could basically achieve their high efficiency, high performance and high power density [1]-[4]. These prototypes of soft-switching symmetrical PWM DC-DC high power converter using the latest IGBT power modules has been partially put into practical use for low voltage large current application in industry. However, the previously-proposed DC-DC converter operates even at hard switching in the power setting ranges of low voltage low current DC outputs. In this case of light load conditions, the DC-DC converter topologies should utilize the allowable switching power semiconductor devices with higher rated voltage because the maximum peak voltage stress applied in some power devices causes through hard switching operation. Though, the power losses of the switches due to hard switching operation are relatively lower than those of snubberless circuit, but considering electromagnetic interference is needed for the DC-DC converter. In order to improve some issues such as large surge voltage and large condition losses due to the high voltage rating switches, this paper deal with three-level phase shifted ZVS-PWM DC-DC converter with neutral point clamping diodes and flying capacitor, which is suitable for wide varying voltage/current applications. In this paper, its operating principle and DC output characteristics are evaluated and discussed on the basis of simulation and experimental results.

II. PROPOSED SOFT-SWITCHING DC-DC CONVERTER

A. Circuit Description

Figure 1 shows a three-level phase-shift ZVS-PWM DC-DC high power converter with a high frequency transformer link. This DC-DC converter topology consists of DC power source $E$ delivered by three phase PFC converter with three

---

Fig. 1. three-level phase-shift ZVS-PWM DC-DC high power converter with a high frequency transformer link.
phase diode rectifier, the smoothing capacitors $C_1$, $C_2$ for dividing input DC voltage, IGBTs $Q_1$-$Q_4$, lossless snubbing capacitors $C_{s1}$-$C_{s4}$ in parallel with the switches in the outer bridge arms and inner bridge arms, flying capacitor $C_u$ and neutral point voltage clamping diodes $D_{cs1}$-$D_{cs4}$ in the primary side high frequency transformer with its turn ratio $N_1$, $N_2$, $N_3$ ($N_2=N_3$), center-tapped high frequency rectifier represented by the lumped L type equivalent circuit due to leakage inductance $L_k$ and magnetizing inductance $L_m$, rectifier fast recovery diode rectifier $D_{o1}$, $D_{o2}$ in the secondary side of high frequency transformer, output inductor filter $L_o$; in some cases, the output inductor $L_o$ and Capacitor $C_o$ filters, and load resistor $R_o$.

B. Gate Pulse Timing Signals

The DC output voltage of proposed DC-DC converter shown in Fig. 1 can be continuously regulated through phase shift PWM scheme. Figure 2 illustrates the gate pulse sequences of phase shift PWM. The phase shift PWM IC used to regulate the DC output power or DC voltage/current by retarding the pulse timing of control phase inner arm switches ($Q_2$, $Q_3$) with respect to reference phase outer arm switches ($Q_1$, $Q_4$). The outer switches, high side arm switch $Q_1$ and low side arm switch $Q_4$ as the reference phase, and the inner arm switches high side arm switch $Q_2$ and low side arm switch $Q_3$ as the control phase are used to determine the gate pulse timing patterns for the proposed DC-DC converter circuit.

C. Principle of Circuit Operation

The new proposed DC-DC converter treated here can operate with 16 state modes during one switching cycle. The circuit operating voltage and current waveforms, and the 16 switching mode transitions as well as the corresponding switching mode equivalent circuits are depicted in Fig. 3 and Fig. 4, respectively. The 8 operation modes in the first half cycle are described below because the second half cycle 8 operation modes (Mode 9-16) become the similar circuit operation as those in the 8 operation modes during the first half cycle.

**[MODE 1]** MODE 1 starts from turning on the switches $S_1$ of $Q_1$ and $S_2$ of $Q_2$ with ZVS and ZCS at the synchronus same pulse timing. The secondary side of high frequency transformer operates free wheeling mode because the rectifier diodes $D_{o1}$ and $D_{o2}$ are conducting under the overlapping cur-
[MODE 2] In MODE 2, the high side switches S1, S2 and diode D_{o1} conduct as soon as the diode D_{o2} is turned off. MODE 2 ends when the switch S1 is turned off.

[MODE 3] In MODE 3, the switch S1 is turned off with ZVS and S2 and D_{o1} still conduct continuously. The lossless snubbing capacitor C_{s1} is charged and C_{s4} is discharged simultaneously through the flying capacitor C_{s6} in this mode. This mode ends when the charging of C_{s1} and the discharging of C_{s2} complete.

[MODE 4] The switch S2 and the rectifier diode D_{o1} keep conducting and diode the D_{4} of Q_{4} is turned on in MODE 4. The flying capacitor C_{s4} is still discharged continuously. MODE 4 ends when the current through C_{s4} reaches zero.

[MODE 5] In MODE 5, the low side diode D_{4} is turned off and the switch S_{2}, the diodes D_{c1} and D_{o1} keep conducting. In this mode, the circulating current flows through D_{c1} and S_{2} because the inverter output voltage in the primary side of high frequency transformer becomes nearly zero due to the existing magnetizing inductance L_{m}. This mode ends when the switch S_{4} of Q_{4} is turned on by the external gating pulse.

[MODE 6] If the gate signal v_{g4} is delivered to the low side switch S_{4} during MODE 5, the circuit operating mode moves to MODE 6. In this mode, although the switch S_{4} begins to be turned on, and the switch S_{2} and the diodes D_{c1} and D_{o1} keep conducting. This mode ends when C_{s4} is charged up and the circuit mode returns to MODE 5 in a certain case.

[MODE 7] In MODE 7, the switch S_{4} is turned off with ZVS by the gate timing pulse rejection, the antiparallel diode D_{4} is turned on and the both diodes D_{c1}, D_{o1} conduct. Lossless snubbing capacitor C_{s2} is charged and C_{s3} in parallel with Q_{3} is charged up.

---

Fig. 4. Switching mode transitions and switching mode equivalent circuits during the first half cycle period.
discharged simultaneously in this mode. This mode ends when charging state of $C_s^2$ and discharging state of $C_s^3$ has just completed.

**[MODE 8]** The inner low side switch $D_3$ of $Q_3$ is turned on, the diodes $D_4$, $D_{c1}$, $D_{o1}$, $D_{o2}$ conduct in MODE 8. The secondary side of high frequency transformer puts into free wheeling mode. This mode ends when the currents through $D_3$ and $D_4$ reach zero. In this time, two low side switches $S_3$ and $S_4$ are turned on naturally with ZVS&ZCS for delivered the pulse $v_{g3}$ to the gate terminals of $Q_3$, $Q_4$.

**[MODE 9-16]** These 8 operating modes described above reveal the similar operation as those of MODE 1 to MODE 8.

This three-level soft-switching PWM DC-DC converter can operate with these 16 operating modes repeated periodically.

### III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Table I lists the circuit parameters and the design specifications in experiment for the proposed three-level DC-DC high power converter with a high frequency transformer and center tapped rectifier. In this case, the phase shift PWM control IC conveniently uses the controller IC; UCC3895 (Texas Instruments). The circuit load in experiment makes use of the electronic power load Takasago RL-6000L (6kW unit, 4 parallel).

#### A. Measured Operating Waveforms

In Fig. 5, the measured voltage and current waveforms under the conditions of phase shift angle $\phi=0^\circ$, $\phi=60^\circ$ and $\phi=120^\circ$ are respectively depicted for design specifications in Table I. As can be seen from Fig. 5(a)(b), all the active switches in the outer and inner bridge arms can achieve soft switching transition commutation. In addition to this, the peak voltage across $Q_1$ and $Q_2$ are clamped to the half of the input DC voltage, 270V. In Fig. 5(c), the inner high side and low side switches $Q_2$ and $Q_3$ operate hard switching turn on. However, the peak voltage across $Q_2$ and $Q_3$ are clamped to the half of the input DC voltage, 270V. In this case, the outer high side and low side switches $Q_1$ and $Q_4$ can perform soft switching transitions. Therefore, this three-level DC-DC converter can substantially reduce the semiconductor switch conduction losses by using the lower voltage rated IGBT modules due to the voltage clamping effectiveness.
B. Power Regulation Characteristics

Figure 6 plots the input DC power regulation characteristics in open-loop control scheme compared with that of the previously-developed symmetrical ZVS-PWM DC-DC converter with active edge resonant cells (AERCs) and that of the proposed three-level phase-shift ZVS-PWM DC-DC converter. As can be seen, the newly-proposed DC-DC converter can respectively regulate input power by phase-shift PWM control strategy from 10kW to 0.2kW, 10kW to 2kW under soft switching operation. On the other hand, the rated input DC power is 15kW in the previously developed DC-DC converter because proposed DC-DC converter is inserted series resonant inductor \( L_r \) in the primary side of high frequency transformer for soft switching operation for the newly-proposed DC-DC converter the output power more than 10kW can be outputted by adjusting the input DC voltage.

C. Power Loss Calculations

Figure 8 depicts the quantitative results of power loss analysis for power devices by using 600V (Q1, Q4) and 1200V (Q2, Q3) voltage rated IGBTs in the three-level DC-DC converter. The total power losses for \( P_{in}=9900W \) is the same value. On the other hand, the power losses at \( P_{in}=1000W \) of three-level DC-DC converter treated here is lower than previously-developed DC-DC converter because semi-hard switching operation by means of snubbing capacitors.

D. Power Conversion Efficiency

Figure 8 illustrates actual power conversion efficiency characteristics compared with those of previously-developed DC-DC converter and selected power semiconductor devices in high side and low side arm inner switches Q2 and Q3 from 1200 rated voltage in the replacement of 600V under the open loop control scheme. Observing this figure, the measured actual power conversion efficiency of the proposed DC-DC converter (see Fig. 1) can achieve 88% in the case of \( \phi=0^\circ \) and over 80% under soft switching operation. In addition, the power conversion efficiency of three-level DC-DC converter could achieve higher than that of the previously-developed DC-DC converter in the low current output setting ranges. Furthermore, the pro-

---

**Table I: Design Specifications and Circuit Parameters**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>( v_{AC} )</td>
<td>3&amp;400Vrms</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( f )</td>
<td>40kHz</td>
</tr>
<tr>
<td>Ripple frequency</td>
<td>( L )</td>
<td>80kHz</td>
</tr>
<tr>
<td>Dead time of Q1&amp;Q4 and Q2&amp;Q3</td>
<td>( L_t )</td>
<td>1.4\musec</td>
</tr>
<tr>
<td>Input side capacitor (Electrolytic DC capacitors)</td>
<td></td>
<td>( C_1, C_2 ) 2.2mF</td>
</tr>
<tr>
<td>Lossless snubbing capacitors</td>
<td>( C_{ss} )</td>
<td>22.0mF</td>
</tr>
<tr>
<td>Flying capacitor</td>
<td>( C_f )</td>
<td>500nF</td>
</tr>
<tr>
<td>Leakage inductance of HF transformer</td>
<td>( L_a )</td>
<td>2.0\muH</td>
</tr>
<tr>
<td>Magnetizing inductance of HF transformer</td>
<td>( L_m )</td>
<td>200\muH</td>
</tr>
<tr>
<td>Additional Series resonant inductor</td>
<td>( L_r )</td>
<td>6.0\muH</td>
</tr>
<tr>
<td>Turn ratio of HF transformer</td>
<td>( N_1:N_2:N_3 )</td>
<td>5:1:1</td>
</tr>
<tr>
<td>Output filter inductance</td>
<td></td>
<td>( L_o ) 60\muH</td>
</tr>
<tr>
<td>Output resistance</td>
<td>( R_o )</td>
<td>100m\Omega</td>
</tr>
<tr>
<td>IGBT Q1, Q4</td>
<td></td>
<td>CM150DY-12NF ( V_{ces}=1200V, I_r=150A(25^\circ C) )</td>
</tr>
<tr>
<td>IGBT Q2, Q3</td>
<td></td>
<td>SKM150GB128D ( V_{ces}=600V, I_r=150A(25^\circ C) )</td>
</tr>
<tr>
<td>Diode D1, D2</td>
<td></td>
<td>FRG25CA120 ( V_{ces}=1200V, I_r=25A(78^\circ C) )</td>
</tr>
<tr>
<td>Diode D3, D4</td>
<td></td>
<td>DSE12x101-06A ( V_{ces}=1200V, I_r=96A*5(70^\circ C) ) (5 in parallel)</td>
</tr>
</tbody>
</table>

---

![Fig. 6. Output power regulation vs. output current characteristics in open loop.](image)
posed DC-DC converter using two types of IGBTs; 1200V, 600V rated voltage devices for Q2 and Q3 can achieve the actual efficiency 90% or more for the rated power settings. The actual efficiency of the proposed DC-DC converter 600V IGBT power devices in Q2 and Q3 can be effectively higher than the previously developed DC-DC converter.

IV. CONCLUSIONS

This paper presented a three-level phase shifted ZVS-PWM DC-DC converter with neutral point clamping diodes and flying capacitor hybrid configuration for a variety of gas metal arc welding, which includes lossless snubbing capacitor in parallel with each reverse conducting power switches. Its operating principle and output steady-state characteristics were discussed and evaluated in simulation results and feasibility study. From these experimental results, the DC output power/voltage regulation characteristics of the proposed three-level soft switching DC-DC converter with a high frequency transformer and center-tapped rectifier were illustrated under a condition of soft switching commutation. Furthermore, the maximum power conversion efficiency 88% could be performed by the experimental setup developed previously. The power losses for power devices were significant for the previously-proposed DC-DC converter. Furthermore, the actual power conversion efficiency for proposed DC-DC converter using the 600V-IGBTs for inner high side arm and low side arm switches Q1 and Q2 could achieve 90% higher or more than all the power setting ranges compared with the previously developed DC-DC converter. As for the other results, the voltage surges and stresses applied to IGBTs were effectively lowered even under hard switching operating ranges. It is noted that the newly-proposed three-level soft switching DC-DC converter could be practically cost effective and the conduction loss reduction and switching losses by using lower rated voltage power switching devices and power modules.

In the future, the following items for practical usage in industry should be considered; (i) detail power loss analysis for each power devices and DC filter component, (ii) SiC-SBD/GaN-SBD could be introduced as the neutral clamping diodes, (iii) the minimizations of phase shift related circulating current in the three-level PWM DC-DC converter should be evaluated by introducing (a) passive lossless voltage clamped topology, (b) tapped inductor DC filter with free wheeling diode, and (c) power recovery circuit due to tapped inductor in primary side, (iv) efficiency practical discussions on current doubler rectifier as well as voltage doubler rectifier, (v) improvement based on the output DC filter inductor such as amorphous core and powder metal core.

REFERENCES


