Design and Implementation of a 40-kV, 20-kJ/s Capacitor Charger for Pulsed-Power Application

Ji-Woong Gong, Hong-Je Ryoo, Suk-Ho Ahn, and Sung-Roc Jang

Abstract—This paper presents the design and implementation of a 40-kV, 20-kJ/s high-voltage capacitor charger based on a series/parallel resonant converter. The inclusion of the parallel resonant capacitor component in this circuit results in the production of a trapezoidal resonant current, which reduces conduction loss. This capacitor is practically realized as a part of the balancing network of the high-voltage rectifiers in the secondary side of the circuit. Particular attention in this paper is paid to the high-voltage transformer, which must be carefully designed to provide the required functionality without negative impact on the resonant circuit. A PSpice simulation has been used to prove that the proposed control method for the circuit is valid. This is supported with the experimental results, which verify that the operation of the circuit is as expected and that the converter is able to meet all the design criteria with an efficiency of up to 96%.

Index Terms—High-voltage capacitor charger (HVCC) power supply, high-voltage transformer, insulation oil, series–parallel resonant converter (SPRC).

I. INTRODUCTION

RECENTLY, the study of high-voltage capacitor chargers (HVCCs) for pulsed-power applications in environmental, material, and military industries has been conducted [1]–[19]. On the basis of the diverse application fields, these chargers require fast charging time, high-voltage output, high power density, and reliability. Thus, a variety of dc–dc converter topologies have been studied in accordance with the aforementioned requirements. Among them, resonant converters have the ability to operate efficiently at high switching frequencies as a result of their inherent soft switching capabilities. Various chargers with current source characteristics, including the series resonant tank, have been developed and operated regardless of the charging voltage of the capacitive load [16]–[18].

The operating mode of a resonant converter that uses a switching-frequency control technique can be classified into discontinuous conduction mode (DCM) and continuous conduction mode (CCM), depending on the relationship between the resonant and switching frequencies. Although a charger under DCM operates as a current source over a wide load range, it suffers from high conduction loss when compared with operation under CCM [9]–[11], [14]. The conduction loss in the CCM can be reduced compared with that of the DCM owing to the low crest factor, but the turn–OFF switching loss must be considered [12]–[14]. Compared with the switching-frequency-control method, the phase-shift pulsedwidth modulation technique allows fixed-frequency operation that takes advantage of the relatively high efficiency in the overall load condition; however, the design of the leading and lagging legs must be considered [14], [15].

This paper proposes a series–parallel resonant converter (SPRC)-based HVCC to capitalize on the constant current source of a series resonant converter and the intrinsic voltage boost-up function of a parallel resonant converter. By designing the parallel resonant capacitors to provide two resonances per switching period, the resonant current waveform can be changed from a sinusoidal to trapezoidal shape for a lower crest factor. The trapezoidal resonant current also reduces the turn–OFF switching loss by allowing an increase in the snubber capacitance owing to the higher energy stored in the resonant tank at the turn–OFF transition. Thus, this modification to the current can result in a reduced conduction and switching loss; the latter being a result of the ability to use a larger snubber capacitor under these circumstances. Moreover, the parallel resonant capacitor facilitates the design of high-voltage transformers because the SPRC voltage gain is larger than that of the series resonant converter.

Although the proposed topology can achieve high power density and high efficiency, the insulation of the high-voltage components such as the transformer and rectifier must be carefully considered to ensure reliability. In high-voltage applications that require an output voltage of more than 30 kV, oil insulation is commonly used to protect the components. Two major methods are available to achieve a high-voltage gain: one method involves the use of the combination of a transformer and a voltage-doubler (VD) circuit, and the other method involves the combination of a voltage multiplier and a transformer. The two methods are similar but exhibit differences. The voltage multiplier circuit requires more rectifier devices but reduces the burden of the high-voltage transformer [19]–[23]. Meanwhile, although the VD circuit requires relatively more secondary turns, a compact design is possible using relatively fewer devices [23]–[25]. In this paper, transformer design with reinforced isolation is presented considering multiple high-voltage windings. Owing to the superior winding method, the insulation between the secondary wires is guaranteed. Thus, the VD circuit was chosen to
Fig. 1. Image of the developed HVCC.

TABLE I
SPECIFICATIONS OF THE DEVELOPED HVCC

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>380 Vac ± 10%</td>
</tr>
<tr>
<td>Maximum charging voltage, ( V_{\text{chrg}} )</td>
<td>40 kV</td>
</tr>
<tr>
<td>Maximum charging current, ( I_{\text{chrg}} )</td>
<td>1 A</td>
</tr>
<tr>
<td>Continuous output power, ( P_{\text{continuous}} )</td>
<td>20 kW</td>
</tr>
<tr>
<td>Peak output power, ( P_{\text{peak}} )</td>
<td>40 kW</td>
</tr>
<tr>
<td>Maximum efficiency, ( \eta_{\text{max}} )</td>
<td>96%</td>
</tr>
<tr>
<td>Maximum power factor, ( \eta_{\text{max}} )</td>
<td>0.96</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>435 mm</td>
</tr>
<tr>
<td>Depth</td>
<td>460 mm</td>
</tr>
<tr>
<td>Height</td>
<td>210 mm</td>
</tr>
<tr>
<td>Power density</td>
<td>&gt; 547 W/I</td>
</tr>
</tbody>
</table>

Additional functions and features of the 40-kV CCPS
- Protection
  - Charger fault
  - Overtemperature
  - Interlock
  - Load fault
- Cooling
  - Forced air cooling for IGBT
  - Oil insulation for high-voltage transformer and rectifier
- Reliability against malfunction
  - Output short during charging
  - Output open during charging
  - Load short during charging
- Operating mode
  - Continuous
  - Discontinuous
- Parallel operation
  - Master
  - Slave

To achieve a high voltage. To explain the detailed design and to verify the proposed HVCC topology, this paper is organized as follows. Section II introduces the high-efficiency resonant converter topology and analysis of the operating mode of the proposed HVCC. The design parameters are verified by a PSpice simulation, and the various losses are estimated on the basis of the improved resonant current. Section III describes the selection of the inverter elements and the implementation of a resonant tank. To reinforce the insulation, the high-voltage components are discussed in terms of the structure. Section IV discusses the various experiments performed under a resistive load and the result of the charging test under a capacitive load. Finally, Section V presents the conclusion.

An image and the specifications of the developed HVCC are shown in Fig. 1 and Table I, respectively.

II. ANALYSIS AND DESIGN OF THE DEVELOPED HVCC

The resonant current waveform of the developed HVCC based on the SPRC is improved to a trapezoidal shape depending on the optimal design of the parallel resonant capacitor. To explain the detailed design and to verify the proposed HVCC topology, this paper is organized as follows. Section II introduces the high-efficiency resonant converter topology and analysis of the operating mode of the proposed HVCC. The design parameters are verified by a PSpice simulation, and the various losses are estimated on the basis of the improved resonant current. Section III describes the selection of the inverter elements and the implementation of a resonant tank. To reinforce the insulation, the high-voltage components are discussed in terms of the structure. Section IV discusses the various experiments performed under a resistive load and the result of the charging test under a capacitive load. Finally, Section V presents the conclusion.

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II. ANALYSIS AND DESIGN OF THE DEVELOPED HVCC

The resonant current waveform of the developed HVCC based on the SPRC is improved to a trapezoidal shape depending on the optimal design of the parallel resonant capacitor.

Thus, it reduces the conduction and turn-off losses owing to the low crest factor and the effect of the turn-off snubber. The SPRC circuit applied to the HVCC is introduced, and the operating mode is analyzed. Additionally, a specially designed gate drive circuit is proposed for a zero voltage (ZV) turn-on. A PSpice simulation has been developed to verify the expected effects of the parallel resonant capacitor and estimate the losses resulting from the improved resonant current waveform.

A. Proposed Topology for Developed HVCC

Fig. 2 shows the proposed HVCC circuit based on the high-efficiency resonant converter topology with a series-parallel resonant tank. This circuit is divided into two sections by the transformer: 1) a primary side composed of full-bridge switches \( S_1 \)–\( S_4 \) and a series resonant tank \( (L_r, C_r) \) and 2) a secondary side that uses rectifier diodes \( D_5 \)–\( D_8 \) and filter capacitors \( C_f_1 \)–\( C_f_4 \). Owing to the feature of the converter operating above the resonant frequency, this design has the advantage of a ZV turn-on. On the other hand, to limit the switching losses when turned off, snubber capacitors \( C_1 \)–\( C_4 \), which were connected in parallel with switches \( S_1 \)–\( S_4 \), were used. The high-voltage transformer and the VD circuit are adopted at the output side to achieve a high step-up gain. In particular, capacitors \( C_p_1 \)–\( C_p_4 \) in the high-voltage parts have the same capacitance and operate as a parallel resonant capacitor with a value that is relatively very small compared with the series resonant capacitor (approximately on the order of 10). Thus, two resonant frequencies occur in one switching cycle because of the time difference in the charging and discharging between the two capacitors.

In view of capacitors \( C_p_1 \)–\( C_p_4 \), the features of the proposed HVCC are as follows.

To achieve a high-voltage output, a series stacking method is required. In a device with a large power rating, the series stacking method is not required; however, its characteristics in terms of the loss and at high frequencies are not good. Therefore, we employ devices with a low saturation voltage and an excellent frequency response.

Among the many stacking methods that use the other component instead of a resistor, one that employs a metal-oxide varistor or snubber is the most common.

The inclusion of passive voltage balancing components in the high-voltage circuit can increase losses. Thus, resistors...
should be avoided where possible and low loss capacitors should be used for dynamic voltage sharing. The capacitor used to balance voltage stress is usually selected to be around 10 times the junction capacitance of the diode [15]. In the proposed circuit, this capacitor is also used as a resonant element owing to the charging and discharging processes per each switching period when the diodes are forward and reverse biased.

The combination of the parallel and the series resonant capacitors (the latter being significantly larger that the former) forms two resonant points in the frequency spectrum for the circuit. This result in the current waveform having a trapezoidal shape. Fig. 3 shows the difference between the improved and conventional resonant current waveforms. This improved resonant current can reduce the conduction loss and increase snubber capacitance compared with the conventional resonant current owing to the low crest factor and fast rising time. The resonant converter in the CCM generally uses a snubber capacitor to restrict the voltage rise and reduce the turn-OFF switching loss. However, it is limited because of the slow rising and falling times of the conventional resonant current. A large capacitance is allowed because the snubber capacitor can fully charge and discharge through the improved resonant current. A suitable design for the snubber is thus required, which considers hard switching, as the energy stored in the resonant tank is different.

**B. Analysis of the Operating Mode of the Developed HVCC**

Each operating mode is shown in Fig. 4. The equivalent circuit of mode 1 operation is especially shown in Fig. 5.

**Mode 1:** Before switches $S_1$ and $S_4$ are turned ON, parallel resonant capacitors $C_{p1}$ and $C_{p4}$ are charged due to the reverse bias condition of the diodes $D_5$ and $D_7$. Meanwhile, parallel resonant capacitors $C_{p2}$ and $C_{p3}$ have a ZV. When $S_1$ and $S_4$ are turned ON, the resonant current flows through series resonant tank $L_r$ and $C_r$, and the secondary side of the transformer transfers energy. As the first resonant current path in the secondary side, $C_{p1}$ and $C_{p4}$ discharge to ZV. Meanwhile, $C_{p2}$ and $C_{p3}$ are charged. The resonant current return path is formed through $C_{f1}$ and $C_{f3}$ during the discharging of $C_{p1}$ and $C_{p4}$.

**Mode 2:** When $C_{p1}$ and $C_{p4}$ discharge to ZV, the resonant current path is continuously formed through diodes $D_5$ and $D_7$. $C_{p1}$ and $C_{p4}$ do not contribute to the resonance. Thus, the resonant frequency is determined by series resonant tank $L_r$ and $C_r$.

![Fig. 3. Comparison of the two resonant current waveforms.](image)

![Fig. 4. Operating mode diagrams of the proposed topology.](image)
Mode 3: When \( S_1 \) and \( S_4 \) are turned OFF by the switching signal, the existing energy on snubber capacitors \( C_2 \) and \( C_3 \) is transferred to \( C_1 \) and \( C_4 \) via the freewheeling path. If the resonant tank has sufficient energy to discharge and charge the snubber capacitors, the turn-OFF loss in \( S_1 \) and \( S_4 \) is reduced.

Mode 4: After fully charging and discharging the energy of the snubber capacitors, the remaining resonant energy is returned via \( D_2 \) and \( D_3 \). Therefore, \( S_2 \) and \( S_3 \) can turn-ON the ZV switching because the voltage across \( D_2 \) and \( D_3 \) is almost zero.

Modes 5–8: Complementary operations in \( S_2 \) and \( S_3 \).

C. Gate Drive Circuit With ZV Detection

After completely discharging the snubber, the voltage across the switch should be zero. However, in case of the switching with a fixed dead time, implementation of soft switching in all load ranges is difficult because the discharging time of the snubber varies depending on the resonant tank energy. To prevent a hard-switching turn-ON, a special circuit is required to detect the ZV condition across the switch and then drive the Insulated-gate bipolar transistor (IGBT). Thus, we propose a gate driver for the HVCC to sense the voltage across the switch and to provide a flexible dead time using an \( RC \) circuit time constant. Although the resonant tank lacks sufficient energy to completely discharge the snubber, the switching signal with a maximum dead time can be operated for continuous charging. Fig. 6 shows the conceptual diagram of the proposed gate driver.

Even if a gate signal with specific minimum dead time is sent to the gate drive, it retains a flexible dead time until the voltage of the IGBT collector and emitter (\( V_{CE} \)) is at ZV. After detecting \( V_{CE} \) as zero, the turn-ON signal is sent to the IGBT gate when the snubber completely discharges. From aforementioned description, it should be noted that the minimum dead time is required for avoiding shoot through in the H-Bridge.

D. Simulation of the Designed HVCC

The detailed design parameters depending on the specifications of the HVCC are shown in Table II and are verified with a PSpice simulation.

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Fig. 7(a) shows the resonant current flowing into the resonant tank and the voltage across the series resonant capacitor. As mentioned earlier, the waveform of the resonant current has a trapezoidal shape. The observed ZV turn-ON is shown in Fig. 7(b). The crest factor is estimated as 1.24, which is lower than that of the general sinusoidal waveform (1.44), using the peak and rms values of the resonant current. Under the CCM, turn-OFF switching loss is inevitable. Thus, various simulations were performed that focus on the switching losses according to snubber capacitance: 100, 150, and 300 nF. The 300-nF capacitor was selected as a suitable value for the minimum loss under the above rating conditions (Fig. 8).

The 300-nF capacitance of snubber helps to reduce the turn-OFF energy loss up to 0.9 mJ by decreasing the \( V_{CE} \) slope when the switch current is decreasing. In addition, the saturation of the magnetic devices such as the inductor and transformer was examined by considering the core size. The overall results of the simulation are summarized in Table III. The measured system efficiency was 94% by considering the total losses (2.4 kW).

III. IMPLEMENTATION OF THE DEVELOPED HVCC

A. Implementation of the High-Frequency Inverter

We chose the inverter components on the basis of the simulation, as discussed earlier. Considering the rms current and \( V_{CE} \), the FF200R12KT4 IGBT module was selected. A relatively simple filter design is allowed for a low-frequency input ripple because the capacitor charger is used to target a larger capacitor. This means that the input filter did not require bulky components such as the dc reactor and electrolytic capacitor; thus, high power density was realized. In addition, this design can improve the power factor through the optimized design of the three-phase rectifier and the dc-link capacitor without employing a power-factor correction circuit. Finally, all components such as the IGBT switch, snubber, three-phase diode, and dc-link capacitor were mounted on a printed circuit board (PCB) plate.

A design approach was considered to meet the required resonant tank parameters, including those of the inductor and the capacitor. Generally, the inductance is proportional to the square of the number of turns and the cross-sectional area of the winding and inversely proportional to the airgap length. A U-shape core was chosen for the convenience of the structure and production, and a PC 40 material core was chosen depending on the operating switching frequency. From the calculation using the resonant current and core geometry coefficient to prevent saturation, the core size was determined to be 120 mm \( \times \) 160 mm \( \times \) 40 mm with a 2-cm gap. Additionally, the number of turns necessary to meet the required inductance was selected as 21. We used a ready-made polypropylene capacitor for the resonant capacitor, and a detailed model was determined by considering the rms current and voltage rating.

B. Implementation of the High-Voltage Components

1) High-Voltage Transformer: The high-voltage transformer must be carefully designed to avoid saturation, minimize loss,
and reach the required insulation levels without negatively affecting operation of the overall circuit [26], [27]. The transformer might be saturated by the operating frequency and voltage at the primary side. Therefore, the magnetizing inductance should be increased to prevent transformer saturation, i.e., an increase in the primary-side winding is required. To maintain the same turn ratio, on the other hand, the secondary winding needs to be increased proportionally. In view of this design, the high-voltage transformer should be considered as follows: 1) the turns of primary winding should be suitable for preventing saturation as well as for allowing easier winding of secondary winding; 2) the turns ratio should be maintained for achieving desired output voltage; and 3) the insulation between the primary and secondary windings and the insulation among the secondary windings were reinforced. Methods such as increasing the number of cores or winding area are used for maximizing the magnetizing inductance, but there exist drawbacks such as bulk and high production cost. Thus, the turns ratio of the secondary winding was increased, which was required to increase the area of the secondary winding. Generally, the secondary side is manufactured as shown on the left-hand side of Fig. 9(a) and uses two or more
layers to meet the requirements of the secondary winding. The secondary winding must add a gap layer for insulation; however, the height of the layer is correspondingly reduced as the number of layers is increased. Furthermore, layer expansion is limited because of the short distance between the two bobbins in the core. To solve this problem, a method was suggested wherein multiple transformers be connected in series behind the rectifier [9]. However, the insulation distance in the secondary-side winding was the main consideration, and the power supply was excessively bulky to ensure the reliability of the insulation.

Therefore, the secondary bobbin of the proposed HVCC was designed as a horizontal layer structure to solve this problem [the right-hand side of Fig. 9(b)]. This bobbin has the following advantages. First, it can be used to maximize the area of each layer, which means that the same number of turns wound per layer can be used to maximize the area of the layer without a winding gap because the voltage between the vertical layers in one layer is relatively small. Second, sufficient insulation distance can be obtained between the adjacent bobbins because the design fully meets the requirement for the number of turns. In addition, the bobbin was specifically fabricated from a Teflon material with excellent insulating properties.

Fig. 9(b) shows the structure of the proposed bobbin. The UU 120 × 160 × 20 core model was used. The primary bobbin surrounded the vertical surface of the core, and the secondary bobbin overlapped on the outside primary surface. The secondary was wound on two horizontal layers using a long wire connected through a hole in the center of the two layers. After the winding was completed, the wire terminal was electrically connected to the adjacent wire. Finally, the number of turns in the secondary side satisfied the requirement for the number of Turns, and the top and bottom of the wire were connected to the high-voltage rectifier.

C. High-Voltage Rectifier

In general, high step-up converters use the VD technique to achieve a high-voltage gain. Fig. 10 shows the VD circuit of the proposed HVCC. The rectifier contains two PCBs.

Each PCB was formed by stacking 21 diodes (D5−1−D5−21 and D8−1−D8−21), represented by one diode symbol (D5 and D8) in Fig. 2. The optimal placement of the required devices depends on the oil tank size. Therefore, we manufactured the PCBs in three layers with seven diodes per layer and placed them in the gaps between the layers to rein-

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**TABLE III**

| Simulation conditions: Vdc = 490 V, f = 23 kHz, Rload = 40 kΩ, Pout = 40 kW |
|---|---|
| Output voltage, Vdc | 40 kV |
| Output power, Pout | 40 kW |
| Peak value of resonant current, Ires,peak | 166.25 A |
| RMS value of resonant current, Ires,rm | 135.43 A |
| Crest factor, CF | 1.25 |
| Peak value of secondary winding current, Isec,peak | 3.75 A |
| RMS value of secondary winding current, Isec,rm | 3.03 A |
| Average loss of each IGBT, PIGBT,avg | 154.18 W |
| Estimated energy losses, Eps, Eps, Eps | 0, 0.9, 5.8 mJ |
| Estimated primary winding conduction loss, Ppri | 130.18 W |
| Estimated secondary winding conduction loss, Psec | 269.33 W |
| Estimated input power line conduction loss, Pline,loss | 51.31 W |
| Estimated total loss, Ptotal,loss | 2.4 kW |
| Estimated overall efficiency, ηtotal,eff | 94% |
| Peak magnetic flux density of resonant inductor B5,peak | 1.02 K |
| RMS magnetic flux density of resonant inductor B5,rm | 0.78 K |
| Peak magnetic flux density of transformer B6,peak | 3.01 K |
| RMS magnetic flux density of transformer B6,rm | 1.86 K |

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Fig. 8. Simulation results of the switching losses according to the snubber capacitance.

Fig. 9. Picture of transformer. (a) Left: comparison of conventional and right: proposed secondary bobbin. (b) Assembled transformer.
force the insulation from the breakdown at the PCB surface. We installed the capacitor for high-voltage balance and parallel resonant capacitance across the diode. The RC divider circuit, which measured and fed the output voltage and charging current, was placed next to the rectifier.

IV. EXPERIMENTAL RESULTS

Various experiments using resistive and capacitive loads were conducted to verify the features and performance of the developed HVCC that applied the proposed high-efficiency resonant converter. The feasibility of the voltage and current control was confirmed by the experimental results. In addition to the waveforms, efficiency, and power factor, the frequency characteristics of the developed HVCC were measured with respect to the output power. Finally, a 40-kV charging test with a capacitive load was carried out.

A. Experimental Results With the Resistive Load

1) Frequency, Efficiency, and Power Factor Characteristics:
Fig. 11 shows the experimental waveforms for a 40-kW load under rated conditions (40 kV and 1 A) using a 40-kΩ resistor. The resonant current waveform is very similar to the above-mentioned shape. The measured peak and rms values are 178 and 136 A, respectively. It should be noted that the polarity of measured resonant current is opposite because the resonant current must lag the full-bridge output voltage for above resonant operation. The test results of the developed HVCC almost match the simulation results. The control range of the HVCC is confirmed to be from at least 6–40 kV. The minimum output voltage is obtained by the relay mode, which is designed to force switching off [13].

Fig. 12(a) shows the developed HVCC operating under similar frequency response characteristics as that of the series resonant converter, as well as the high efficiency within the rated condition under the improved resonant current waveform. Using power analyzer (Fluke 423), the efficiency was measured from three-phase ac input to high-voltage dc output. Fig. 12(b) and (c) shows the efficiency and power factor curve with maximum values of 96% and 0.96, respectively. The operation of HVCC is desired within the range from 20 to 40 kV because it has a high efficiency of over 90%.

2) Temperature Measurement: This application was developed to charge the electric armor capacitor for 30 s, which requires 600 kJ of energy. The reliability assessment involved a long-term operation test using MV 100 for 1 h (Fig. 13).

Using a forced-air cooling system, the IGBT temperature began to saturate at approximately 70 °C. The oil tank and peripheral components showed a continued rise in temperature. However, the elevated temperature was not expected to cause any major problems to the charging process.
B. Capacitor Charging Test

The developed HVCC was tested using a capacitive load to verify the performance of the HVCC, such as charging time and average charging current. Fig. 14 shows the capacitor charging test result with an 11-μF capacitor from 0 to 40 kV. The measured average charging current and charging time were measured at 1.08 A and 0.408 s, respectively, which closely matched the calculated results. The charging energy of the capacitive load was 8.8 kJ and the average charging energy was 21.56 kJ/s.

The resonant current was measured for every 10 kV. When the charging voltage of the capacitive load was low, the resonant current waveform failed to form a trapezoidal shape because the parallel resonant capacitor successively charged and discharged. As the charging voltage approached the rated voltage, the resonant current waveform changed to a trapezoidal shape. Additionally, hard switching did not occur because of the complete discharge of the snubber in all charging-voltage ranges. Therefore, we verified that a 300-nF capacitance is suitable for the HVCC.

V. Conclusion

This paper has examined the performance of a 40-kV, 20-kJ/s HVCC in terms of its design, simulation, implementation, and test results. This HVCC is based on a high-efficiency SPRC, whose parallel resonant capacitor is located at the transformer secondary side to balance the voltage across the rectifier diodes and to improve the resonant current waveform. In particular, because the parallel capacitance was relatively small compared with the series capacitance, two resonant frequencies existed in one switching cycle. Therefore, the conventional sinusoidal shape of the resonant current waveform was transformed into a trapezoidal shape owing to the time difference in charging and discharging between the two capacitors. Thus, the conduction loss is reduced by the low crest factor. Additionally, the capacitance of the turn-OFF snubber can be increased through the fast rising time of the resonant current.

For the insulation reinforcement, the high-voltage components such as the transformer and rectifier were impregnated in the oil tank. In the high-voltage transformer case, breakdowns occurred depending on the structure and material of the bobbin. To solve this problem, a bobbin fabricated from Teflon and a horizontal layer structure was proposed. To obtain a higher voltage gain and reduce the transformer burden, a VD circuit was designed and adopted.

The proposed 40-kV, 20-kJ/s HVCC was developed with a high power density of 547 W/L. A 96% efficiency and a 0.96 power factor were achieved under a resistance load. The function of the capacitor to balance the diode voltages was verified by measuring the voltage in each diode. A long-term operation test was performed to test the insulation and reliability.

Finally, a charging test was conducted using an 11-μF capacitance. The results verified that charging to 40 kV required 0.408 s, and the average charging current was 1.08 A.

In our future work, we will use the proposed HVCC to study the performance enhancement of a dc power supply, such as heat emission, output filter design, and ripple response of the main controller.
REFERENCES


Ji-Woong Gong received the B.S. degree in electrical engineering from Chonnam National University, Gwangju, Korea, in 2012, and the M.S. degree in electrical engineering from the University of Science and Technology, Daejeon, Korea, in 2014. He has been with the Korea Power Exchange, Seoul, Korea, since 2011. His current research interests include the soft-switched resonant converter applications and high-voltage pulsed-power supply systems.

Hong-Je Ryoo received the B.S., M.S., and Ph.D. degrees in electrical engineering from Sungkyunkwan University, Seoul, Korea, in 1991, 1995, and 2001, respectively. He was with the Wisconsin Electric Machines and Power Electronics Consortium, University of Wisconsin-Madison, Madison, WI, USA, from 2004 to 2005, as a Visiting Scholar for his post-doctoral study. Since 1996, he has been with the Korea Electrotechnology Research Institute, Changwon, Korea, where he is currently a Principal Research Engineer with the Electric Propulsion Research Division and a leader of the Pulsed-Power World Class Laboratory. He has been a Professor with the Department of Energy Conversion Technology, University of Science and Technology, Daejeon, Korea, since 2005. His current research interests include pulsed-power systems and their applications, and high-power and high-voltage conversions.

Dr. Ryoo is a member of the Korean Institute of Power Electronics and the Korean Institute of Electrical Engineers.
Suk-Ho Ahn (M’11) received the B.S. degree in electrical engineering from Incheon National University, Incheon, Korea, in 2009. He is currently pursuing the M.S. and Ph.D. degrees with the University of Science and Technology, Daejeon, Korea. His current research interests include the soft-switched resonant converter applications and battery charger systems.

Sung-Roc Jang was born in Daegu, Korea, in 1983. He received the B.S. degree from Kyungpook National University, Daegu, in 2008, and the M.S. and Ph.D. degrees in electronic engineering from the University of Science and Technology, Daegoeon, Korea, in 2011. He has been a Senior Researcher with the Electric Propulsion Research Center, Korea Electrotechnology Research Institute, Changwon, Korea, since 2011. His current research interests include high-voltage resonant converters, and solid-state pulsed-power modulators and their industrial applications.

Dr. Jang was a recipient of the Young Scientist Award at the 3rd Euro-Asian Pulsed-Power Conference in 2010, and the IEEE Nuclear Plasma Science Society Best Student Paper Award at the IEEE International Pulsed-Power Conference in 2011.