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Pulsed corona generation using a diode-based pulsed power generator

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Pulsed plasma techniques serve a wide range of unconventional processes, such as gas and water processing, hydrogen production, and nanotechnology. Extending research on promising applications, such as pulsed corona processing, depends to a great extent on the availability of reliable, efficient and repetitive high-voltage pulsed power technology. Heavy-duty opening switches are the most critical components in high-voltage pulsed power systems with inductive energy storage. At the Ioffe Institute, an unconventional switching mechanism has been found, based on the fast recovery process in a diode. This article discusses the application of such a “drift-step-recovery-diode” for pulsed corona plasma generation. The principle of the diode-based nanosecond high-voltage generator will be discussed. The generator will be coupled to a corona reactor via a transmission-line transformer. The advantages of this concept, such as easy voltage transformation, load matching, switch protection and easy coupling with a dc bias voltage, will be discussed. The developed circuit is tested at both a resistive load and various corona reactors. Methods to optimize the energy transfer to a corona reactor have been evaluated. The impedance matching between the pulse generator and corona reactor can be significantly improved by using a dc bias voltage. At good matching, the corona energy increases and less energy reflects back to the generator. Matching can also be slightly improved by increasing the temperature in the corona reactor. More effective is to reduce the reactor pressure. © 2003 American Institute of Physics. [DOI: 10.1063/1.1606119]

I. INTRODUCTION

During the last decade, high-voltage pulsed power and pulsed plasma techniques have been extensively investigated for chemical and physical processing.¹ Processes vary from chemical synthesis to decomposition and from electromagnetic pulses to acoustic waves. Potential applications are: flue gas cleaning, odor control, inactivation of microorganisms, wastewater cleaning, tar removal from biogas, methane reforming, hydrogen production from fossil fuel or biomass, material surface treatment, and nanoparticle generation.

Repetitive high-voltage pulsed power generators are the enabling technology for extending research and development on promising applications and successful introduction in industries. Prototypes of efficient nanosecond pulse generators are available and have been demonstrated in laboratory and in field trials. These generators employ a heavy-duty spark-gap switch combined with a transmission-line transformer.² Lifetime and reliability are adequate for industrial demon-

strations. Treatment of gas flows up to 100.000 N m³/h is possible. We expect to reach a average corona output power of 100 kW within the next year.³

The introduction by the Ioffe Institute of an unconventional switching mechanism, based on the very fast recovery of a drift-step recovery diode (DSRD), allows methods for pulsed power generation.^{4,5} This article describes a pulsed power circuit based on DSRD switching. The circuit has been tested at resistive loads and several pulsed corona reactors. Methods to optimize the energy transfer to a corona reactor have been evaluated.

II. PRINCIPLE OF THE DSRD BASED PULSED POWER GENERATOR

Work started in 1983 in the Ioffe Institute in St. Petersburg led to the development of pulsed power generators combining inductive energy storage and a special semiconductor opening switch, the so called drift step recovery diode, DSRD. The diode utilizes the super fast voltage recovery in silicon *p-n* junctions during forward to reverse conduction of high currents (Fig. 1). Blocking occurs when the charge injected during forward conduction equals the

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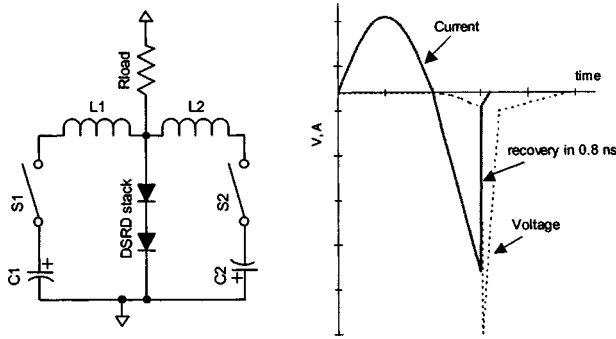


FIG. 1. Principle of the diode based pulsed power generator.

charge extracted during reverse operation. The DSRD is claimed to have unlimited lifetime and can operate at pulse repetition rates up to 1000 pps. Diodes can be stacked to obtain high hold-off voltages.

Very fast recovery was observed in a silicon $p^+p'nn^+$ diode structure, manufactured by deep (100–130 μm) diffusion of Al into n -Si, followed by shallow diffusion of B and P with high surface concentration (10^{20} cm^{-3}). Detailed descriptions of the construction, physical basis and conditions for nanosecond recovery in a DSRD are given by Grekhov.^{4,5} The DSRD diodes used in this work have a silicon wafer diameter of 40 mm and 460 μm thickness. A p^+pnn' structure was formed in this wafer by simultaneous diffusion of aluminum (p layer) and phosphorus (n' layer). The thickness of the diffusion layers is 120 μm for the p layer and 70 μm for the n' layer. The p^+ layer (25 μm) was formed by boron diffusion.

The principle of a DSRD based nanosecond pulsed power generator is shown in Fig. 1. Initially, both capacitors are charged: C_1 to a positive voltage, C_2 to a negative voltage. When switch S_1 is closed, a forward current I_F starts to flow in loop C_1-L_1 -diode, pumping an electron-hole plasma into the diode junction. At the moment of current zero switch S_2 will be closed. Now the plasma in the p and n regions of the semiconductor is pulled off from the diodes by a reverse current pulse I_R in the circuit diode- L_2-C_2 . Due to fast recovery of the pn junction blocking capability, this current commutates from the diode to the load R_L , forming a high-voltage output pulse U_R . The rise time of this voltage depends on the recovery time of the diodes. The energy of the output pulse is determined by the energy stored in L_2 .

III. CIRCUIT DESCRIPTION

Figure 2 shows the basic electric circuit of the generator. At the initial state, transformer (TR) is unsaturated, inductances L_1 and L are saturated and capacitor C_0 is charged up

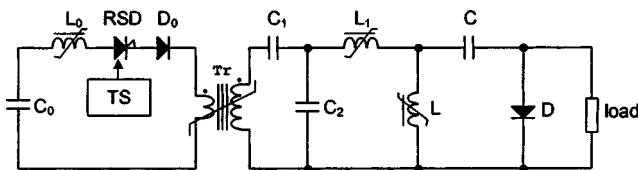


FIG. 2. Electric circuit of the diode based pulsed power generator.

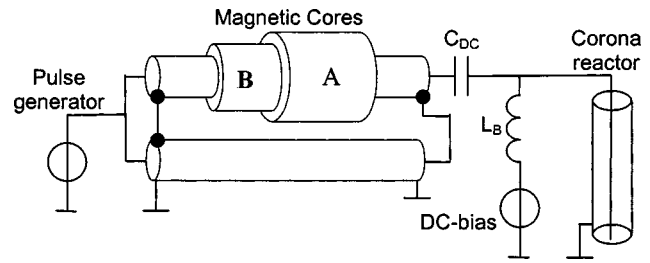


FIG. 3. A pulsed corona system, energized by a diode based pulsed power generator and connected via a TLT. Also a dc bias voltage can be used.

to $U_{C0}=0.9 \text{ kV}$. When the RSD switch⁶ is triggered by the triggering circuit (TS), capacitor C_1 is charged via the circuit $TR-L-L_1-C_1$. Charging occurs in about 3.5 μs to $U_{C1}=28 \text{ kV}$. Now the transformer TR is saturated and capacitor C_2 will be charged through circuit C_1-C_2-TR ; inductances L_1 and L are not saturated during this step.

Then L_1 is saturated and C_2 discharges through the circuit C_2-L_1-C-D in about 0.3 μs . This is the pumping cycle; a forward current I_F passes through the DSRD stack and pulls on plasma into the diodes. When the total charge has been transferred from C_2 to C , inductor L is saturated and capacitor C discharges via the circuit $C-L-D$. The corresponding current through the DSRD stack pulls off the plasma from the diodes. In about 80 ns this current reaches its maximum value. Now the current commutates in about 3 ns to the load, forming a high-voltage output pulse.

A generator of this type can easily be connected to a transmission line transformer (TLT), as is shown in Fig. 3. Detailed descriptions of a TLT (including modeling, magnetic core selection, construction, and energy efficiency) are given by Yan² and Smith.⁷ The TLT used here consists of two 50 Ω coaxial transmission lines (RG218), with a length of 1.5 m. At the generator side, both lines are connected in parallel, thus providing a low impedance for the generator (25 Ω). At the reactor side, the lines are connected in series. This output impedance of 100 Ω provides a better matching with a corona reactor. In addition, the output peak voltage will be doubled.

The performance of a TLT depends to a large extent on the choice of magnetic cores. We use two types of cores. One type should increase the secondary mode impedance, thus providing a very high energy efficiency. An energy efficiency of about 97% has been obtained using Metglas cores with a microgap. The other type of core should absorb remaining energy in the circuit after plasma quenching, and limits the switching currents during short circuit or breakdowns in the reactor. High resistivity ferrite cores are used for this purpose. The main functions of the TLT used in this work can be summarized as: (i) achieve a higher output impedance for better matching with a corona reactor; (ii) increase the output voltage; (iii) protection of the switch against short-circuits and breakdowns; and (iv) enable easy coupling with a dc bias voltage.

The pulse voltage can be superimposed on a dc bias voltage via a coupling capacitor C_{DC} and a blocking inductor L_B . Advantages of using a dc bias voltage are: (i) simulta-

neous corona plasma processing and electrostatic precipitation; (ii) increased average corona power, while both the energy in the coupling capacitor C_{DC} and the energy delivered by the pulse generator are transferred to the corona discharge; and (iii) better impedance matching and energy transfer between pulse generator and corona reactor (see next sections). When using a dc bias, the total voltage at the corona reactor is given in Eq. (1), where the voltage V_{loss} corresponds to the voltage drop over the coupling capacitor C_{DC} . Now the total energy per pulse ε (in J/L) can be determined according to Eq. (2), where T is the pulse duration

$$V(t) = V_{pulse}(t) + V_{DC} - V_{loss}, \tag{1}$$

where

$$V_{loss} = \frac{1}{C_{DC}} \int_0^t i(\tau) d\tau,$$

$$\varepsilon = \int_0^T V_{pulse}(t) \cdot i(t) dt + \int_0^T V_{DC} \cdot i(t) dt - \int_0^T V_{loss} \cdot i(t) dt. \tag{2}$$

The output voltage and current are measured directly at the output of the TLT. Since we like to evaluate the performance of the pulse generator, only values corresponding to the first term in Eq. (2) will be given in this article.

IV. TESTS WITH A RESISTIVE LOAD

The pulse voltage, current, power, and energy per pulse as measured at the output of the TLT for a matched resistive load of 100 Ω are given in Fig. 4. The pulse voltage is about 60 kV with a rise time of 9 ns and a pulse width of 22 ns. The peak power is about 50 MW and the energy per pulse is 0.9 J, giving an average output power of 900 W at 1000 pps. For a higher load resistance, the output voltage increases to over 100 kV at 500 Ω (Fig. 5). However, the energy per pulse drops with increasing load resistance due to impedance mismatch.

V. TESTS ON A WIRE-PLATE CORONA REACTOR

The system has been tested on a wire-plate corona reactor. The reactor has a plate-plate gap distance of 116 mm. The total length of the corona wires is 12 m and their diameter is 1 mm. Wave forms can be seen in Fig. 6. Due to improper impedance matching between the generator and the corona reactor, part of the energy reflects back towards the generator [Fig. 6(b)]. Also oscillations occur on the voltage and current wave shapes.

Proper impedance matching is necessary for a good energy transfer efficiency. A requirement for matching is a proper choice of the peak voltage. At higher peak voltages, the generated streamer current (or the total number of streamers) can be increased to such a level that the reactor impedance tends to be equal to the output impedance of the pulse source.² For this work, the output voltage of the pulse generator could not be varied. However, a dc bias voltage can set the total peak voltage. This significantly improves the

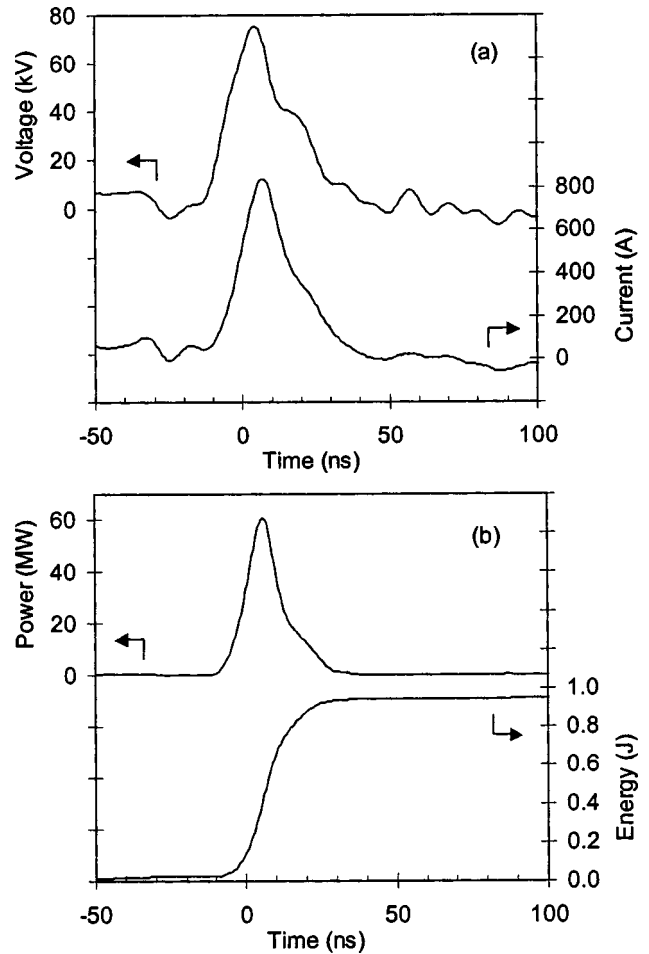


FIG. 4. (a) Pulse voltage, current, (b) power and energy, measured at the TLT output for a resistive load of 100 Ω.

matching [Fig. 6(b)]. Both the reflected power (the negative part of the power curve) and the reflected energy (the drop in the energy curve) are nearly zero at a 25 kV dc bias.

The effect of the dc bias voltage is also shown in Fig. 7. The amount of energy that reflects back to the generator is less at higher dc bias voltages. At 25 kV less than 15% reflects back, while at 0 kV about 65% reflects back. When less energy reflects back, the corona energy in the reactor

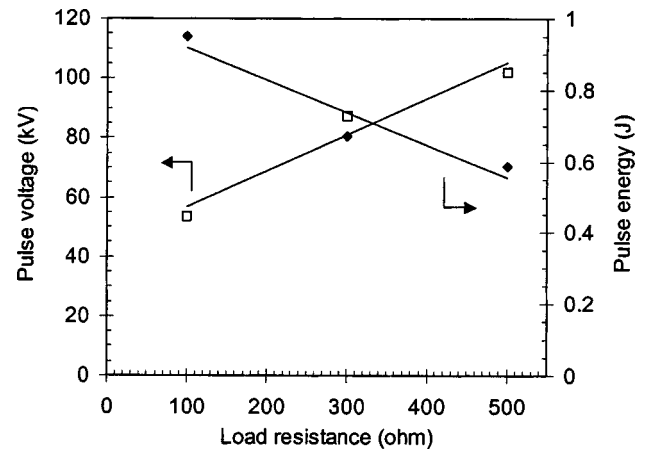


FIG. 5. Pulse voltage and pulse energy for various resistive loads.

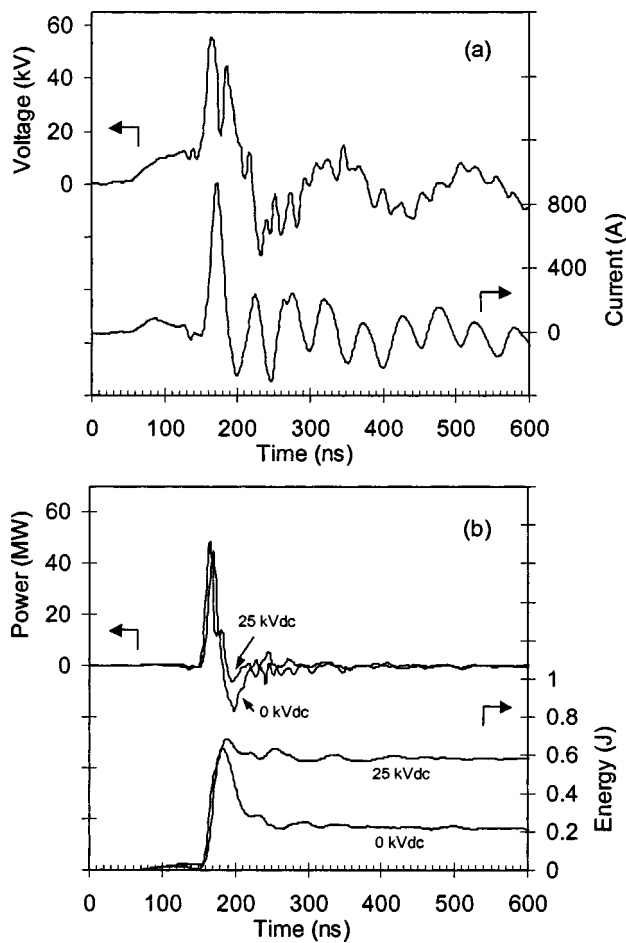


FIG. 6. (a) Voltage and current wave form for a wire-plate corona reactor, at 25 kV dc bias. (b) Power and energy per pulse at 0 and 25 kV dc bias.

increases; from 0.2 J without dc bias to 0.6 J at 25 kV dc bias.

In order to evaluate the reliability of the pulse generator, long duration tests were carried out. The total duration of various runs was about 4 h. During these tests, various breakdowns occurred in the corona reactor. In addition, various runs were carried out with improper matching, resulting in large amounts of energy reflected back to the generator. No problems with the generator were observed. Operation

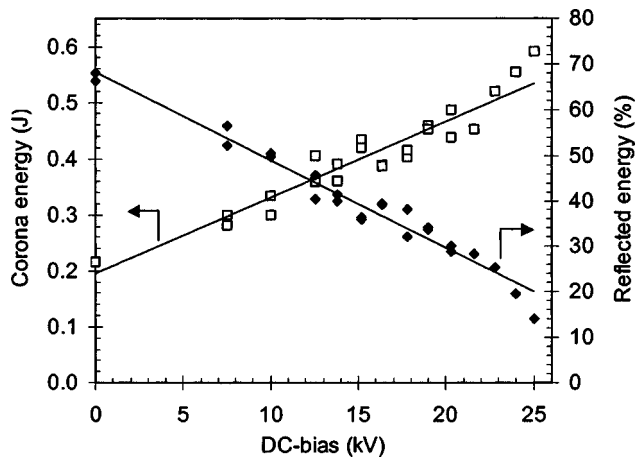


FIG. 7. Corona energy and reflected energy vs the dc bias voltage.

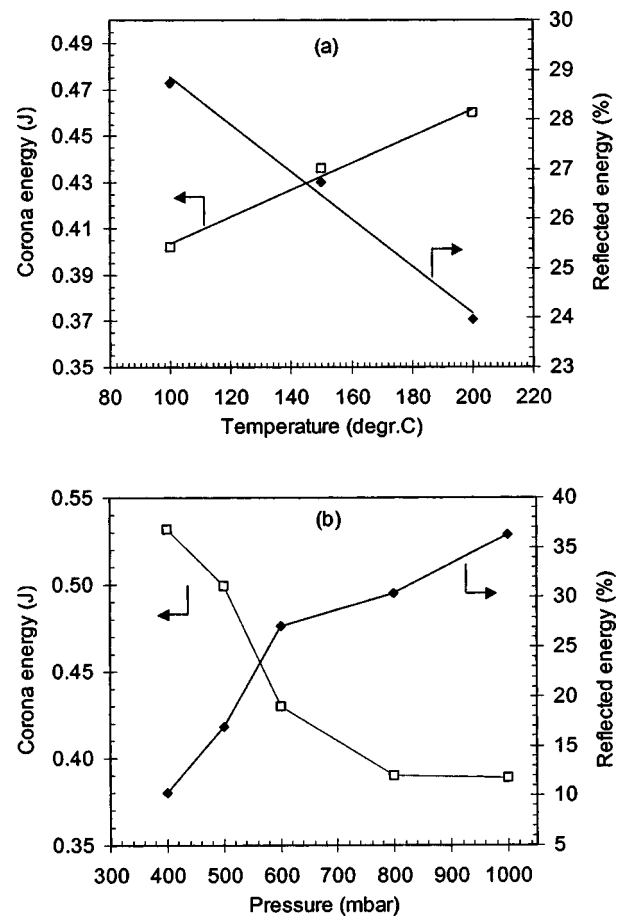


FIG. 8. Corona energy and reflected energy vs (a) the reactor temperature (at 1 bar) and (b) the pressure inside the reactor (at 20 °C).

was stable and temperatures of the various components of the generator remained within acceptable values.

VI. ENERGIZING A PULSED CORONA TAR CRACKER

To supply combustion engines or gas turbines with fuel gas obtained from biomass gasification, it is necessary to remove heavy hydrocarbons (tars) from the biogas. We are investigating pulsed corona as an alternative method for catalytic and thermal tar removal.⁸ We coupled the DSRD-based pulse generator to the wire-cylinder reactor of our tar removal system (reactor diameter is 250 mm, 3 m length). No dc bias voltage could be used, so other ways to optimize matching must be found.

Streamer properties depend mainly on local E/n values near the wire electrodes, where E is the electric field strength and n is the gas density. It is clear that increasing the total peak voltage results in higher E/n values and thus in more and/or more intense streamers. The same might be expected at lower n values, thus at increased temperature or reduced pressure. At higher temperatures, indeed less energy reflects back to the generator and the corona energy becomes higher [Fig. 8(a)]. However for proper matching much higher temperatures seem to be necessary. Reducing the pressure has the same effect; at low pressure less energy reflects back and the corona energy is higher [Fig. 8(b)]. The reflected energy can be reduced to about 10% at 400 mbar.

ACKNOWLEDGMENTS

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