Solid-State Bipolar Pulsed-Power Modulator Based on a Half-Bridge Power Cell Structure

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Abstract—This paper addresses the design of a solid-state bipolar pulsed-power modulator based on a series of stacked power cells that realize a simple and robust structure. Each cell is charged in parallel by an LCC resonant converter independently of the discharging loop. A passive cell-balancing design is implemented. The power cell using insulated gate bipolar transistors (IGBTs) can operate in bypass mode without an additional component, and the circuit operation was analyzed. A simple gate driving method, which provides synchronized gate signals without an extra power source of each gate driver using two control loops and isolation transformers, is implemented for the proposed bipolar pulsed-power modulator based on stacked cells. Moreover, an unexpected gate turn-on problem was solved by an additional off signal. To validate the proposed structure and the gate driving scheme, a three-cell, 1.2-kV, 110-A, 1.5- to 4-μs, 3-kHz laboratory experimental prototype test was conducted. The results proved the reliability of the proposed solid-state bipolar pulsed-power modulator.

Index Terms—Capacitor charger, gate drive circuit, power cells, solid-state bipolar pulsed-power modulator.

I. INTRODUCTION

T

HE environment and sanitation have become popular topics in science and industrial technology in the twenty-first century. Accordingly, interest in pulsed electric fields (PEFs) and dielectric barrier discharges (DBDs) for liquid food pasteurization, wastewater treatment, and air purification systems is increasing [1]–[5]. Research on the topologies of the bipolar pulsed-power modulator has been conducted actively because the power supply based on the bipolar topology is more suitable for these applications than the unipolar topology.

As a method of constructing a bipolar pulse modulator, structures combining a unipolar solid-state Marx generator and an H-bridge have been introduced [6], [7]. Because a series stack of insulated gate bipolar transistors (IGBTs) is implemented to generate high voltage over the rated voltage of the switch used in the inverter, a voltage-balancing technique between the IGBTs is needed. To address this issue, a cascade bipolar arrangement of two unipolar pulsed-power modulators has been suggested [8]. Similarly, combinations of submodules have been presented to increase the output voltage [9], [10].

In a voltage-multiplier-based bipolar pulsed-power modulator, only capacitors and switches have been used with low-voltage stress [11]. However, the number of components is doubled and complicated charging modes are required to increase the number of stages. A topology for the modified voltage multiplier has been proposed as one of the methods to reduce the number of circuit elements [12]. In bipolar pulsed-power modulators based on a voltage multiplier, however, the power source does not charge the storage capacitor directly and the average power is limited.

Solid-state Marx-generator structures have been adopted for several bipolar pulsed-power modulators [13]–[15]. In this topology, each of the cells is charged by the input power source and voltage balancing can be achieved. Switches for charging as well as switches for generating bipolar pulses are required, and each of the charging switches needs switching control. An improved structure with a reduced number of components has been suggested [16].

Generally, bipolar pulsed modulator based on a half-bridge inverter is not used because it is difficult to charge bipolar high voltage to generate high-voltage bipolar pulses. In [17], it is tried to use half-bridge cell stacking to generate the high-voltage bipolar pulse. But, this topology has drawbacks that modulations of pulse width, pulse repetition rate, and the output voltage level are limited.

Stacked power cells topologies need a synchronized switching signal and isolated power for driving switches. The general gate driving method to provide isolated and synchronized gate signals needs a separate power source for each gate driver [18]. To generate high-voltage pulses, the number of discharging switches increases and many power sources for gate driving are required, complicating the structure and switching control. Implementing a control-loop gate driving method is a solution to this limitation of the conventional method [19], [20]. When gate driving with the control-loop method, ON–OFF pulses from the pulse control inverter enter into a single loop and are delivered to each of the gate drivers simultaneously via small transformers. A 40-kV solid-state unipolar pulsed-power modulator realizes the compact structure and simple switching control using the control-loop gate driving method [20].

In this paper, a solid-state bipolar pulsed-power modulator based on a series of stacked power cells is proposed with a simple scheme for minimizing the number of components. The proposed power cell based on a half-bridge structure realizes a bypass mode without an additional component. The proposed
topology has achieved synchronized switching control by applying a modified control-loop gate driving method for bipolar pulsed-power modulators. Because the control loop provides the gate drivers with isolated and synchronized signals as well as power for gate driving, no additional power source is required, simplifying the structure of the proposed modulator. An LCC resonant converter with current source characteristics was designed as a capacitor charger. Independently of the discharging loop, storage capacitors of each power cell are charged in parallel via a multiwinding transformer of the capacitor charger and a voltage-doubler rectifier, requiring no additional charging switch. Moreover, charger design techniques for passive cell balancing are employed. Finally, to prove the reliability of the proposed structure and gate driving method, a laboratory prototype has been fabricated and tested.

II. Bipolar Circuit Operation

The proposed power cell, based on a typical half-bridge structure, consists of two IGBT switches and two storage capacitors. Both IGBT switches are designated as positive and negative discharging switches. The storage capacitors are charged in parallel by a capacitor charger. A positive or negative pulse is generated depending on the switch being turned on. When the same-side switches of \( N \) stacked power cells are turned on simultaneously, the cells are connected in series and the pulse of \( N \cdot V_c \) (where \( V_c \) is the voltage of a single capacitor) is discharged to the load. In addition, the proposed power cell realizes bypass operation without additional components.

A. Operation Principle

The proposed bipolar pulsed-power modulator operates basically as a positive pulse discharging mode and a negative pulse discharging mode, as shown in Fig. 1. Bypass modes essential for the series stack of power cell structure are also implemented, achieving robust operation.

1) Positive Discharging Mode: Fig. 1(a) shows the operation when the storage capacitors \( C_2, C_4, \ldots, C_{2N} \) charged in parallel are connected in series when switches \( S_2, S_4, \ldots, S_{2N} \) are turned on. The \( N \) series connected capacitors generate a positive pulse, and the output pulse voltage to the load is as follows:

\[
V_o = +N \cdot V_c \tag{1}
\]

where the voltage of a single storage capacitor is \( V_c \). When the positive pulse is generated, voltage \( 2V_c \) is applied to the collector–emitter of the opposite-side switches that are turned off, which is utilized to determine the rated voltage of a single discharging switch.

2) Positive Bypass Mode: To generate a positive pulse, all the positive discharging switches should be turned on. The positive bypass mode operates when the gate signals are not well synchronized, or a malfunction occurs in the gate driver of the switch. Without a bypass circuit, the sum of the voltages on the series connected capacitors can damage the switch which fails in synchronization. The bypass operation, in which the antiparallel diode of \( S_3 \) provides the current path when \( S_4 \) is not turned on, is shown in Fig. 1(b).

The opposite polarity voltage \( -V_c \) is generated in the dysfunctional cell, and, as a result, the voltage applied to the load is

\[
V_o = + (N - 2) \cdot V_c \tag{2}
\]

The voltage across the collector–emitter of \( S_3 \) is \( -2V_c \), which is below the rated voltage, and the circuit is safely protected. As a result, without additional bypass elements, the bypass operation increases the reliability and robustness of the proposed pulsed-power modulator.

3) Negative Discharging Mode: The negative discharging mode is similar to the positive discharging mode. As shown in Fig. 1(c), the serial connection of the charged storage capacitors \( C_1, C_3, \ldots, C_{2N-1} \) generates a negative pulse and the output pulse voltage to the load is

\[
V_o = -N \cdot V_c \tag{3}
\]
4) Negative Bypass Mode: In the case of the synchronization failure or malfunction of the gate driver in the negative discharging mode, similar to the positive bypass mode, the antiparallel diode of the opposite switch provides the current path to enable bypass operation. The operation of the negative bypass mode when $S_3$ is not turned on is shown in Fig. 1(d). The output pulse voltage in the negative bypass operation is

$$V_o = -(N - 2) \cdot V_c. \quad (4)$$

III. Design and Implementation of the Proposed Bipolar Pulse Modulator

The overall scheme of the proposed bipolar pulsed-power modulator is shown in Fig. 2. A three-cell bipolar pulsed-power modulator, comprising a current source capacitor charger using an LCC resonant converter and three power cells, is designed to validate the proposed topology. The LCC resonant converter comprises an LCC resonant tank (series resonant inductor $L_s$, series resonant capacitor $C_s$, and parallel resonant capacitor $C_p$), a multiwinding isolation transformer, and an H-bridge with snubber capacitors in parallel with each switch. Also, three parallel secondary windings of the multiwinding transformer are connected in parallel with the power cells through voltage-doubler rectifier circuits.

A. Capacitor Charger

The LCC resonant converter is used to charge the storage capacitors independently of the discharging loop through the multiwinding isolation transformer and rectifier. Employing multiwinding transformers for each loop provides the advantages of low cost and a simple structure [19]. Low conduction loss and switching loss can be obtained by using an LCC resonant converter operating in a continuous conduction mode, and the charging voltage can be controlled by adjusting the switching frequency. In addition, the leakage inductance and parasitic capacitance of the multiwinding isolation transformer were utilized for a part of the LCC resonant tank.

The parallel resonant capacitor ($C_p$) can change the current waveform into a trapezoidal shape, which decreases the crest factor [21]. Also, a high resonant current can be obtained through the operation to charge $C_p$. Before the switches are turned on, sufficient resonant current enables the complete discharge of the snubber capacitors, which is designed to minimize the turn-off loss of the switches, within the operating frequency range.

Under light-load operation, however, the snubber capacitor that is incompletely discharged due to the low resonant current can lead to hard switching. Therefore, the operating frequency is determined by considering both the rated operation and the frequency range where hard switching does not occur. The series resonant frequency of 9 kHz and the parallel resonant frequency of 139 kHz were set according to the operating frequency, and the parameters of the resonant tank were determined accordingly. A C2M0040120 silicon carbide (SiC) power MOSFET was selected as a semiconductor switch for the full-bridge inverter by considering the maximum resonant current value and switch characteristics at high-switching-frequency operation. The specifications and design parameters of the LCC resonant converter are summarized in Table I.

B. Isolation Multiwinding Transformer and Series Resonant Inductor

The process of designing the transformer and series resonant inductor of the resonant LCC converters is as follows. The primary-side turns are determined so that the transformer is not saturated by the input voltage during the minimum-switching-frequency operation. The transformer turns ratio is calculated according to the voltage ratio between the primary and secondary sides, and the number of secondary windings can be easily calculated by multiplying the transformer turns ratio and the number of primary turns. In addition, a bobbin design is implemented to ensure insulation between the primary and secondary windings and between each of the three parallel secondary windings [22]. The series resonant inductor

![Overall configuration of the proposed N-power-cell stacked bipolar pulsed-power modulator. (a) Capacitor charger and pulse generator. (b) Gate drive circuits and double control loops.](image-url)
TABLE I

SPECIFICATIONS AND DESIGN PARAMETERS FOR THE CAPACITOR CHARGER

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{rated}}$</td>
<td>1.2 kW</td>
</tr>
<tr>
<td>Single-phase AC input voltage</td>
<td>220 V$_{\text{rms}}$ ± 10%</td>
</tr>
<tr>
<td>Rectified DC input voltage</td>
<td>310 V ± 10%</td>
</tr>
<tr>
<td>$V_{\text{out}}$</td>
<td>1.2 kV (400V/cell)</td>
</tr>
<tr>
<td>$f_{\text{sw}}$</td>
<td>85–240 kHz</td>
</tr>
<tr>
<td>Snubber capacitor</td>
<td>1 nF</td>
</tr>
<tr>
<td>Series resonant inductor ($L_s$)</td>
<td>263 μH</td>
</tr>
<tr>
<td>Series resonant capacitor ($C_s$)</td>
<td>1 μF</td>
</tr>
<tr>
<td>Parallel resonant capacitor ($C_p$)</td>
<td>4.95 nF</td>
</tr>
<tr>
<td>Turns ratio (transformer)</td>
<td>22:31 (3 parallel)</td>
</tr>
<tr>
<td>Core (transformer)</td>
<td>PC40 EIC120 CORE</td>
</tr>
<tr>
<td>MOSTET</td>
<td>CREE, C2M0040120</td>
</tr>
<tr>
<td>Rectifier diode</td>
<td>CREE, C3D25170H</td>
</tr>
</tbody>
</table>

is implemented so that the sum of the value of the transformer leakage inductance and the value of the inductance of the series resonant inductor is the $L_s$ design value of the resonant tank. The $L_s$ design value takes into account cell balancing as explained in Section III-C. The air gap and the number of turns of the series resonant inductor are determined so that it is not saturated by the resonant current. Furthermore, because the resonant LCC converter operates at a high frequency of 85 to 240 kHz, a 0.08-mm 500 Litz wire is used as the winding of the resonant inductor and the primary winding of the transformer.

C. Voltage Balancing of the Secondary Winding

Each of the three parallel secondary windings of the transformer is connected to the two storage capacitors of the power cell through a voltage-doubler circuit, as shown in Fig. 2. When three secondary parallel windings and the primary winding are coupled, the structural differences cause the difference in the leakage inductances between the secondary windings, inducing voltage unbalancing of the power cells. The voltage unbalancing becomes even worse as differences between secondary parasitic elements become larger.

To solve the unbalancing of power cells, a primary-side series resonant inductor with an inductance factor of 20 greater than the differences of the secondary-side leakage inductances is needed. The series resonant inductor significantly reduces the influence of differences in leakage inductance, minimizing cell unbalancing.

D. Cell

The proposed power cell is based on a simple half-bridge structure consisting of two IGBTs and two capacitors. When the upper or the lower discharging switches in each power cell are turned on at the same time, the charged storage capacitors are connected in series and generate a pulse. At this instant, the voltage across the two storage capacitors is applied to the opposite-side switches that are not turned on. Under the rated condition, a single capacitor is charged to 400 V, so the 800-V voltage is applied to the switch, which is the main consideration in selecting the discharging switch. Also, an antiparallel diode of the switch for bypass operation should be considered. An FGL40N120AND 1200-V NPT IGBT was selected as the discharging switch of the power cell, and its specifications are summarized in Table II.

E. Control-Loop Method for Gate Driving Circuit

General topologies adopt switching control based on optical fiber for providing an isolated and synchronized gate signal. This method needs an independent power source for each gate driver, complicating the structure and increasing the cost [18]. A gate driving circuit based on the control-loop method eliminates this drawback [19], [20]. The ON–OFF pulse of the control inverter, controlled by the pulse controller, enters the single control loop and is simultaneously transmitted to each of the gate drivers via the isolation transformer. The ON–OFF pulse is not only a switching signal but also a power source for the gate driving circuit. Implementing this method simplifies the structure and minimizes the number of control components.

The conventional control-loop method was modified and applied to the proposed bipolar pulsed-power modulator. Double control loop is used for bipolar pulse discharging, and each control loop consists of a winding and a control inverter, as shown in Fig. 2(b). Two control inverters are driven independently for positive and negative pulses. In using a double control loop, one loop is utilized for positive discharging signal and the other for a negative discharging signal. The output pulse width is adjusted by the interval between the ON pulse and the OFF pulse from control inverter. Also, the repetition rate of the pulse generation is adjusted by the switching frequency of the control inverter. An overview of the gate driving of the pulse generator is shown in Fig. 3.

F. IGBT Turn-On Problem in the Off-State

The control inverter, the H-bridge controlled by the pulse controller, generates a positive voltage (ON pulse) and a negative voltage (OFF pulse), as illustrated in Fig. 3. Through the control loop, these outputs of the control inverter are transmitted to the gate driver as power and the gate signal for the gate driving circuit. When the gate driver receives the ON pulse from the control loop, 20 V is applied to the gate–emitter of the discharging switches until it receives an OFF signal.

During the interval of the ON–OFF pulse signal, turn-on is maintained, which generates a positive or negative output
The parasitic capacitances of the discharging FGL40N120AND 1200-V NPT IGBT are as follows:

$$C_{ge} = 3075 \ \text{pF}, \quad C_{ce} = 245 \ \text{pF}, \quad C_{gc} = 125 \ \text{pF}.$$  

Because $V_c$ (the increment of $V_{ce}$) is divided into $V_{cg}$ and $V_{ge}$ in inverse proportion to each of the capacitances, $V_{n,ge}$ under rated condition is approximately calculated as

$$V_{n,ge} \equiv V_c \frac{C_{ge}}{C_{ge} + C_{gc}} \approx 16 \ \text{V}. \quad (9)$$

$V_{n,ge}$ above the threshold voltage is reduced via a pull-down resistor ($500 \ \Omega$) in the gate driver, which takes a certain amount of time until it becomes lower than the threshold voltage. That is, when the positive discharging IGBT is turned on, the negative discharging switch is turned on for a certain period of time and the same phenomenon occurs in the negative discharging mode. This phenomenon may damage the circuit of the power cell.

In this paper, as shown in Fig. 3, when transmitting a pulse to an IGBT for output pulse discharging, an “additional gate-off pulse” is transmitted to the opposite switch, which should be turned off, preventing switch damage. $V_{ge}$, which is increased due to a sudden rise of voltage across the IGBT, is instantly reduced by the gate-off pulse, and abnormal operation does not occur.

IV. EXPERIMENTAL RESULTS

Based on this paper, various experiments were conducted to verify the characteristics and performance of the proposed structure and gate driving method. A laboratory prototype of a 1.2-kV, 110-A, 1.5- to 4-μs, 3-kHz, three-cell bipolar pulsed-power modulator with a noninductive resistor load has been employed for experimental verification. A Yokogawa DLM2024 (2.5 GS/s and 200 MHz) was used as an oscilloscope, a Tektronix P6015A (20 kV, 75 MHz, and 1000:1) was used as a voltage probe to measure the load voltage and current, and a Pearson Electronics model 4997 (100:1) was used as a current probe.

To verify the bypass operation, the output pulse voltage in the discharging mode and in the bypass mode were compared by turning off the negative discharging IGBT of the first cell under 600-V output condition which is half of the rated condition, as shown in Fig. 4. In the negative bypass mode, the output pulse voltage is about −200 V, which is minus the two capacitor voltages at −600 V output pulse voltage in the negative discharging mode. When the negative discharging switch of the first cell is not turned on in negative discharging, the voltage across the positive discharging IGBT of the first cell, $V_{CE,1p}$, is about 0 V. This means that the body diode of the IGBT is forward-biased and conducts current. It is verified that the bypass mode is operated when the discharging switch is not turned on. In addition, in the OFF-state, $V_{CE,1p}$ and $V_{CE,1n}$ are floated. A Yokogawa 701921 differential probe (1000:1) was used to measure the voltage across the discharging IGBT. To validate cell balancing, the voltages of the three power cells were measured under 800-V charging conditions. Fig. 5 shows that voltage differences of <±3% among the three cells were measured.
Experimental results comparing bypass operation with normal operation.

Comparison of charging voltage of each cell.

Voltage and current waveforms of the bipolar pulsed-power modulator underrated condition.

differential probe (1000:1) was used to measure the power cell voltage.

The experimental waveforms show a single pulse at rated operation (1.2 kV and 110 A) in Fig. 6. To vary the charging voltage of the power cell, the switching frequency of the charger was controlled by the charger controller, and the experiment was performed over a wide range from light-load operation to the rated operation. The output pulse voltage was increased by 200 V from 400 to 1200 V, as shown in Fig. 7(a).

The pulse width can be varied by adjusting the interval between the gate ON–OFF signal from the pulse controller. The experimental waveforms of the pulse width, which is increased from 0.5 to 4 μs in steps of 0.5 μs under the rated condition, are shown in Fig. 7(b).

The repetition rate of the pulse output can be controlled by adjusting the frequency of the control inverter in the pulse controller. Fig. 7(c) shows the output pulse waveform with a repetition rate of 3000 pulses/s. The specifications of the laboratory prototype of three-cell bipolar pulsed-power modulator are summarized in Table III.

To verify the feasibility of the proposed topology in high voltage, an experimental prototype with stacked six power cells was tested. Fig. 7(c) also shows 5-kV bipolar pulse waveforms.

V. CONCLUSION

A bipolar pulsed-power modulator based on a series of stacked power cells has been proposed. The proposed topology consists of series-connected power cells and a storage capacitor charger using an LCC resonant converter. A power cell with a simple and robust structure has been suggested. The power cell operates in bypass mode when synchronization fails without an additional component. A modified control-loop gate driver circuit has been applied to the proposed topology. Synchronized gate signals can be obtained without separate power sources for each of the gate drivers, which minimizes the number of components. Moreover, it is easy to vary the

<table>
<thead>
<tr>
<th>Input voltage</th>
<th>220 V_{dc, rms} ± 10%</th>
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<tr>
<td>Maximum output voltage</td>
<td>1.2 kV</td>
</tr>
<tr>
<td>Maximum output current</td>
<td>110 A</td>
</tr>
<tr>
<td>Maximum average power</td>
<td>1.2 kW</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1.5–4 μs</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>~3,000 pulses/s</td>
</tr>
</tbody>
</table>
pulse width and repetition rate. In this study, the use of an additional gate-off pulse solves the arm short problem that both switches are turned on. A 1.2-kV, 110-A, 3-kHz, three-power-cell stacked bipolar pulsed-power modulator was tested to validate the reliability of the proposed topology. In addition, the 5-kV test verified that the proposed half-bridge structure can be effectively used at high voltage as well.

REFERENCES


