Robust Design of a Solid-State Pulsed Power Modulator Based on Modular Stacking Structure

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Abstract—**This paper describes the design of a robust high-voltage solid-state pulsed power modulator (SSPPM), which requires reliable series stacking and driving of a number of semiconductor switches. For voltage balancing against overvoltage during both at transient and at steady-state, the power-cell-based modular stacking structure consists of an energy storage capacitor, bypass diode, and switching device (such as an insulated-gate bipolar transistor or a metal–oxide–semiconductor field-effect transistor (MOSFET)). In addition to the reliable voltage balancing of each switching device, the modular power cell stacking structure provides a fault-tolerant design by allowing individual protection circuit for each switching device. In this paper, the inclusion of a compensating third winding is proposed. This compensating third winding solves the voltage unbalance issue, which results from difference of leakage inductance of separate located transformer core, using magnetic flux compensation. A protection method using this compensating winding is also suggested to detect abnormal occurrences in each power cell under operating conditions. Additionally, an arc current protection circuit to ensure continuous operation of the SSPPM is designed. Through simulation and experimental results of tests on the SSPPM with the structure outlined earlier, it is verified that the proposed design can be used effectively, as it exhibits both robustness and reliability.**

Index Terms—**Protection circuit, pulsed power applications, solid-state pulsed power modulator (SSPPM).**

I. INTRODUCTION

RECENTLY, studies on the use of solid-state pulsed power modulators (SSPPMs) in pulse power applications have been undertaken, with a focus on device lifetime problems, pulse repetition rate and pulse width variation, and adjustment of pulse voltage, along with the need for direct current high-voltage power, etc. [1]–[9].

Configurations of existing SSPPMs include a pulse modulator using a high-voltage semiconductor device and a pulse modulator using a boost transformer, a Marx-generator-type pulse modulator with a semiconductor switching method, a pulse modulator applying a vector inversion technique, and a multilevel-type pulse modulator.

A pulse modulator using a high-voltage semiconductor device is composed of a basic circuit implemented through the use of a capacitor and a semiconductor switch. It operates by supplying instantaneous power through a semiconductor device after the capacitor is charged. Depending on the required generated pulse rating, repetition rate, and pulse rise time, high rating switches such as a GTO or an IGCT can be used in isolation, or low rating switches such as an insulated-gate bipolar transistor (IGBT) or a MOSFET can be connected in series. This method has the advantages of compact design, because of the simple circuit and wide variable pulse width range (through control of the switch) and easy repetition rate control. However, in order to generate a pulse with fast rise time and high repetition rate, the serial stacking of a switch is inevitable. This is because of constraints on the voltage rating of a semiconductor device. Further, it is difficult to expect efficient and reliable operation because an RCD snubber circuit for voltage balancing is required, and therefore losses increase. In addition, a switch actuation circuit is complicated, so it is not easy to protect against an arc current generated by the loads. Another disadvantage of this design is that the output pulse voltage is limited by the maximum output voltage of the charging capacitors [10]–[13].

A pulse modulator with a step-up transformer has the structure of boosting pulse generated by the capacitor's charging voltage and by switching that places the step-up pulse transformer, used for increasing the pulse voltage, to the rear of the switch. This is then applied to the loads. The advantage of a circuit with a step-up pulse transformer is that it can apply a high-voltage pulse to loads with a relatively low capacitor maximum voltage charge, and it therefore has the voltage rating of a semiconductor device. This can increase pulse voltage regardless of the rated voltage of a capacitor charger and reduce the number of semiconductor devices stacked in a series. However, the compact design of the circuit causes difficulties as the size of the power supply is increased, because of the additional pulse transformer, and the pulse width variation is limited. Additionally, a pulse with a fast rise time is difficult to achieve as a result of the leakage inductance of the transformer. A magnetic-pulse compression circuit can also be used; however, the overall efficiency is then reduced to 80%, and therefore, it is generally difficult to achieve high efficiency, even including the efficiency of the transformer. Further, the circuit configuration is complex because an additional configuration of the reset circuit is required to prevent saturation of the transformer. In addition, a parallel configuration is also required because the current stress is increased, while the voltage stress of the energy storage capacitor and semiconductor switch can be reduced using a step-up boost transformer [14].

A Marx-generator-type pulse modulator method using a semiconductor switch (instead of the conventional gas discharge

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switch in the Marx generator structure) passes a high-voltage pulse to loads by charging a large number of capacitors in parallel, through charging elements such as high-voltage charger and resistors, inductors or diodes, and then reconfiguring them in series with switches. Charging elements are also called isolation elements, because they provide a path for parallel configuration during charging while having high impedance during pulse discharge. Diodes play the role of removing the parallel configuration path while being reversely biased during discharge, as well as provide high impedance to high frequency signals. Large values are used in the case of resistance. A Marx-generator-type pulse modulator has the advantages of generating a high-voltage output pulse without the use of a pulse transformer, while using a capacitor charger with a low output voltage rating. In addition, pulse width and repetition rate variation are easy to achieve. However, serial stacking of the semiconductor switch is required, depending on the output voltage of the charger, and synchronization for the gate signal also needs to be considered. On the other hand, this design is disadvantageous in terms of cost and production efficiency because a number of charging devices and capacitors are required, and therefore, the circuit configuration is complicated. Moreover, to ensure reliability, a protection circuit to protect the semiconductor switch against arc condition is required [15], [16].

A pulse modulator applying a vector inversion technique charges the charger with 2 multiples of the amount of transformers, by using a number of coupled transformers and applying high voltages to loads by configuring them in series. When the charging switch (connected in series with the capacitor charger) is turned on, the capacitor (wired to the transformer) begins charging. If the switch is located between and connected to a primary and secondary transformer winding, after the capacitor is fully charged, one of two capacitors connected to each transformer changes polarity and all of the capacitors are then configured in series. This pulse modulator can function as a high-voltage pulse generator with a switch stack and a capacitor charger of low rated voltage. The structure is similar to the Marx generator system; however, the circuit configuration is relatively simple because transformers are used instead of charging elements. However, current stress is significant in the elements of this modulator, as a result of the use of a transformer. Additionally, cost and power density become problematic as an additional charge switch for charging and a number of transformers are used. Further, the design of this modulator prevents the pulse width from being controlled, and it is therefore difficult to utilize it in a variety of applications [17], [18].

A multilevel-type pulse modulator divides and shares high-voltage pulses using a number of capacitors and semiconductor switches without stacking semiconductor switching elements. The main features of this circuit are that a number of capacitors are configured in series using a high-voltage capacitor charger, and each capacitor is connected to the semiconductor element through a diode. Additionally, the voltage applied to each semiconductor element (without a separate voltage balancing circuit) is clamped to one capacitor voltage. This design has excellent efficiency and is inexpensive, because voltage balancing can be implemented without an additional snubber circuit. Further, implementation is easy, and a reliable operation can be expected because it is not necessary to consider synchronization of the switching signal. In addition, the multilevel-type pulse modulator can be used for various applications because not only the pulse width and the pulse repetition rate can be varied but also the voltage value of the pulse can be varied. On the other hand, the maximum output voltage is limited because, in order to generate a high-voltage pulse, a high-voltage capacitor charger with the same output voltage needs to be designed. This is disadvantageous in terms of production costs because, as an energy storage capacitor configured in series goes toward low pressure, the serial configuration of a large number of clamping diodes is required [19]–[23].

A simple and reliable pulse modulator using a semiconductor switch series configuration method in the power cell structure and composed of an energy storage capacitor and a bypass diode, along with a semiconductor element that counteracts the disadvantages of the configuration of conventional SSPPMs, is proposed. This paper introduces a serial configuration pulse modulator with such a power cell structure and suggests a design for facilitating a higher level of reliability of this type of modulator [24]–[26].

In this paper, a pulse modulator design to solve the charging voltage unbalance problem of the charging capacitors is proposed, through the addition of a compensating winding. This is used to compensate for the differences between the charging voltages occurring during the charging capacitor charging process. The power cells in the pulse modulator are connected in series, and a method for detecting any connection errors, part damage, or any abnormalities occurring in real time in the power cells during each power stage of system operation is outlined. Additionally, an arc protection circuit is proposed along with an explanation of its protection method. This works to guarantee the operation continuity of the pulse modulator during pulse power applications requiring continuous processing. To prove the effectiveness of the design and protection method proposed in this paper, a simulation is used to examine the response of the pulse modulator to actual charging voltage unbalance and arc discharge occurrence. The results are then discussed.

II. DESIGN OF THE SSPPM

A. Operation Principle of the Proposed Topology

Each power cell includes bypass diodes connected at both ends of a semiconductor switch, a rectification diode connected at the end of a charging capacitor, a gate signal to drive the semiconductor switch through the supply of the gate power (which is the control signal supplied by the control inverter) insulated in the control loop of a single turn, and a power switch driver (gate drive circuit).

Fig. 1 illustrates the conduction device and current path when a pulse generator based on an IGBT switch with *N* power cells connected in series runs in the normal operation mode. When all switches are driven, the voltage charged in the energy storage capacitor of each power cell (V_{ch}) leads to connection in series, and a voltage of $N \times V_{ch}$, in proportion to the number of stages of the power cell, is given to the load (V_{load}). At this time, the

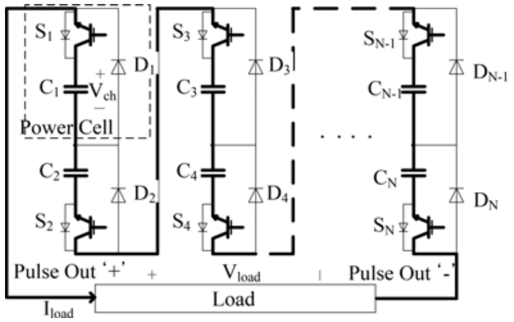

Fig. 1. Normal operation mode of a power cell-based stack.

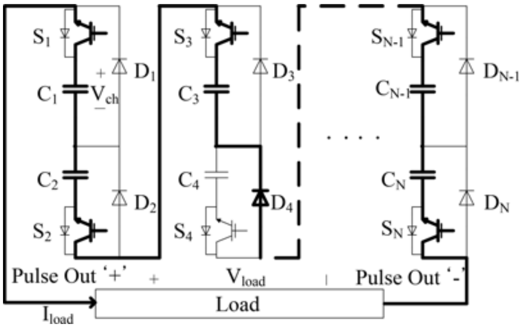

Fig. 2. Malfunctioning operation mode of a power cell-based stack.

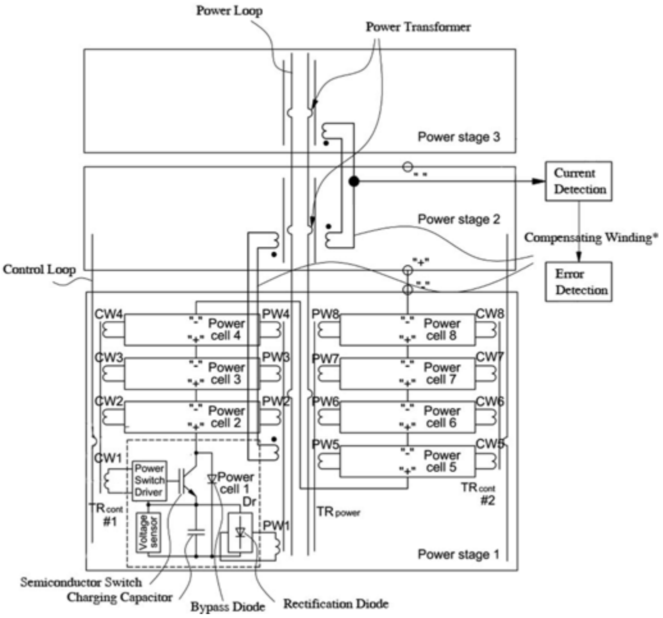

Fig. 3. Scheme of the pulsed power modulator with compensating winding.

voltage supplied to the reverse-biased bypass diode is equal to the charged voltage of each cell. It is an advantage to minimize the number of diodes, which should be connected in series here, to facilitate voltage clamping. The power-cell-unit-based serial drive structure proposed in this paper does not cause any damage, even if each switch drive signal is not synchronized. The reason for this is that when one switch is out of synch or has some problem with its drive circuit, the semiconductor device can be protected by the bypass diode, as shown in Fig. 2. For instance, when a fault in switch S4's drive circuit causes a failure, which prevents the switch from being turned on, the bypass diode D4 begins to conduct and creates a current path. Further, through the bypass diode, only the voltage of capacitor C4 is supplied to both ends of S4, and thus, it can be protected against overvoltage. At this time, the voltage given to the load is $(N-1)V_{ch}$.

Such a feature makes it possible for each semiconductor switch to drive individually, so it is therefore easy to build protection circuits using semiconductor devices. Hence, the advantage of using the protection circuit in the gate drive circuit leads to improved reliability of the arc and short circuit. In addition, the voltage level of the output pulse can be adjusted to the unit of the charged voltage.

B. Voltage Unbalancing Detection and Protection

The pulsed power modulator which is presented in this paper uses multiple secondary winding structure of transformer in order to charge a number of capacitor, simultaneously. As shown in Fig. 3, one power stage consists of a number of power cell explained previously, and one ferrite core which has multiple secondary windings for charging capacitors of each power cell with the same voltage. Whole pulsed modulator consists of many pieces of power stage. That is, from one primary winding (power loop), separate ferrite cores are designed for charging all capacitors of power cells with the same voltage. A detailed structure of capacitor charging circuit has been introduced in [25]. In the series configuration method of the pulse modulator using a power cell structure, there may be a difference in the charged voltage between each charging capacitor, even if power is applied to each charging capacitor within each power cell for the same period of time. In particular, the problem becomes serious if there are differences in the charged voltages of the capacitors between power stages. The main cause of these differences in charged voltage is the leakage inductance occurring in the transformer of the power stage while current is flowing along the power loop. Therefore, in order to compensate for this difference, a compensating winding connected between the power transformers of the upper and lower power stages (between power stages) should be inserted, installed, and wound so that it can be of subtractive polarity (third winding in the transformer).

The compensating winding is inserted into the power transformer composed of a power loop and, at this time, the compensating winding is adjusted so that the magnetic flux can maintain an equilibrium state without the need for a separate control circuit and compensating control between the upper and the lower transformers. If the compensating winding is installed, the magnetic flux reaches an equilibrium state, as the current flows from a large to a small magnetic flux. As shown in Fig. 3, the charged voltage unbalance between the charging capacitors (caused by leakage inductance generated in the transformer) can be solved simply by compensating for the magnetic flux.

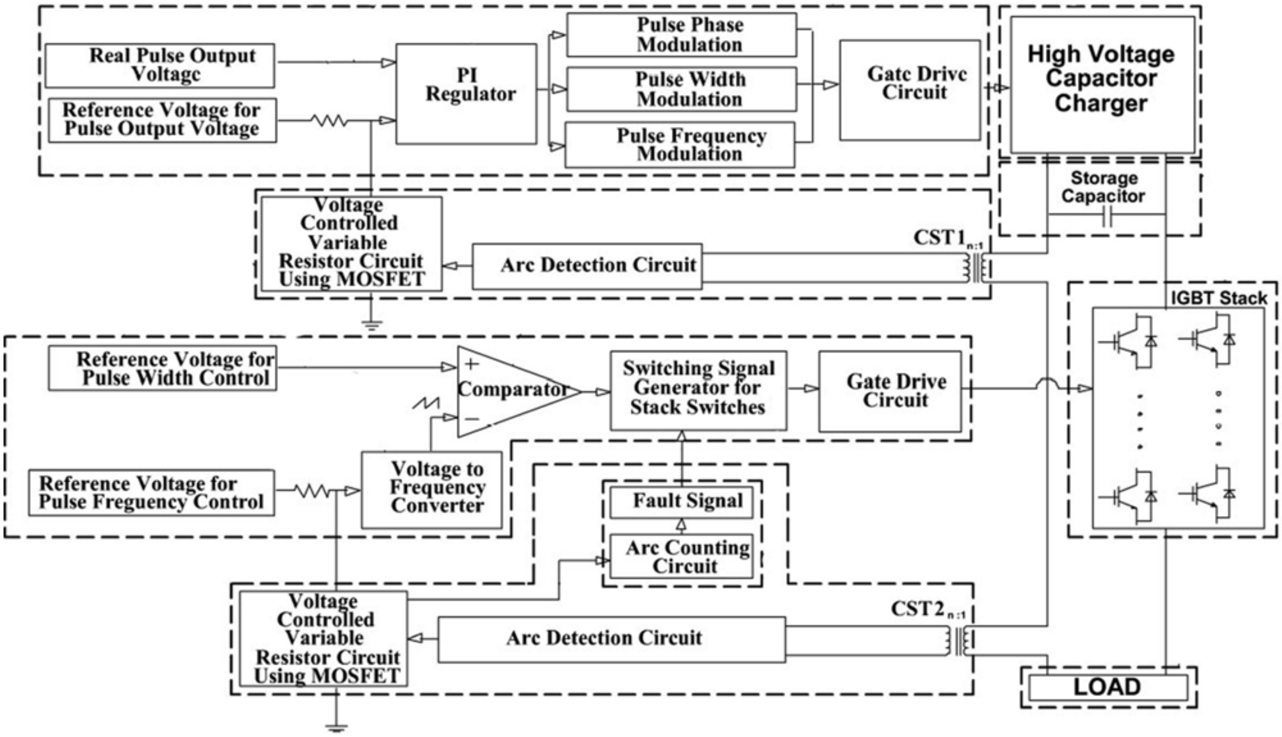

Fig. 4. Diagrams of the proposed arc protection method.

On the other hand, when one or some power cells do not operate, as a result of wiring errors or part burnout, etc., the problematic cell must be identified while the pulse power supply is in operation. However, even if some or all the cells have a problem, it is not easy to determine the source of the issue. Since the pulse power of a very high voltage is output by the charging voltage of all the cells connected in series with each other, whether a particular cell is abnormal or not cannot be determined from the high-voltage output, even if it is apparent that some cells have problems. Here, the proposed method that can detect if an error occurs within the power cells constitutes each power stage in high-voltage pulse power devices, while the device is in real-time operation.

The method for detecting an error in the pulse power supply must be applicable to a plurality of power cells with a semiconductor switch and a charging capacitor connected in series to constitute a power stage configuration, as well as a plurality of power stages connected in series. It functions by detecting the current flowing through the compensating winding. The error detection functions by comparing the current detected by the current detection apparatus with a given reference value and thereby determining whether the current flowing in the compensating winding is greater than this reference value. If an error is detected within the power stage, a signal is then output based on the detection result.

C. Arc Protection Method in Terms of Operation Continuity

When an unexpected excessive current is applied, such as an arc current, a method exists for initiating a protection mode and turning off the semiconductor switch. This works by configuring a separate discharge path in the control circuit in order to protect the semiconductor switch and the internal elements of the pulse power supply. If an arc current is detected in a high-voltage charger through voltage sensing of the storage capacitor storing energy, the operation of the high-voltage charger is stopped. However, if the existing pulse power supply protection circuit and the protective measures outlined earlier are in use, a problem arises with regard to the operation continuity of the pulse power supply, because the high-voltage charger or semiconductor switch stops working whenever an arc current occurs.

However, an alternative method requiring the user to lower the reference voltage by adjusting the variable resistance in the case of an arc current occurs. This connects the variable resistance on the side of the reference voltage determining the pulse frequency through application to the control circuit of the semiconductor switch, or the reference voltage determining the output voltage of the high-voltage charger through application to the control circuit of the high-voltage charger. However, this method is inconvenient in that a user must monitor when arc currents are generated and must then adjust the variable resistance directly.

In order to resolve the previous issues, a pulse power supply protection circuit and protective measures are proposed to protect the internal elements of the pulse power supply. These measures are automatically driven in the event of an arc current, so that the operation that was ongoing prior to the arc current generation can be resumed after a certain period of time.

If the pulse power supply protection circuit and the protective measures outlined in this paper are applied, the internal elements

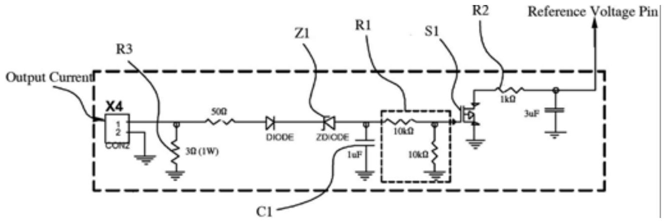

Fig. 5. Arc detection and voltage-controlled variable resistor circuit.

of the circuit can be protected in the event of an arc current without stopping the pulse power supply operation. In addition, the protection circuit is operated automatically without separate user interference as the voltage is charged and discharged in the capacitor. In addition, once a certain amount of time has elapsed after the protection circuit has been activated, the pulse power supply automatically returns to its previous state (prior to the arc current generation) and, at this point, the required amount of time can be changed easily by adjusting the time constant value. In addition, there is an advantage that if the arc currents continue to occur, the trip circuit operates automatically, and therefore, the pulse power supply stops working and the internal elements can be protected.

Fig. 4 illustrates the control circuit of the high-voltage charger that is used to charge the charging capacitor in the pulse modulator. In this figure, there is a PI regulator that has a reference voltage and real voltage input, which are used to determine the output voltage of a charger. In addition, the control circuit of the semiconductor switch stack component includes a V/F converter, which has the reference voltage used to determine the pulse frequency as an input, and a comparator, which has the reference voltage used to determine the signal and pulse widths originating from the V/F converter as inputs.

The pulse modulator protection circuit proposed in this paper detects the output current of the charging capacitor or the semiconductor switch stack part, and it functions to protect the semiconductor device in the pulse modulator if an arc occurs. When it is connected to the high-voltage charger control circuit of the pulse power device protection circuit, it instantly adjusts the reference voltage used to determine the output voltage of the high-voltage charger and the reference voltage used to determine the pulse frequency, thus preventing the pulse modulator from stopping while protecting the internal device against the arc current. In addition, in this case, if the arc current continues to occur, it creates a trip circuit that works to protect the internal device.

The proposed circuit as shown in Fig. 5 comprises a detection part to detect the output current of the storage capacitor or a semiconductor stack, capacitor C_1, resistors R_1 and R_2, and switch S_1. C_1 charges the voltage if an arc current is detected from the output current of the detection part and discharges the voltage charged for the time set up by R_1. S_1 changes from the nonconduction state to the conduction state when there is a connection with R_1 and when an arc current is generated. R_2 is connected to S_1 in order to distribute the reference voltage used to determine the output voltage from the supply to the control circuit of the high-voltage charger in the conduction state of the switch or the reference voltage used to determine the pulse frequency from the supply to the control circuit of the previous semiconductor switch stack component.

The detection circuit plays the role of detecting the output current of the storage capacitor or the semiconductor switch stack part. As shown in Fig. 4, the detection part detects the output current of the storage capacitor through CST1 (current sensing transformer 1) and the output current of the semiconductor switch stack part from CST2 (current sensing transformer 2). The voltage value transformed in resistor R_3 or the Zener voltage value of the Zener diode can be used to judge whether or not the output current detected by the X_4 terminal is an arc current. When an arc current occurs, the Zener diode begins to conduct, and the other semiconductor devices in the protection circuit of the pulse modulator can operate. At this time, the resistance value of R_3 is determined by the output current detected by X_4 and the number of coil turns of CST1 and CST2, as illustrated in Fig. 4. When C1 detects an arc current from the output current of X_4, it charges voltage and discharges the voltage charged for the time set up by R_1. C_1 can be charged by the subtraction of the Zener voltage of the Zener diode from the voltage supplied by R_3, and C_1's voltage is charged for the time set up according to the time constant determined by R_1. Then, C_1 can be discharged. In other words, the discharge time can be adjusted by R_1 and the capacitor.

When S_1 is connected to R_1 and an arc current is generated, the switch changes from the nonconduction state to the conduction state as C_1 is discharged. R_2 is connected to S1 in order to distribute the reference voltage used to determine the output voltage from the supply to the control circuit of the high-voltage charger in the conduction state of S_1 or the reference voltage used to determine the pulse frequency from the supply to the control circuit of the semiconductor switch stack component. As shown in Fig. 4, the control circuit of the high-voltage charger includes a PI regulator, which has the reference voltage and real voltage, which are used to determine the output voltage of the high-voltage charger as inputs. R_2 is connected to the reference voltage used to determine the output voltage of the high-voltage charger. When S1 is changed from the nonconduction state to the conduction state decreasing drain–source resistance of S_1, some of the reference voltage used to determine the output of the high-voltage charger is distributed by R_2. As the reference voltage decreases, the output voltage of the high-voltage charger also decreases and the power supplied to the semiconductor switch stack component is reduced, and thus it is possible to protect the semiconductor devices. As S_1 is changed from conduction state to the nonconduction state increasing drain–source resistance of S_1, it fails to influence the reference voltage used to determine the output voltage of the high-voltage charger, and the pulse power device automatically returns to the operation state directly before the occurrence of an arc current event. In other words, before the occurrence of an arc current event, the reference voltage used to determine the output voltage of the high-voltage charger returns to the state in which the voltage is supplied to the control circuit of the high-voltage charger.

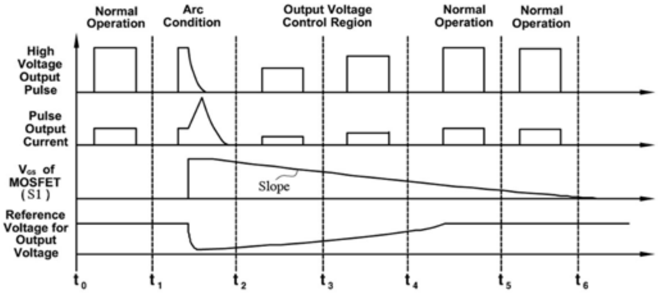

Fig. 6. Graph of output changes in protection circuit over time.

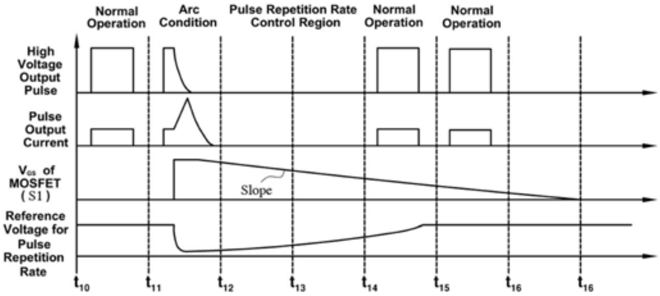

Fig. 7. Graph of changes in pulse repetition rate in protection circuit over time.

Fig. 6 illustrates the changes in the output values over time. In the $t_0 - t_1$ section, the reference voltage used to determine the high-voltage output pulse, the pulse output current, and the output voltage remain at a certain level in the state before the occurrence of an arc current, and S_1 is in the no-conduction state. In the $t_1 - t_2$ section, as an arc current is generated, and the protection circuit is activated. When S_1 is changed to the conduction state, the reference voltage used to determine the output voltage is lowered by R_2. In the $t_2 - t_4$ section, as the lowered reference voltage is supplied, the high-voltage output pulse and the pulse output current become lower than those before the activation of the protection system. This indicates that the semiconductor devices in the pulse power system can be protected. As the voltage charged for the time set up by the time constant of C_1 is discharged, the gate–source voltage of S_1 has a constant inclination and slowly decreases, and the inclination is related to the time constant. In addition, as the drain–source resistance of S_1 slowly increases, the reference voltage used to determine the output voltage also increases slowly. In the $t_4 - t_6$ section, it automatically returns to the state prior to the activation of the protection circuit. This is a clear representation of how the pulse modulator operates.

Fig. 7 shows the changes in output values over time when the protection circuit is applied to the control circuit of the semiconductor switch stack component.

III. Experimental Results

In this study, the proposed method of improving the reliability of an SSPPM and applicable protection circuits is verified through various experiments, including tests involving cell unbalance and arc currents, in order to show that they do not affect the effective operation of the pulse modulator.

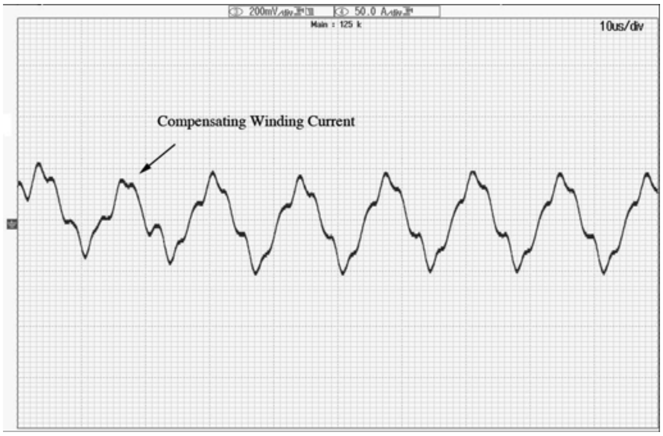

Fig. 8. Compensating winding current sensing voltage in the normal state (compensating winding current sensing voltage: 200 mV/div, time: 10 μs/div).

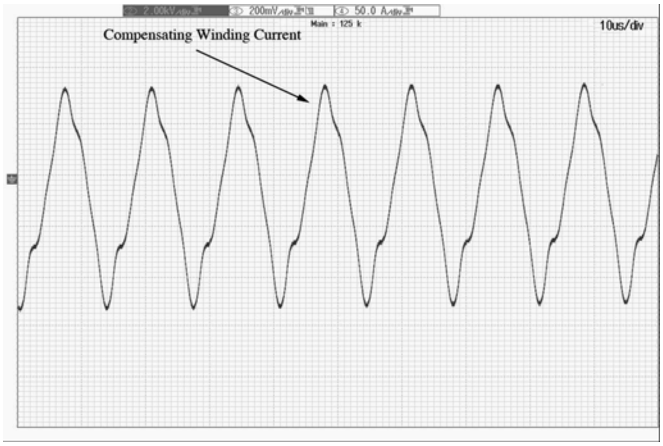

Fig. 9. Compensating winding current sensing voltage in the state of imbalance (compensating winding current sensing voltage: 200 mV/div, time: 10 μs/div)

This is the comparison of the current flowing on the compensating winding when IGBT of a particular stage is intentionally shorted in order to induce the voltage unbalancing of power stage. The measurement position of Figs. 8 and 9 is the measurement of compensating winding current sensing voltage at the current detection part as shown in Fig. 3. Fig. 8 shows the waveform of the compensation winding current and the resonant current at the high-voltage capacitor charger, which supplies the power cell voltage when the normal modulator is in operation. Fig. 9 shows the waveform of the resonant current and the compensating winding current when the power cell is in an unbalanced state, with one of the power cell switches shorted.

When the voltage is balanced, the peak-to-peak voltage in the compensation winding is approximately 400 mV. On the other hand, when an unbalance occurs, the compensation winding achieves cell balancing, allowing the current to flow and the voltage to increase to approximately 1 V. If the output of the compensation winding of the pulse modulator controller is

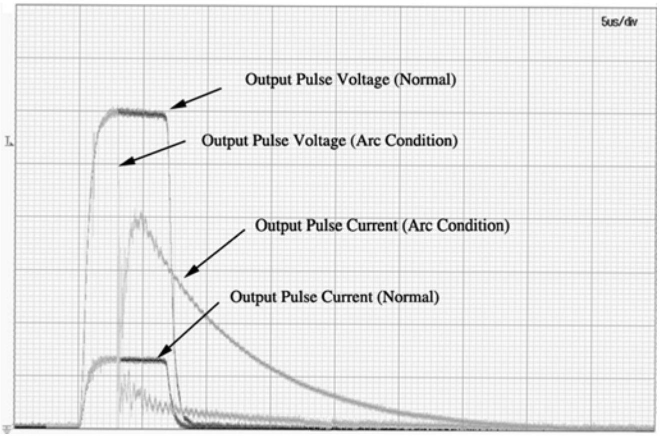

Fig. 10. Voltage and current waveforms under normal and arc condition (output pulse voltage: 5 kV/div, output pulse current: 20 A/div, time: 5 μs/div).

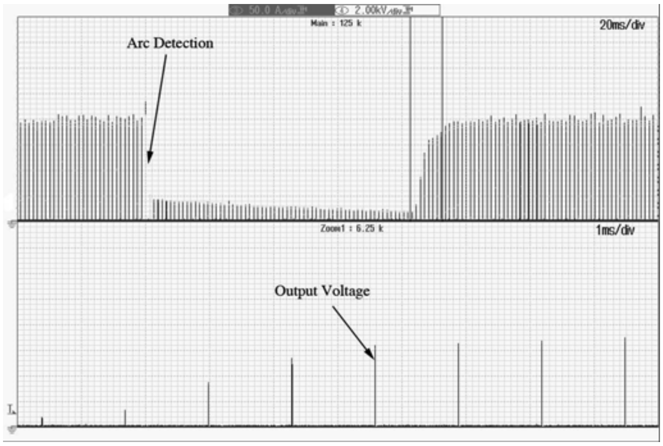

Fig. 11. Change in the output voltage waveform according to the arc current (output voltage: 2 kV/div, time: 20 ms/div, 1 ms/div).

connected to the input of the comparator and the trigger level is adjusted, any problems and errors in the wiring or parts of the power cell can be detected on a real-time basis.

Fig. 10 shows the operation of arc protection circuit inside gate drive circuit. Compared to the normal operating pulse (30 kV, 28 A), the output pulse current at arc condition shows instantaneous increase of current with rapid slope. The protection circuit inside gate drive circuit detects the gigantic current and turn off IGBT as soon as possible. By means of fast protection of gate drive circuit, all the IGBTs are turned off and the output pulse current decreases through bypass diode. A detailed operation and analysis of the protection circuit inside gate drive circuit was presented [25].

Figs. 11 and 12 show the operation of the proposed protection circuit for repetitive pulse. For avoiding damage of IGBT due to the repetitive arc current, additional protection circuits by means of decreasing output pulse voltage and repetition rate are proposed and verified by experimental waveform in Figs. 11 and 12, respectively. Figs. 11 and 12 show extended time-scale in order to show the operation in which output pulse voltage and

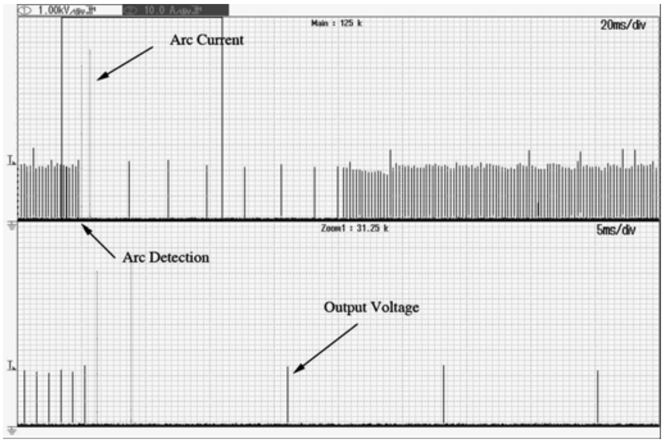

Fig. 12. Change in waveform in the pulse repetition rate according to the arc current (output voltage: 1 kV/div, arc current: 10 A/div, time: 20 ms/div, 5 ms/div).

repetition rate are gradually restored after output pulse voltage and repetition rate were decreased when arc occurred. In these figures, the pulse width is set as 5 μs.

Fig. 11 shows the result of the first method proposed by this paper in which when an arc current is generated, the output voltage of the pulse modulator is lowered to protect the switching device. After the generation of the arc current, the output of the pulse modulator is decreased and then the output voltage is slowly increased for recovery to the normal state.

Fig. 12 shows the result of the test in which when an arc current occurs, the pulse repetition rate of the pulse modulator is lowered to protect the switch. It was found that after the occurrence of the arc current event, the pulse repetition rate of the pulse modulator was lowered and then slowly recovered to the normal state. There was no damage to the power cell switch during the arc test. On the other hand, in the case of an IGBT, the transistor can withstand ten times the rated current of the instantaneous arc current but, in the case of a continuous arc current, the IGBT may be damaged. In this study, it is confirmed that the suggested method can protect the IGBT from the arc current if the output voltage is decreased from the arc current or if the pulse repetition rate is lowered below the level where the IGBT can be damaged.

IV. CONCLUSION

In this paper, the series stacking type pulse modulator for the power cell was introduced to enhance the reliability of the solid-state pulsed modulator. Also, the compensating winding was suggested to compensate the difference in charging voltage of power cell in the power cell-structured-pulsed modulator. In addition, the method was proposed to detect any error in winding or parts in the pulsed modulator on real-time basis. Also, the method was proposed in which the continuity of operation is ensured and the pulsed modulator can be protected from the arc current when the arc current often happens in the pulsed power applications. The proposed protection circuit and the protection method have been discussed and their excellence of the design of the protection circuit and protection method has been verified through the tests.

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