An All-Solid-State Pulsed Power Generator for Non-Thermal Plasma Discharge Applications[1]

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Abstract – Non-thermal plasma discharge requires a pulsed power generator with a high repetition rate, short pulse width, fast rise voltage and a long lifetime. This requirement will give a challenge to pulsed power generator, especially to the switch devices. Normal switch devices tend to have limited lifetime and average power level, which hinder their practical aplications.

In our work, an all-solid-state pulsed power generator is presented. It consists of a resonant charging circuit, a fast charger with high frequency controlled by a high speed semiconductor switch, a step-up transformer, a magnetic compression switch and the load. In this circuit three stages of pulse compress from millisecond to nanosecond is achieved. The resonant charging circuit provides primary power supply in tens of milliseconds scale. The fast charger charges the capacitor in the last stage in several microseconds. At the last stage, the magnetic compression switch transfers low inductance from high inductance and compresses the current pulse into short one. A semiconductor switch controls the frequency of the load discharge. The whole pulse power generator operates with high frequency and efficiency. It has high reliability and long lifetime, which is very useful in applications of non-thermal plasma discharge. This paper discusses the basic principle of pulsed power generator and put the focus on the system analysis and design.

1. Introduction

Nonthermal plasma has been extensively investigated recently years because it can be effetely used to modify a number of hazardous compounds rendering them less harmful to environment [1–3]. A principal advantage of nonthermal plasma processing is that the majority of the energy invested in the process is utilized for the acceleration of electrons without significantly heating the bulk of the gas. Therefore chemical reactions that are normally associated with very high bulk temperature can be realized near room temperature. Nonthermal plasma treatment of gaseous effluents can be significantly more efficient than other treatment methods. A nonthermal plasma can be produced at atmospheric pressure by a transient electrical discharge in which high energy electrons are created in a low temperature background gas. Plasma discharge reactor is designed as a coaxial stricture consisting of an outer and a center electrode. Typically the gas to be treated enters the tube at one end and exits the structure at the other end. The plasma discharge can be represented as a lumped time varying resistance, occurs when the breakdown voltage of the gas in the tube is reached, in parallel to a stray capacitance. The energy per pulse dissipated in the discharge was approximately 60 mJ. The system could be operated at a repetition frequency greater than 1 kHz with peak output voltage of up to 30 kV.

Non-thermal plasma discharge can be achieved by applying a positive high – voltage pulse to a field enhancing wire electrode in the center of a tube. The high electric field developed in the gas region between the electrodes causes partial ionization of the gas which provides a source of free electrons. The desired free radicals can be produced. In order to prevent the undue acceleration of ions and the development of an arc between the electrodes, high voltage pulse should be a fast rise time (~ 1000 V/ns) and relatively short pulse duration (> 100 ns).

2. Basic Principles of Pulse Compression

A pulsed power generator is shown in Fig. 1. It consists of a resonant charging circuit, a fast charger with high frequency (1 ~ 10 kHz), pulse magnetic switch and the load. The load is the plasma discharge reactor that can be represented as a lumped time varying resistance (R_3) in parallel to a capacitance of reactor tube (C_4). The resonant charging circuit is comprised of L_1, L_2 and C_1, it provides a resonant current for transformer TX1. During the normal operation, the energy per pulse dissipated into the load is much less than the stored energy in C_2, the charging time for C_2 is charged from a residual voltage is much less than one cycle time as shown in Fig. 2. There is a relationship between the voltage and charging time, $C_2(U - U_{re}) =$
$= It_{ch-1}$. The intermediate storage capacitor C_2 is charged by rectifying bridge in one cycle time interval in the initial time. Capacitor C_3 is charged by C_2 through a inductance L_3, which compensates the energy per pulse dissipated into the load. The fast charger transfers the energy required by the load from
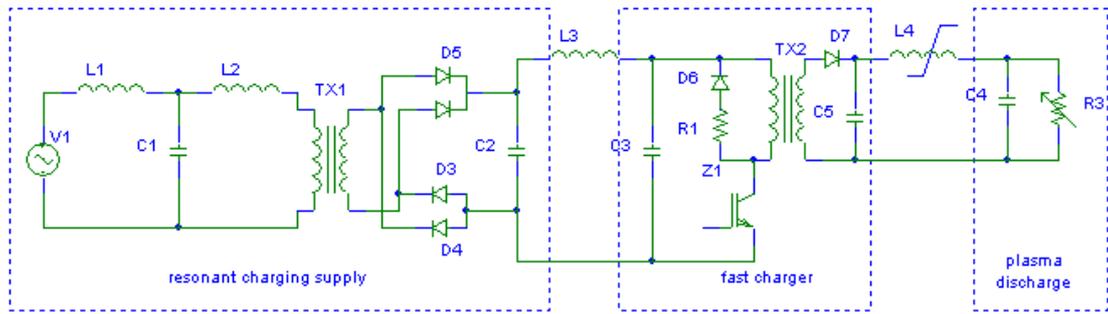
Fig. 1. A pulse power generator with pulse compression

C_3 to high-voltage capacitor C_5 with less capacitance in microsecond time interval as shown in Fig. 3. The high power semiconductor switch is used to control the frequency of load discharge. Once the capacitor in parallel to the secondary of transformer is fully charged, the magnetic switch saturates and the capacitor switches on the load with tens of nanosecond rise time as shown in Fig. 4. Whole pulse power generator has only one semiconductor switch which determines the frequency of plasma discharge. Three stages have independent working mode, that is, later stage is not affected by former stage. But the pulse width of later stage is compressed into a short one.
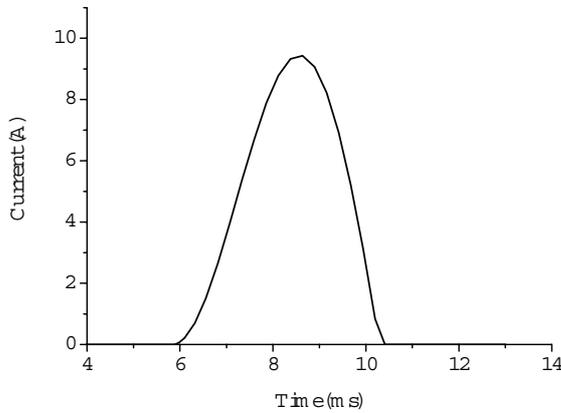
Fig. 2. A current waveform from the resonant charging circuit
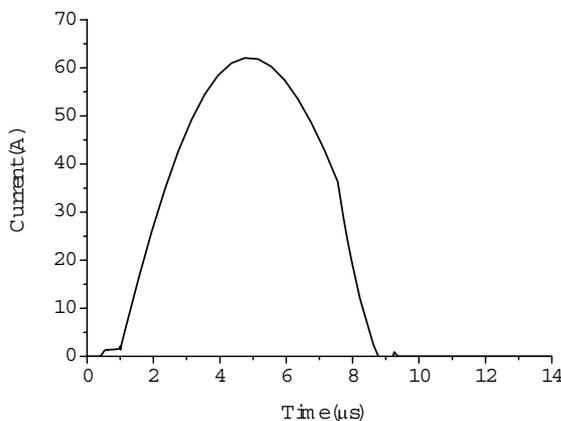
Fig. 3. A current waveform from the fast charger
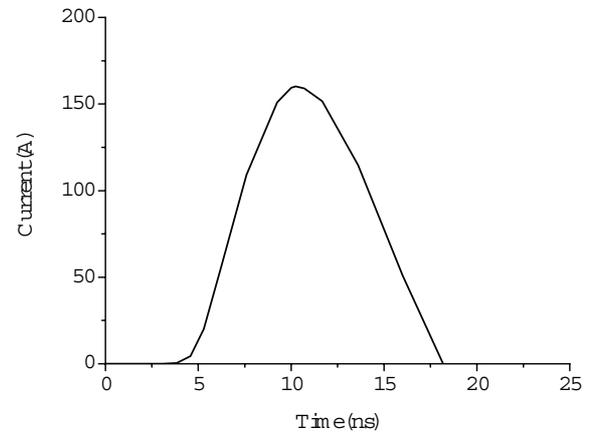
Fig. 4. The current waveform from the plasma discharge reactor

3. Resonant Charging Circuit

The advantage of the resonant charging circuit is that it has a relatively fast charging time and high charging efficiency. The parameters in the resonant charging circuit meet the condition as following:

$$\omega^2 L C_1 = 1 , \qquad (1)$$

where $L = L_1 = L_2$, $\omega = 2\pi f_0$, f_0 is the supply frequency.

According to the reference [4], when characteristic coefficient $Q = \dfrac{\omega L}{R} \geq 20$, coupling coefficient $k = 0.95$, the efficiency of resonant charging circuit is larger than 88%. It is favorable to improve Q and k for the pulse power generator.

4. Fast Charger

The fast charger of a flyback mode of operation is chosen based on following considerations, first it immune to transients associated with the discharge of the load. In this mode the primary semiconductor switch of the resonant charger is in the off state when the capacitor in the secondary is discharged. Secondly it

operates in high efficiency mode if the parameters of the primary and secondary of transformer match well. In order to lower the over-voltage applied into the semiconductor switch and improve the working efficiency of transformer, the secondary capacitor should be fully charged time in a quarter of cycle. At the same time all energy stored in the capacitor discharged into the primary of the transformer completely during the switch is closed. The quarter of a cycle time is determined by the inductance and capacitance in. Here the resistance of the primary and secondary in the transformer is neglected (normally, the resistance is much less than the impedance):

$$t_{ch-2} = \frac{\pi}{2}\sqrt{L_p C_p} = \frac{\pi}{2}\sqrt{L_s C_s}. \qquad (2)$$

The probable maximal voltage in the secondary is

$$U_{2m} = U_0 \sqrt{C_p / C_s}. \qquad (3)$$

If

$$C_p = N^2 C_s; \qquad (4)$$

$$L_s = N^2 L_p, \qquad (5)$$

the output voltage in the secondary is

$$U_{2m} = N U_0. \qquad (6)$$

The conduction time of the semiconductor switch is matched with the charging time t_{ch-2}, which prevents the semiconductor switch from overvoltage at the opening moment and improve the operation efficiency of pulse power generator.

5. Pulsed Discharging into Load

The magnetic switch has two functions for the discharge of the load. First, it can isolate the charge of storage capacitor from the load. Secondly it can minimize the rise and fall time, which does not suffer from many of the limitations, associated with discharge switches such as relatively long recovery times and serious electrode erosion problem. Once the capacitor C_5 is fully charged, the magnetic switch saturates discharging the capacitor C_5 into the load. During C_5 is charged, the saturated delay time t_s of magnetic switch is

$$t_s = \frac{SN\Delta B_s}{U_N}, \qquad (7)$$

t_s corresponds to the charging time t_{ch} of capacitor C_5.

If the stray capacitance of plasma discharge tube is neglected, the risetime of load voltage pulse is determined by the L/R time constant of discharge circuit,

which the leading edge of the pulse rises from 10 to 90% of its peak value. It is given by

$$t_r = 2.2 \frac{L_{sat}}{R_l}, \qquad (8)$$

where L_{sat} − saturated inductance of the magnetic switch; R_l − load resistance.
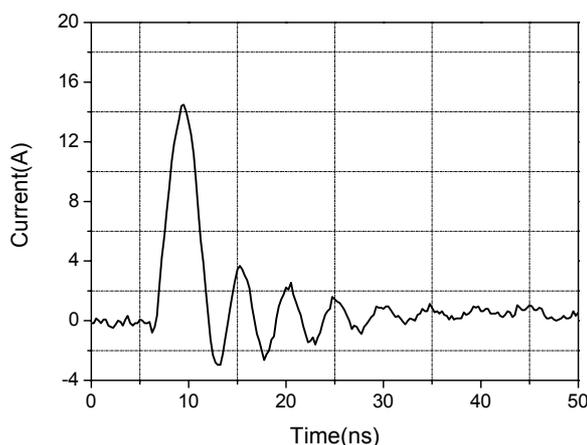
Fig. 5. A current waveform when C_3 discharge into the primary

6. Operation

Typically current pulse in the primary windings of the set-up transformer in the resonant charge circuit is shown in the Fig. 5. The voltage waveform from the plasma discharge reactor is shown in Fig. 6, from which we can see that the pulse rise time in the load is about 50 ns. Pulse duration is about 80 ns.
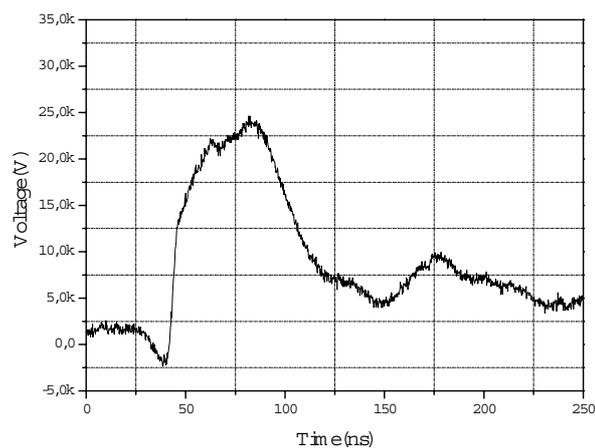
Fig. 6. Voltage waveform from the plasma discharge reactor

7. Conclusion

In this paper we have presented a pulsed power generator which can produce a high repetitive rate pulse with nanosecond duration and risetime. The operation principle and design has been described.

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Reference

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