IGBT 기반 고압 펄스전원장치

Pulsed Power Modulator based on IGBTs

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Abstract

In this paper, a novel new pulse power generator based on IGBT stacks is proposed for pulse power application.

Proposed scheme consists of series connected 9 power stages to generate maximum 60kV output pulse and one series resonant power inverter to charge DC capacitor voltage. Each power stages are configured as 8 series connected power cells and each power cell generates up to 850VDC pulse. Finally pulse output voltage is applied using total 72 series connected IGBTs. The synchronization of gating signal is important for series operation of IGBTs. For gating signal synchronization, full bridge inverter and pulse transformer generates on-off signals of IGBT gating and specially designed gate power circuit was used.

Proposed scheme has lots of advantages such as long lifecyle, compact size, flat topped pulse forming, small weight, protection for arc, high efficiency and flexibility to generate various kinds of pulse output.

1. Introduction

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

Recently some kinds of pulse power supply topology which uses a semiconductor switches as a main switch were 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 new 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 60kV 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. Detail simulation and experimental waveforms shows that proposed scheme has many advantages.

2. IGBT based pulse power generator

2.1 Structure of the pulse power generator

The specification of developed pulse power supply can be summarized as follows.

- Pulse output voltage: 0-60kV
- Pulse width: 2uS – 20uS
- Pulse repetition rate: 20 –2000Hz
- Pulse rising time < 500nsec.

The structure of the proposed pulse power generator is shown in fig. 1. It is made of nine stages comprising of eight power cells, a power transformer(TR_{power}) and two control transformers(TR_{cont}). 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 TR_{power} 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. The problem of equalization of tensions of differently loaded power cells fed from a common current source is solved by using a special sharing mechanism.

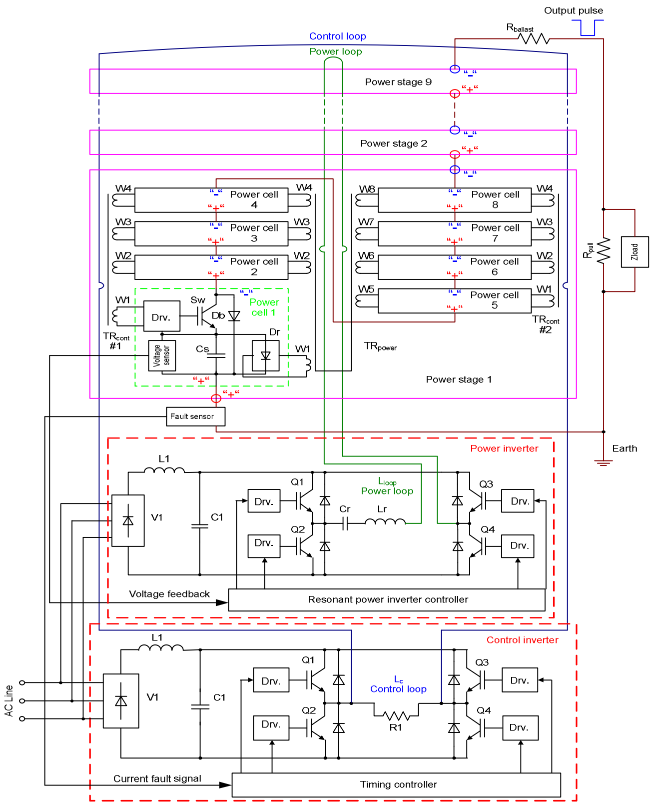


Fig.1. The structure of the proposed pulse power generator.

A very simple "healthy system" senses a unbalance between the cells and corrects it in proper manner. The power cell includes 1200V/ 200A high speed IGBT as a main switch, a power switch driver Drv, a bypass diode Db, a storage capacitor Cs and a full-bridge rectifier Dr linked to the power transformer winding Wi. The bypass diode plays double role, conducting a current flow out from the other cells in case of given cell switch is open and also works like a snubber diode blocking spikes across the switch so that no additional damping elements required. The availability of the passive bypass path takes away the problem of severe synchronization of power switches. The storage capacitor value is big enough to provide a low decline of the output pulse top at its longest duration and the maximum load current at the same time. The maximum voltage across the capacitor is rated as 850 V.

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 pulse 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 pulse power generator outlet is ended with a small value noninductive resistive ballast $R_{ballast}$ for 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 pulse 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 pulse power generator is less than 5% of the controlled one. Even in a standby mode when no pulses generated and the energy consumption of the cells is very small due to their low quiescent current, the five-percent difference is accurately kept.

2.2 Series resonant inverter for capacitor charging

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 Cr, inductor Lr and the current loop L_{loop} having an inductance of 2.6uH. 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 to100 kHz.

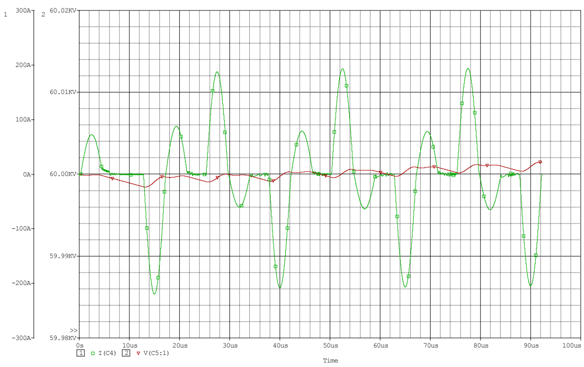


Fig. 2. The charging current of the power inverter and dc charging voltage.(Simulation results)

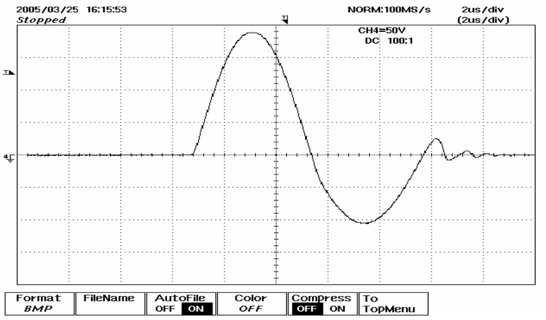


Fig. 3. The charging current of the power inverter at half load condition.(Experimental result. 50 A/ div.)

A current flowing through the loop has clear sinusoidal shape and unipolar waveform within a half switching cycle at maximum output power of 10kW. When light loaded, the current goes in both directions during a half cycle as it can be shown in Fig. 2 (simulation result) and Fig. 3 (real shape). Due to the fact that average charging current supplied to a load within one operating cycle is always restricted and does not depend on load conditions, the total maximum energy of the inverter is restricted too. So there is no need for implementation of additional overload protection circuit to limit it. When the pulse power generator output is overloaded, its output voltage goes down automatically keeping the load power at well predictable level and one can say the pulse power generator works like a current source at heavy load.

2.3 Gate driver circuit

As it was mentioned above the power switch Sw of each cell is ignited by means a specially developed driver Drv. It was shown in Fig. 4. The driver takes control signals from the control transformers T_{cont}. A short pulse of positive turn-on pulse determines the rising edge of a gate pulse for the cell power switches and the negative turn-off pulse determines the falling edge of the gate pulse. It was well described in fig. 5.

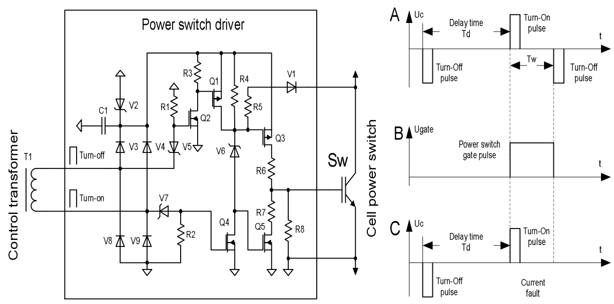


Fig. 4. The simplified scheme the power switches driver and its control diagrams at different operating modes.

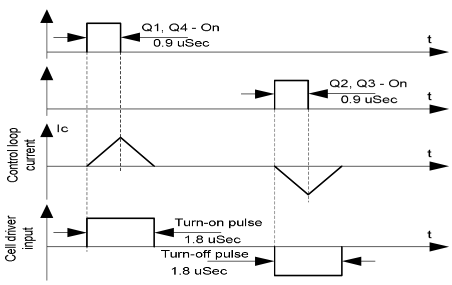
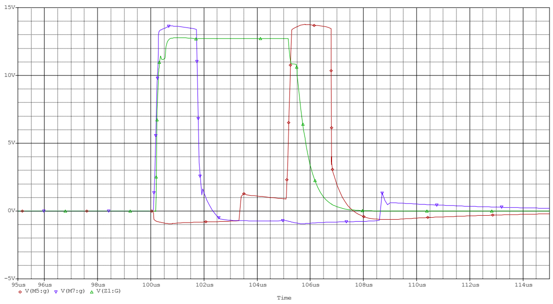
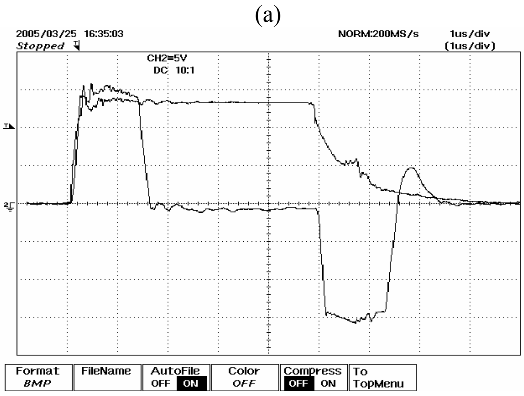


Fig. 5. The simplified timing diagram of one working cycle of the control inverter and the current loop waveform.



(a)



(b)

Fig. 6. Control pulses and the gate signal of power switch.(a) simulated (b)experimental result. 5 V/ div.

The commands are formed by a control inverter driven from a timing controller in fig.1. Each working cycle starts with a turn-off pulse in order to precharge driver's storage capacitor C1. Than, after a delay time T_d of 100 uS a turn-on command appears and the driver forms positive voltage level at the gate of the switch Sw. As soon as the IGBT Sw turns on it starts to keep itself in turn on condition. A forward biased diode D1 pulls down the gate of a transistor Q3 and in such a manner a self toggle latches. Next turn-off pulse deactivates the driver and the power switch Sw accordingly is turn offed. In case of a current fault the IGBT Sw is not saturated and the Q3 is off when said above turn-on command is absent. In such a way the power switch turns off smoothly due to a slow discharge of the gate capacitance via a resistor R8. In that case no turn-off command is sent shown at "C" in Fig. 4 because it was inhibited by blocking signal from current fault sensor placed in the grounding point of the pulse power generator and the power switches are self protected.

The timing controller of the control inverter counts a number of current faults per second. The amount of faults per second can be preset in advance (from 10 to 20 usually) depending on a short circuit current level monitored by the fault sensor. The over current level depends on a particular operating mode. When the number of faults exceeds the preset value, the timing controller stops pulse power generator operation. A function of an automatic restart after a short circuit currents while has been included for convenience.

As it was mentioned earlier control inverter is a simple IGBT bridge loaded with the control loop inductance of about 4 uH. As same as the power loop the control one is made with a high voltage stripped cable but it has smaller diameter. The current flowing through the control loop has almost triangle shape shown in fig. 5.

The current pulses of both polarities are symmetrical and bring the same energy to the drivers. The current pulses of both polarities are symmetrical and bring the same energy to the drivers. The waveforms of the control signals at the cell driver input and the gate power switch are presented in Fig. 6.

There are two small size current transformers T_{cont} on each power stage of the pulse power generator pierced with the control loop. Each transformer T_{cont} has four separated windings to make gating signal for each switch. All gate drivers are properly operated in a sequence of switch on and switch off simultaneously.

3. Experimental results

The pulse power generator was tested at a resistive dummy load and a real nonlinear plasma load in different modes.

Fig. 7 shows waveforms when pulse power generator is working at 60kV in dummy load condition. It can be observed that it show fast rising time less than 300nsec from 0 to 60kV.

Fig. 8 compares normal operation waveforms with those of short circuit condition. When short circuit condition is generated during normal operation short circuit current is rising up to 1200A maximum but it is protected by the gate protection circuit in safe manner.

The pulse power generator test was made with PSII chamber and resultant waveforms are shown in fig. 9 and fig. 10 depending on various plasma condition.

The generator demonstrated good enough dynamic characteristics. Even at heavy load, rise and fall times less then 300nsec were observed. When tested with real nonlinear plasma load under numerous break down conditions the pulse power generator shows very high reliability and immunity to any troubles in the load.

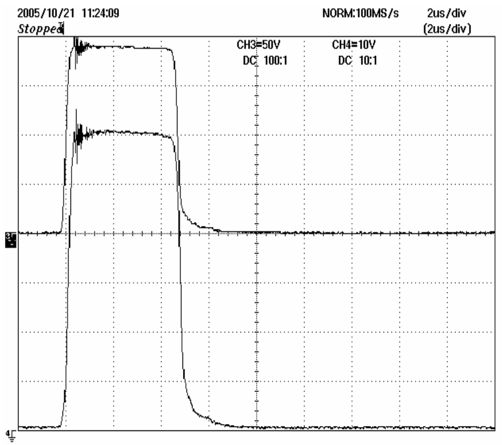


Fig. 7. Pulse power generator test at a resistive dummy load. (Upper: output current, 50A/div. Lower: output voltage, 10 kV/div)

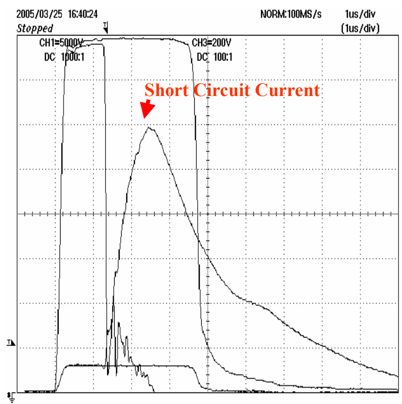


Fig. 8. Short circuit protection at a resistive dummy load. (Upper: output voltage, 5 kV/div (Longer pulse – normal mode, shorter pulse – break down). Lower: load current, 200 A/div.)

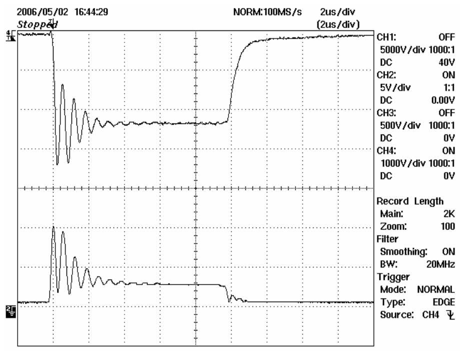


Fig. 9. Pulser test at real plasma load (facile conditions). Upper cover: load voltage, 10 kV/div ("KERI" made pulsed divider used). Lower cover: load current, 100 A/div.

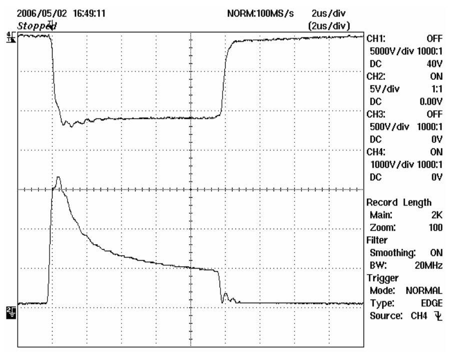


Fig. 10. Pulser test at real plasma load (heavy conditions). Upper cover: load voltage, 10 kV/div ("KERI" made pulsed divider used). Lower cover: load current, 100 A/div.

4. Conclusions

In this paper, a novel IGBT based pulse power generator shown in fig. 11 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 850VDC to archive maximum 60kV pulse generation. To synchronize gate signals for 72 series operation of IGBTs and to protect IGBT switches at breakdown condition, a simple and robust gate driver circuits are designed.

Proposed pulse power generator was tested under dummy load and plasma load condition. It was confirmed that our pulse power generator shows good control characteristics that is required for pulse power application. The proposed pulse power supply based on IGBTs has following features.

1) Compact size and lower weights were archived by using series resonant charging inverter and simple construction.
2) High efficiency during overall conditions. (>90%)
3) Simple and reliable gate driver circuit was developed to help reliable series operation of IGBTs. And there are no need of additional circuits for synchronization.
4) Dynamic voltage sharing without active control was accomplished and voltage difference between power cells are restricted less than 5%.
5) Flat topped pulse waveform without voltage decreasing.
6) Self regulated overload protection without additional circuits.


(a)
(b)

Fig. 11. The pulse power generator overview.(a) resonant inverter charger (b) pulse output power stages

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