Solid State Marx Generator Using Series-Connected IGBTs

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***Abstract*—This paper describes a newly developed novel repetitive impulse voltage generator using a boost converter array. To solve problems such as short life time, low operating frequency, and the fixed pulse width of conventional generators, the proposed generator is designed with a boost converter array that employs series-connected capacitors and insulated gate bipolar transistors. The circuit can easily obtain a high-voltage pulse without any high-voltage direct current source and pulse transformer. Thus, the proposed circuit not only allows elimination of the expensive high-frequency transformer but also allows operation at a frequency up to several kilohertz with high reliability and longer life span. To validate the proposed circuit, two pulse generators rated at 1.8 kV, 40 A and 20 kV, 300 A are implemented and tested.**

***Index Terms*—Boost converter, pulse generator, pulsed power, series-connection.**

I. Introduction

PULSED power is to make a unique phenomenon using high density and very short energy pulse for an application which needs physical or electrical reaction. It has been used and developed for a long time in several applications as shown in Table I. Several types of pulsed power have been introduced for medical, military, and commercial applications [1].

The Marx generator is a very simple circuit producing a high-voltage pulse without any pulse transformer and very high input voltage, as shown in Fig. 1. Thus, it is widely used in laboratories as an impulse generator [2]. However, the spark gap switch of the Marx generator has some drawbacks: short lifetime and low operational frequency. In particular, the Marx generator needs a special triggering device for precise turn-on of switch.

Most of earlier researches on pulsed generators used high-voltage sources with stacked transmission lines in combination with a spark gap or vacuum tube [3]. Other high-voltage pulse generation circuits used high-voltage direct current (dc) power supply along with energy storage for the pulse-power loads. These systems are expensive, inefficient, and limited in peak power output.

These prior-art methods require several power conversion steps, which cause a complex circuit structure and low reliability. To solve these problems, some state-of-the-art methods using power semiconductor devices and pulse transformer were proposed in recent years. However, they have some limitations to increase rise time and power rating simultaneously.

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TABLE I
PULSE GENERATOR APPLICATION

Application		Pulse generator
Industry	laser welder	pulsed Nd: YAG, CO2
	photolithography	pulsed- X-ray
	metal forming	pulsed magnetic forming
	rock fracturing	pulsed power supply
	surface finishing of metal	pulsed laser light
	steel casting	pulsed electromagnetic field
	powder forming	exploding wire, MHD
	fabric sterilization	rf power
	pulsed U. V. for paint	pulsed U. V. source
	pulsed electrostatic precipitator	pulsed E field
	microwave oil sludge separation	pulsed microwave
Medical	eye surgery	pulsed laser
	bone repair	pulsed low power
	injection materials through the skin without needles	pulsed linear motor
Environment	ultra-low concentration analysis	pulsed laser
	destroying of toxic gases and water purification	pulsed E field
Agriculture	killing bacteria by E fields	pulsed high voltage source
	pulsed X-ray for feed grain preservation	pulsed X-ray

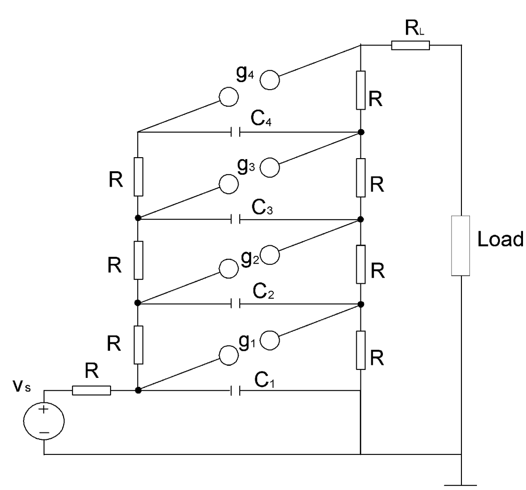

Fig. 1. Marx generator.

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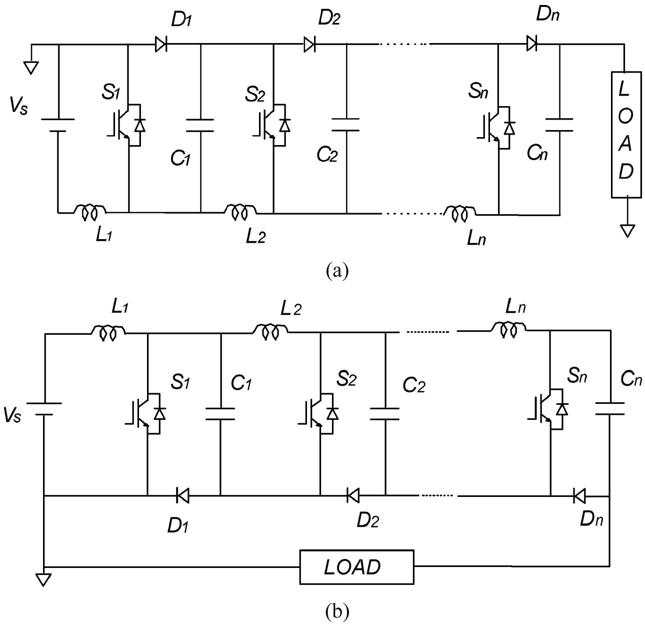


Fig. 2. Configuration of the proposed circuit. (a) Positive output pulse circuit. (b) Negative output pulse circuit.

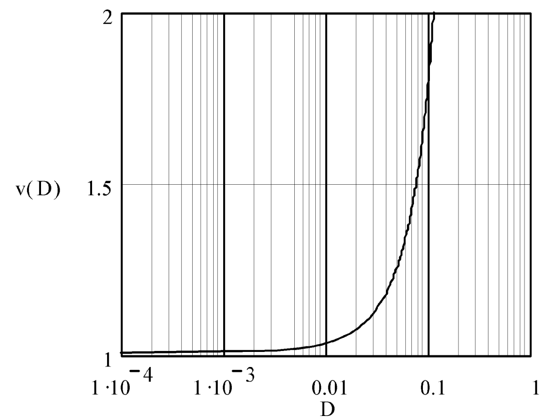


Fig. 3. Boost rate of output voltage with discontinuous inductor current.

In this paper, a novel pulse generator using a boost converter array is proposed. As shown in Fig. 2, it does not need any pulse transformer and high-voltage dc source. It has the following features: fast rise time, flat-top pulse, easy high-voltage pulse forming and expansion with boost-converter arrays, high-frequency operation, and easy extension by series-connection of capacitors and switches.

The proposed circuit is, therefore, very reliable and suitable for high-voltage pulse generator applications. Moreover, it can be improved by using series-connected switches, which allows reduction in line inductance and the number of devices by increasing the input voltage [4], [5]. The voltage rating of the switches can be increased by series-connection using some simple voltage balancing circuits.

To verify the proposed circuit, a 1.8 kV, 40 A and a 20 kV, 300 A prototype pulse generators were fabricated and fully characterized with theoretical analysis, practical design, and test results. Overall performance of the pulse generator will be presented with experimental results.

II. Configuration and Principle

A. Circuit Configuration

The structure of the proposed circuit consists of n number of switches, capacitors, inductors and diodes, as shown in Fig. 2. It apparently forms a boost converter array. In particular, it can be designed to obtain positive or negative pulses by the position of the ground and load. The discharge current of the boost voltage of capacitors can be neglected if the duty ratio of the output pulse is very small (less than 0.01). For continuous inductor current conditions, the nth capacitor voltage can be expressed as follows:

$$V_{cn} = V_{cn-1}\frac{1}{1-D}, \qquad D = \frac{T_{\rm on}}{T_s} \tag{1}$$

where D is the duty ratio, $T_{\rm on}$ is the pulse width, T_s is the pulse period, V_{cn} and V_{cn-1} are capacitor voltages of nth and $(n-1)$th. Therefore, nth capacitor voltage is

$$V_{cn} = V_S\frac{1}{(1-D)^n} \tag{2}$$

where n is the number of boost converters. For discontinuous inductor current conditions, the nth capacitor voltage is given by

$$V_{cn} = \left(\frac{T_s D^2 V_{cn-1}^2}{2LI_o} + V_{cn-1}\right) \tag{3}$$

where L is the inductance of inductor, V_{cn-1} is the capacitor voltage at the input side of V_{cn}, and I_o is the average value of output current.

Fig. 3 shows the boost rate of output voltage when inductor current is discontinuous. Note that if the duty ratio is low enough, the boosted voltage is minor. Therefore, the output voltage is almost the multiples of the input voltage for the low duty cycle.

In the meantime, if the number of boost stacks is increased, the line inductance is also increased. Because the rise time of the output pulse increases proportionally with line inductance, it should be reduced. In this paper, a series-connected switch using an insulated gate bipolar transistor (IGBT) module is used to increase the input voltage and to reduce the number of converter array and devices.

B. Operational Principle

The basic operations of the proposed circuit can be divided into to three modes. The first mode is from the time after charging to the turn-on of switches. The second mode is when switches are turned on. The third one is the capacitor charging mode.

Fig. 4 shows the operation modes and waveforms of the circuit for positive pulse generation. To simplify the description, it is assumed that all diodes and devices are ideal and boost voltage is negligible because the duty ratio of the pulse is less than 0.01.

Mode 1) There is no current flow in the circuit. The voltage of capacitors is maintained at the input voltage level, and diodes and switches are turned off. Therefore, the voltage applied to overall components is the

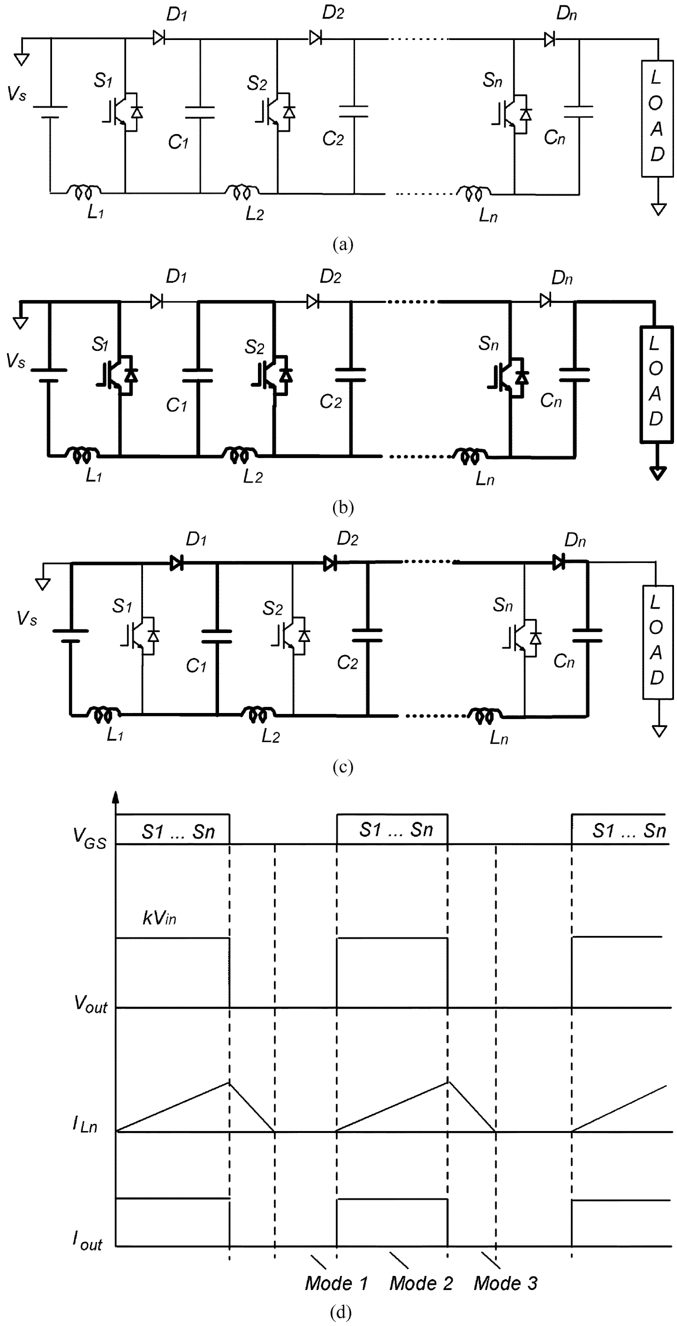


Fig. 4. Operational modes and waveforms. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Waveform.

input voltage. Thus, it does not need high voltage isolation.

Mode 2) All switches are turned on at this time and capacitors are connected in series. The output voltage is applied to the load and is in proportion to the sum of voltage of the series-connected capacitors. At this time, the terminal of the load side has high voltage potential. There it needs to be isolated between the low voltage side and the output side during the pulse period. Therefore, isolation voltage can be lowered compared to high dc voltage isolation.

Mode 3) After the switches are turned off, the capacitors are charged to the input voltage level through the path of input, inductors and diodes.

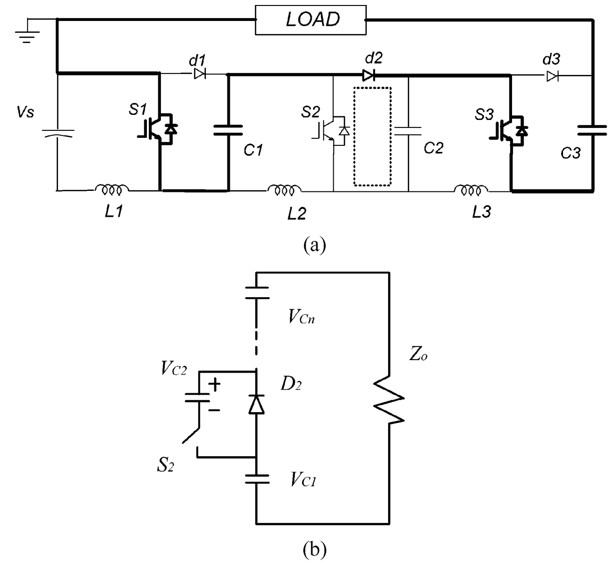


Fig. 5. Clamp operation of the proposed circuit. (a) Circuit schematic. (b) Equivalent circuit.

These three modes are explained on the basis of the assumption that all parameters are ideal. However, in a real circuit, time delay of the driving signal can result in difference among switch voltage levels. Fortunately, this problem is naturally solved by the proposed circuit structure where the equivalent series connected capacitor and diode are in parallel with the switch to provide voltage clamp so as to prevent switch over voltages.

C. Features and Design of the Proposed Circuit

1) Features: The proposed circuit generates high-voltage pulses only during turn-on period of switches. Therefore, isolation of all circuits is strictly required and is considered only for the high pulse voltage. Contrary to the conventional pulse generators, the proposed circuit uses power semiconductor as switches, which has several advantages such as long lifetime and high operational frequency up to a few kilohertz.

One of the most important features of the proposed circuit is a balanced clamping operation against switch over-voltages. The over-voltage of each switch can be naturally clamped by capacitors in parallel with switches, as shown in Fig. 5. If the switch voltage is increased over the capacitor voltage, the diode automatically turns on to clamp the switch voltage to the capacitor voltage. Thus, the difference of gate drive delays and the switch characteristics does not result in the device voltage breakdown. In addition to the above main features, the proposed circuit has the following advantages.

1) No need for a pulse transformer or high-voltage dc power source.
2) The pulse voltage is controllable by drive signal.
3) Easy change of pulse polarity by adjusting the position of ground and load.

In terms of switch rating, the maximum value of the output pulse current has to be lower than the pulse switch current rating.

If output voltage of several kilovolts is applied to short out the load circuit, an extremely high current will flow to the load with only a few microseconds or submicroseconds. Therefore, the switch selection criterion is based on the short circuit current

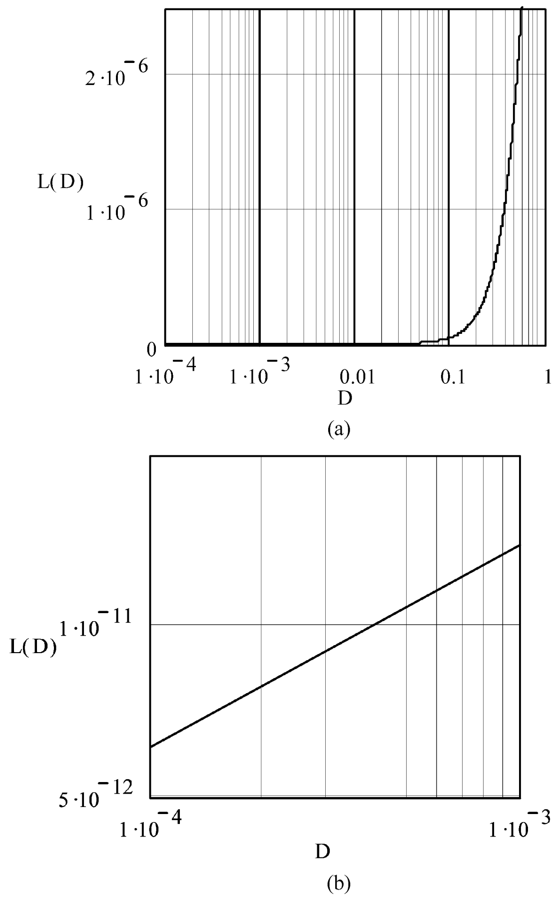


Fig. 6. Inductance condition for discontinuous current. (a) Maximum value of the inductor and duty cycle. (b) Expanded portion of (a).

capability. For the low-power prototype, the switch is designed with a continuous current of 40 A and a short circuit current of 200 A under 1 kHz frequency and 300 V input voltage. The IGBT with 600 V, 50 A rating is selected for this case.

For the high-power prototype, the maximum continuous pulse current and short-circuit current are 300 and 1000 A, respectively. Therefore, the 1200 V, 400 A IGBT is selected.

2) Design of the Proposed Circuit: In our experiments, the maximum pulse width is 5 μs under 1 kHz switching, so the duty cycle is less than 0.005, which yields very little voltage boost; i.e., the adjacent stage capacitor voltages are nearly identical. With such a low duty cycle, the inductor current can easily become discontinuous. The loss caused by reverse recovery current of the diode is avoided if the inductor current is discontinuous. Therefore, the main design criterion for inductor is the completion of capacitor charge and discharge within a switching period, and the condition to satisfy discontinuous current condition is shown in (4)

$$\frac{2LI_o(1+D)}{D^2V_{Cn}} < T_s \tag{4}$$

where I_L is the peak inductor current, V_{Cn} is the nth capacitor voltage, D is duty cycle, I_o is output average current, and n is the number of series boost circuit stacks. From (4), the inductor value can be obtained as

$$L_{1\cdots n} \leq \frac{T_sV_{Cn}D^2}{2I_o(1+D)}. \tag{5}$$

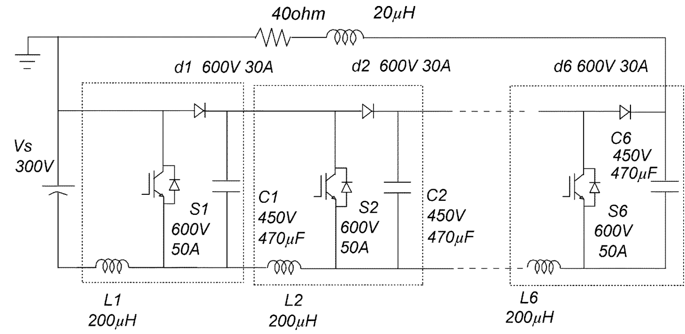


Fig. 7. Experimental circuit.

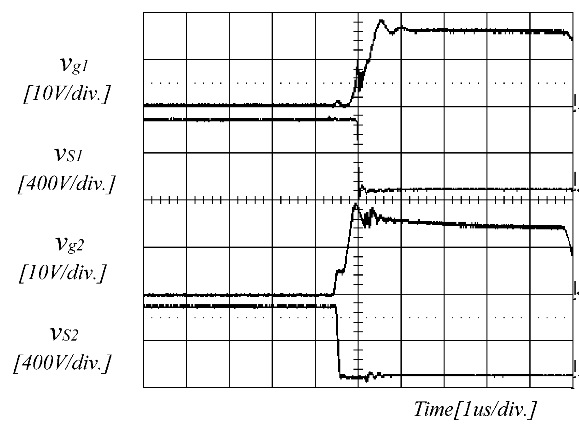


Fig. 8. Drive signals of IGBTs and their switch voltages.

The relationship between duty cycle and inductor for discontinuous current can then be shown in Fig. 6. Here, the output voltage and current are normalized on the per unit basis. As implication in (5), when D is small enough (< 0.01), the maximum inductor value for discontinuous condition is changed only a little, and the change is almost linear with logarithm horizontal scale, as shown in Fig. 6(b).

For the design of pulse capacitors, voltage drop during discharging has to be considered, and the capacitor value can be determined as follows:

$$C_{1\cdots n} = \frac{\tau \times V_{\text{out}}}{\Delta v \times R_{\text{load}}} \tag{6}$$

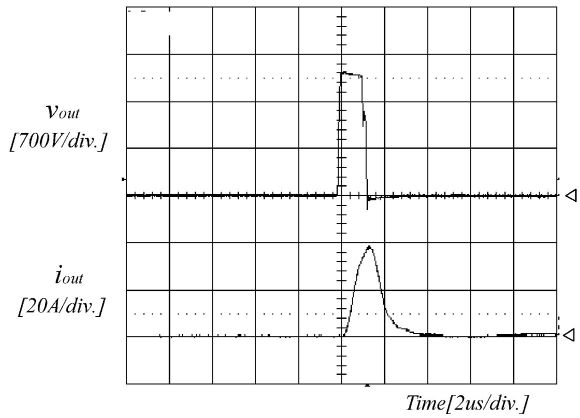
where τ is the pulse width, V_{out} is the pulse voltage, R_{load} is the load value, Δv is the voltage drop.

III. Experimental Results

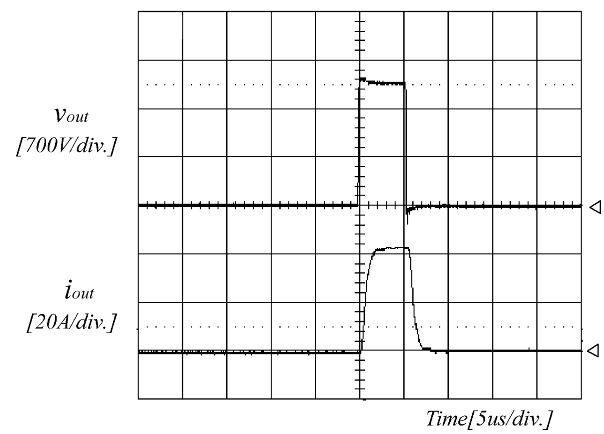
A. Small Power Prototype

The 1.8 kV and 40 A proposed pulse generator was built and tested to verify the principle of operation. Fig. 5 shows the experimental circuit with the parameters and the part numbers of components used. A 600 V-50 A IGBT are used as a single switch and six IGBTs are used, as shown in Fig. 7. The pulse width is varied from 1 to 5 μs for 1 kHz operation. Inductor value is sufficiently low to ensure a discontinuous current.

Fig. 8 shows the experimental waveforms of the switch voltage and gate voltage. It can be seen that the 0.5 μs difference in gate signals has little influence on switch voltage because of the clamping operation. Figs. 9 and 10 shows the high-voltage pulse waveforms. We note that the pulse width



(a)



(b)

Fig. 9. Output pulse waveforms under different times. (a) 1-μs pulse. (b) 5-μs pulse.

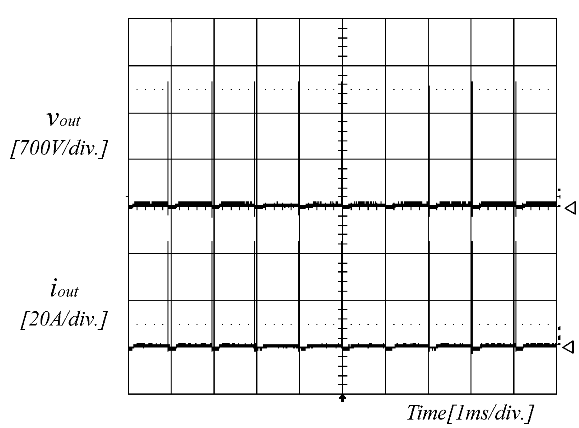


Fig. 10. Output pulse waveforms at the wide time.

is also changeable from 1 to 5 μs and operation frequency is possible up to 1 kHz. All waveforms are well-matched as the expected ones.

Fig. 11 shows the output pulse when one switch is not operated. The proportional voltage to the operating switches is obtained.

B. High Power Prototype

The proposed pulse generator using series-connected IGBTs has been built and tested to verify the principle of operation.

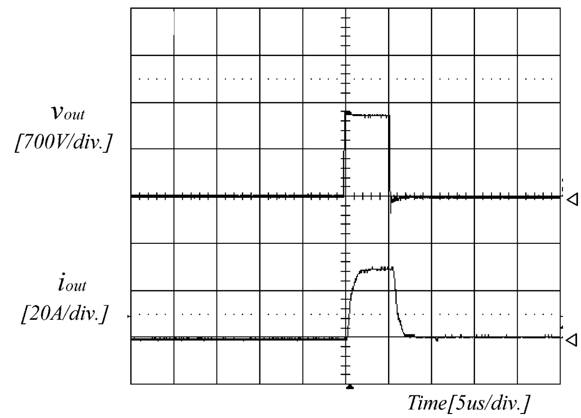


Fig. 11. Output pulse waveforms when one switch is not operated.

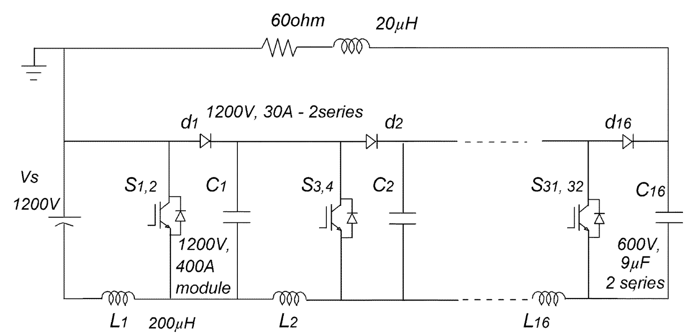


Fig. 12. Experimental circuit.

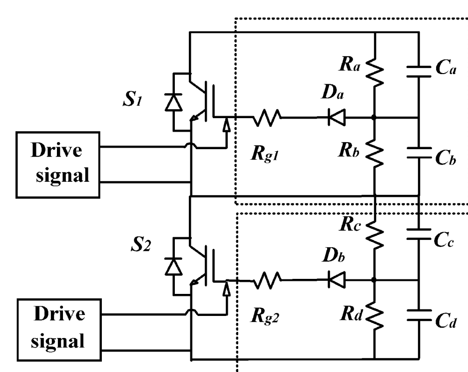
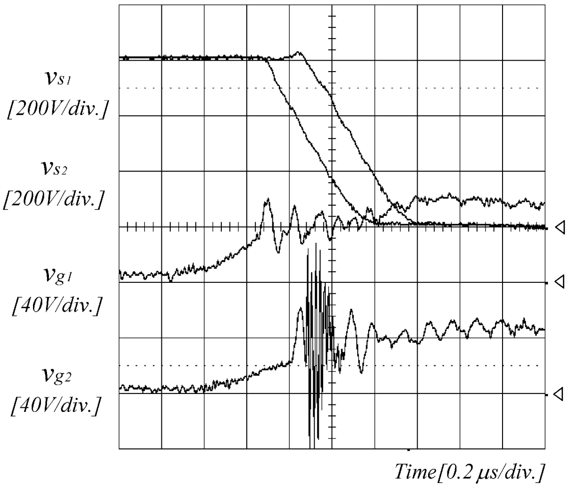


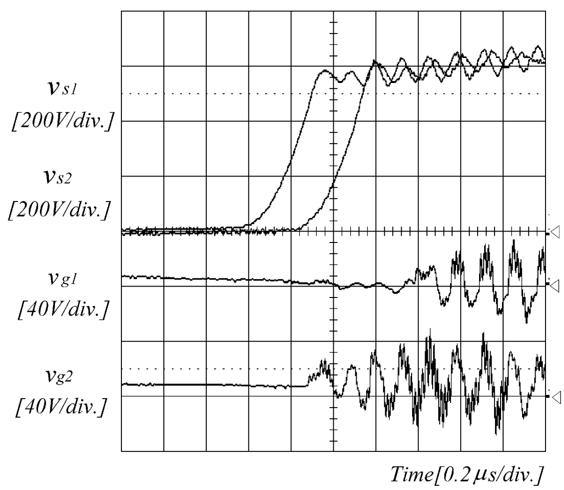
Fig. 13. Series-connected IGBT switches along with their voltage balancing circuits.

The maximum pulse rating is 20 kV, 300 A, 5 μs, and 1 kHz. Fig. 12 shows the experimental circuit and the used circuit parameters and the parts numbers. A total of 16 IGBT modules are used to make the pulse generator. As shown in Fig. 13, to increase the rating of a switch voltage, two switches of an IGBT module are connected in series along with the voltage balancing circuits shown in the dotted boxes [5]. Fig. 14 shows the transient turn-on and turn-off voltage waveforms of the series connected switches, which indicate a mismatch between two gate drive signals. In spite of such an obvious differentiation between gate drive delays, the voltages of switches are well-balanced.

Figs. 15 and 16 show the experimental high-voltage pulse waveforms. Note that the pulse width is about 5 μs and pulse voltage is about 20 kV and 300 A. The rise time of the pulse is less than 1 μs, and the operating frequency is 1 kHz.



(a)



(b)

Fig. 14. Voltage waveform of a series connected switches. (a) Turn on. (b) Turn off.

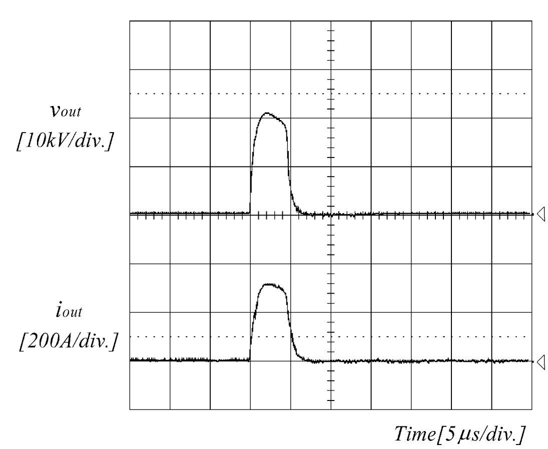


Fig. 15. Output pulse voltage and current waveforms.

IV. Conclusion

This paper has described the features and operation of the novel pulse generator using boost converters. Experimental results were discussed with a low power 1.8 kV–40 A and a high power 20 kV–300 A pulsed generators using boost converter. The proposed circuit has various advantages over conventional pulse generators by eliminating the high-voltage transformer, resulting in high-frequency operation, simple structure, and high efficiency.

Also, it has the following features: fast rise time, flat pulse top, easy expanding to higher stack voltage with boost-converter arrays, high-frequency operation, and easy series-connection of switches. In particular, series-connected IGBT modules were used to increase input voltage and voltage rating of switches, which reduces line inductance because the number of converter arrays and devices were decreased.

Therefore, the proposed converter is very promising for various high-voltage pulse applications such as high-voltage testers, laser equipments, and environmental applications.

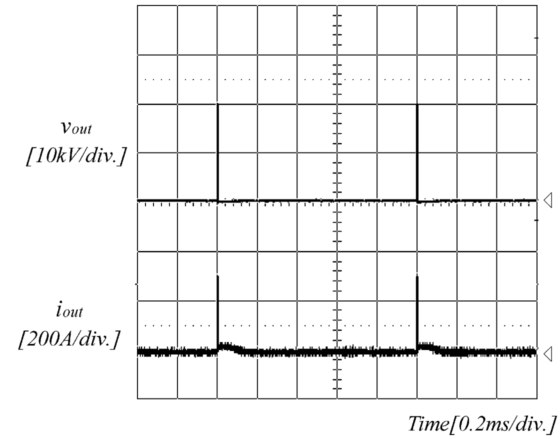


Fig. 16. Output pulse waveforms at a wide time.

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Dr. Rim, in testimony to his esteemed status, the ministry of Science and technology of Korea chose him as one of nationally recognized researchers in 1997. He was granted the National Research Laboratory Fund for pulsed power technology development by the Ministry of Science and Technology of Korea in 1999. He is a member of various professional organizations including KIEE and KITE. He is also a member of Phi Kappa Phi.

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Dr. Lai received several distinctive awards including a Technical Achievement Award from the Lockheed Martin Award Night, two IEEE IAS Conference Paper Awards from the Industrial Power Converter Committee, and one IEEE IECON Best Paper Award. He chaired the 2000 IEEE Computers in Power Electronics (COMPEL 2000). He was the founding Chair for the 2001 IEEE/DOE Future Energy Challenge. Currently, he is the General Chair for the IEEE Applied Power Electronics Conference and Exposition (APEC 2005).