

Development of 60 kV, 300 A, 3 kHz Pulsed Power Modulator for Wide Applications

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In this paper, a novel pulsed power generator based on IGBT stacks is proposed for wide pulsed power applications. Because it can generate high voltage pulsed output without any step-up transformer or pulse forming network, it has advantages of fast rising time, easiness of pulse width variation, high repetition rate and rectangular pulse shapes. Proposed scheme consists of multiple power stages which were charged parallel from series resonant power inverter. Depending on the number of power stages it can increase maximum voltage up to 60 kV or higher with no limits of power stages. To reduce component for gate power supply, a simple and robust gate drive circuit which delivers gate power and gate signal simultaneously by way of one high voltage cable is proposed. For gating signal and power a full bridge inverter and pulse transformer generates on-off signals of IGBT gating with gate power simultaneously and it has very good characteristics of protection of IGBT switches over arcing condition. It can be used for various kinds of pulse power application such as plasma source ion implantation, sterilization, water and gas treatment which requires few kHz pulse repetition rate with few to ten of microseconds pulse width.

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1. Introduction

For the pulse power supply, there are several kinds of models widely used such as Marx generator, hard-tube type pulse generator, thyatron type pulse power generator with pulse forming line and etc. [1–3]. These kinds of pulse power supply generally used mechanical switches such as spark gap and thyatron for their main switches.

Recently some kinds of pulse power supply topology which uses semiconductor switches as a main switch have been proposed because it has some advantages such as long life-cycle, high pulse repetition rates, compact size and low weight [5–7].

In this paper a novel semiconductor switch based pulse power supply using series resonant capacitor charging inverter and modified marx generator is proposed.

Total 72 series connected IGBTs are forming up to 60 kV pulse output voltage and very simple gate driver circuit is designed to synchronize IGBT gate signals without any trouble. Also, it shows good characteristic of arc protection which is obligatory for pulse power application.

The structure and distinctive features of proposed pulse power supply are described. The developed pulse power supply was tested for various kinds of applications and detailed experimental waveform shows that proposed scheme has many advantages.

2. Pulsed power generator based on semiconductor switches

2.1. Structure of the pulsed power generator

The structure of the proposed pulsed power generator is shown in Fig. 1. It is made of nine stages comprised of

eight power cells, a power transformer (TRpower) and two control transformers (TRcont). Each power cell consists of one IGBT (Eupec Inc, BSM300GB120DLC, 1200 V, 300 A), one storage capacitor (Electronic Concepts Inc, UL30BLO120, 120 μ F, 1000 V) and one bypass diode (Ixys Inc, DSEI60-12 A, 1200 V, 60 A) with full bridge charging rectifier circuits. The size of the power stage is 50 cm (W) \times 40 cm (D) \times 10 cm (H) and total size of 60 kV pulsed power generator with 15 kW charger is 61 cm (W) \times 61 cm (D) \times 130 cm (H). A high frequency series-resonant current source inverter is employed to charge capacitor of each power cells. The charging energy supplied to the storage cells is controlled by means of inverter operating frequency variation. Each power transformer has eight isolated windings W1...W8 placed in such a manner to equalize their leakage inductances.

In turn each winding is connected to the input rectifier Dr of a particular cell. The power loop passes through the cores of the power transformers so that each one has one turn primary winding. The number of the secondary turns has been chosen to properly match the impedance of the resonant inverter supplying the power loop at full load and to avoid transformer core saturation at any conditions.

Eight cells assembled in series make up one stage of the generator. All connections within cells and stages have been minimized and configured in order to provide self compensation of forward and backward current with a goal of reducing the stray inductance of the pulsed power generator. One can see that the generator has flexible structure. Any polarity of the output pulse can be easily obtained by reconnection of inputs and outputs of the stages. The pulsed power generator outlet is ended with a small value noninductive resistive ballast Rballast for

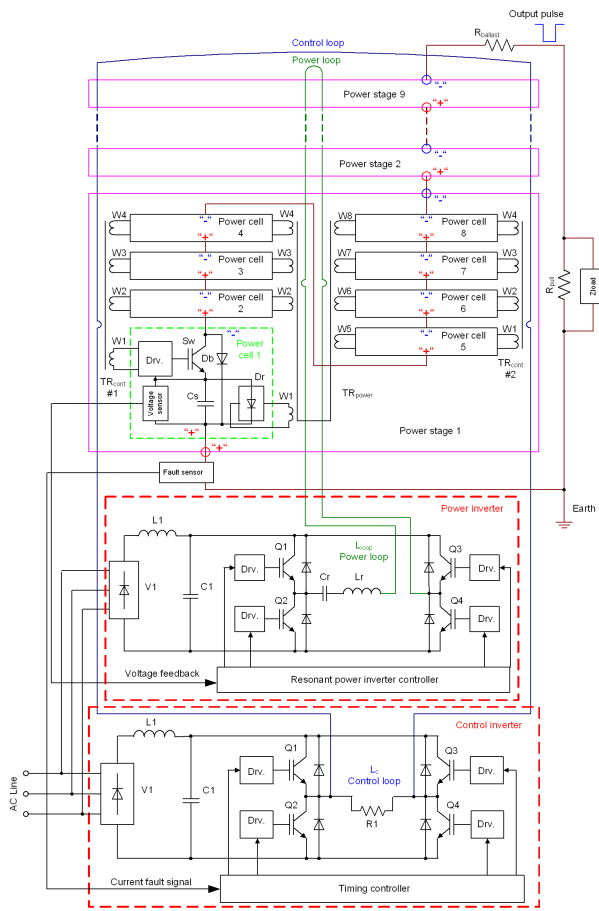


Fig. 1. Proposed pulsed power modulator structure (size: 61 × 61 × 130 cm).

better oscillations damping at a complex load and a pull-down resistor R_{pull} to reduce the stay-off voltage of the generator. The other lowest point is ended with a fault current sensor that monitors a load current with a goal of fault condition determination.

In general, the pulsed power generator works like a voltage source keeping constant amplitude of a flat top at different load resistance values. To realize this, the voltage of the power cell connected to earth is stabilized with a feedback loop taking a real time signal from the storage capacitor of cell. Mentioned above tension sharing technique assures the voltage difference between any power cells of the pulsed power generator is less than 5% of the controlled one. Even in a standby mode when no pulses are generated and the energy consumption of the cells is very small due to their low quiescent current, the five-percent difference is accurately kept.

The inverter used for charging of the storage capacitors of the generator is a simple series full bridge resonant inverter (refer to Fig. 1). Four switches Q1...Q4 driven from the inverter controller via drivers run at the maximum frequency of about 50 kHz under full load and at frequency of order 10...20 Hz in the standby mode.

A resonant tank includes a capacitor C_r , inductor L_r and the current loop L_{loop} having an inductance of $2.6 \mu H$. Power loop is performed with a non-shielded high voltage cable which has a big enough diameter of inner wire. The tank engine frequency is equal to 100 kHz.

2.2. Proposed current loop gate driver circuit

The proposed gate driver circuit is shown in Fig. 2. In this scheme, both gate control signal and gate power are delivered by attractive way of control loop simultaneously. It does not require additional isolated power for feeding gate circuit and any optic cable for signal transfer. And it shows very good characteristics of short circuit protection.

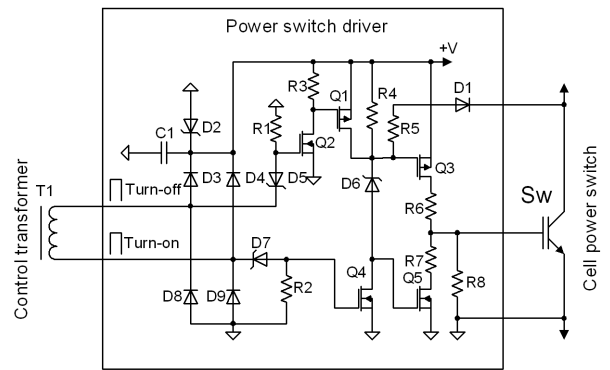


Fig. 2. Proposed simple gate driver circuit using high voltage cable with arc protection.

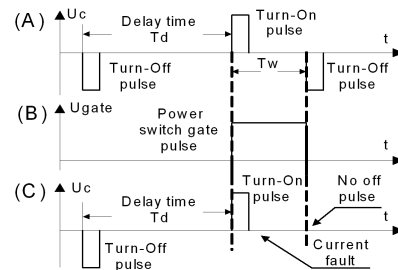


Fig. 3. Driver operation principle illustration.

A high voltage cable having proper isolation, which is designed as control loop, passes through a toroidal core of control transformer T1 forming primary winding as single turn. The direction and the real level of the current in control loop are very important design factors in proposed scheme.

Because all the signal and power required to operate all the gate of series IGBTs is delivered by control loop current using single turn high voltage cable, it can reduce the complexity and system cost largely.

Since the power switch is controlled by means of short pulse of different direction currents which mark the body of a real control pulse, it can easily adjust the pulse width during operation. It is shown in Fig. 3.

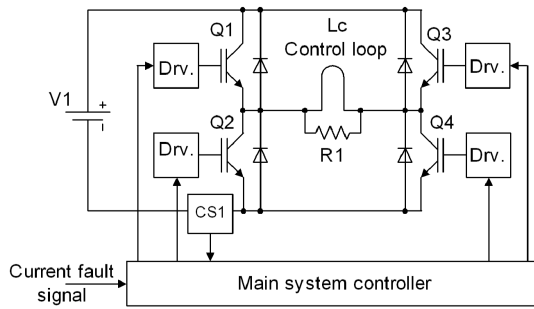


Fig. 4. Control inverter simplified scheme.

The current pulses are generated by a full bridge inverter managed by the main system controller in Fig. 4. The inverter loaded with the inductance of the control loop but an additional inductor or resistor can be placed in series to it for operation.

3. Experimental results

Figures 5–7 show pulsed power generator experimental waveforms for various output condition with resistive load conditions using resistor. Figure 5 shows voltage

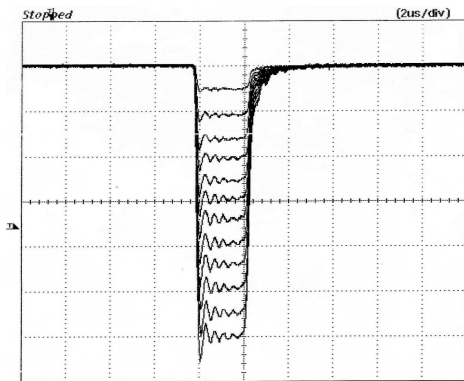


Fig. 5. Pulse output voltage variation with resistive load (5 kV ~ 60 kV, 10 kV/div.).

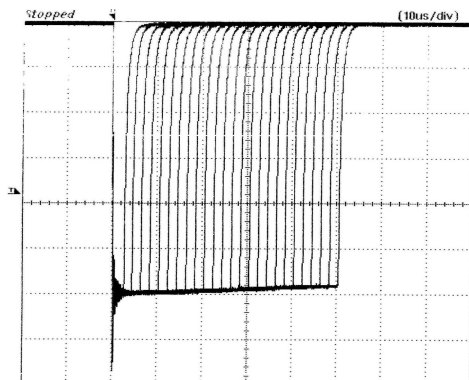


Fig. 6. Pulse width variation waveforms with resistive load ($2 \mu\text{s} \sim 50 \mu\text{s}$, 10 kV/div.).

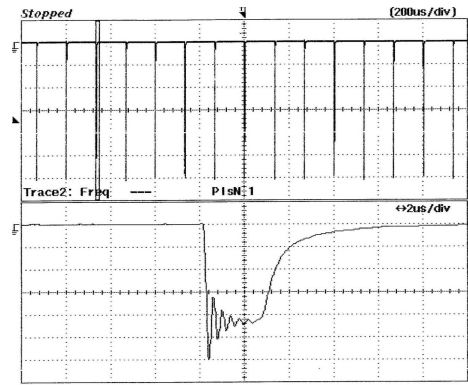


Fig. 7. Maximum pulse repetition rate waveform with resistive load (3 kHz, 10 kV/div.).

variable waveform from 5 kV to 60 kV. It can generate any voltage within 60 kV pulse output. Pulse width variation experimental results are shown in Fig. 6. It can generate pulse width from $2 \mu\text{s}$ up to $50 \mu\text{s}$. Figure 7 shows maximum pulse repetition rate operation of 3 kHz output pulse. It can be operated with repetition rate for continuous operation.

Figure 8 shows arc protection performance when it was operated with plasma chamber. If arc is generated, it automatically cuts off the gate voltage and IGBT switch is protected from short circuit current.

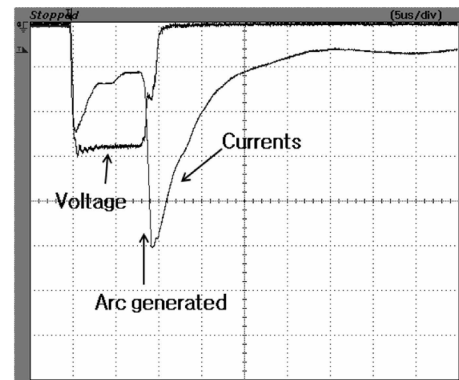


Fig. 8. Arc protection waveforms when it is operated with plasma chamber (100 A/div., 10 kV/div.).

4. Conclusions

In this paper, a novel IGBT based pulsed power generator is proposed. The proposed scheme consists of series connected 9 power stages and each power stage has series connected 8 power cells. Each cell generates up to 850 V DC to archive maximum 60 kV pulse generation.

Proposed pulsed power generator was tested under dummy load and plasma load conditions. It was confirmed that our pulsed power generator shows good control characteristics that is required for pulsed power ap-

plication. The proposed pulsed power supply based on IGBTs has following features.

1. Compact size and lower weights were achieved by using series resonant charging inverter and simple construction.
2. High efficiency during overall conditions ($> 90\%$).
3. Dynamic voltage sharing without active control was accomplished and voltage difference between power cells were restricted to less than 5%.
4. Novel gate driver circuit which delivers gate signal and power simultaneously with safe arc protection was designed.
5. Self regulated overload protection without additional circuits.

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