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**Citation for published version (APA):**

Pemen, A. J. M., Grekhov, I. V., Heesch, van, E. J. M., Yan, K., & Nair, S. A. (2003). Repetitive high-voltage pulse generation using a solid-state opening switch. In *Proc. XIIIth International Symposium on High Voltage Engineering, Delft, 25-29 August 2003* Millpress.

**Document status and date:**

Published: 01/01/2003

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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## Repetitive high-voltage pulse generation using a solid-state opening switch

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**Abstract** - Heavy-duty opening switches are the most critical components in high-voltage pulsed power systems with inductive energy storage. For industrial applications such as pulsed corona processing, long lifetime, high repetition rate, high reliability and high efficiency are required. At the Ioffe Institute, an unconventional high-voltage switching mechanism has been found, based on the fast recovery process in a diode. This paper discusses the application of such a 'drift-step-recovery-diode' for high-voltage pulse generation.

The principle of the diode-based nanosecond high-voltage generator will be discussed. The generator will be coupled to a load via a transmission-line-transformer. The advantages of this concept, such as easy voltage transformation, load matching and switch protection, will be discussed. The developed circuit is tested at various corona reactors. Methods to optimize the energy transfer to a load have been evaluated. With respect to possible applications of the system, results will be presented on tar removal from biogas.

### 1. Introduction

High-voltage pulsed power and pulsed corona plasma techniques are leading to a new area of technologies for chemical and physical processing. Processes vary from chemical synthesis to decomposition and from electromagnetic pulses to acoustic shock waves. Many potential applications are extensively investigated, for example: flue gas cleaning, odor control, inactivation of micro-organisms, wastewater cleaning, tar removal from biogas, methane reforming, hydrogen production from fossil fuel, material surface treatment, and nanoparticle generation. Important issues for industrial applications are: (i) power capacity, energy efficiency and reliability of pulsed power generators, (ii) optimized interactions between the generator and the process, and (iii) on-site tests and demonstrations.

The research in this field at Eindhoven University covers fundamental processes of corona discharges [1], pulsed power technology [2], corona and torch plasma for gas [3] and water treatment [4], electrical diagnostics [5] and EMC techniques [6]. A few of the advantages of pulsed corona are: (i) combined plasma processing, aerosol formation, and particulate/aerosol removal, (ii) good operation at high gas temperatures,

(iii) runs under wet and polluted conditions, and (iv) very suitable for large volume gas cleaning.

The energy efficiency and costs of pulsed corona plasma processing depend mainly on the high-voltage pulse generator. Prototypes of efficient nanosecond pulse generators are available and have been demonstrated in laboratory and in field trials. The best and most cost effective pulse generator now available employs a heavy-duty spark-gap switch combined with a transmission-line-transformer [2], see Table I. Lifetime and reliability are adequate for industrial demonstrations. Gas flows up to 100.000 Nm<sup>3</sup>/hr are possible. We expect to reach the milestone of 100 kW output power within the next year (Table I).

The introduction by the Ioffe Institute [7] of an unconventional switching mechanism, based on the very fast recovery of a drift-step recovery diode (DSRD), allows new methods for pulsed power generation. This paper describes a pulsed power circuit based on DSRD-switching. The circuit has been tested at resistive loads and several corona reactors. Methods to optimize energy transfer to a reactor have been evaluated. The system has been used for tar removal from biogas.

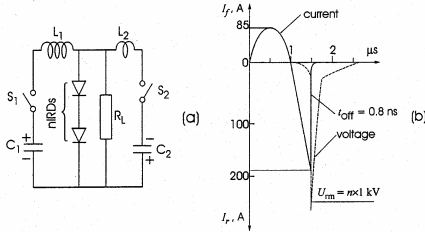
**Table I** Actual specifications of our pulsed power generators and our targets for the coming years.

	<i>Actual</i>	<i>Target for coming years</i>
Average power	10 kW <sub>avg</sub>	100 kW <sub>avg</sub>
Peak output voltage	100 kV	100 kV
Peak output current	1000 A	20 kA
Output impedance	50 ohm	5 ohm
Peak output power	80 MW	2 GW
Energy per pulse	12 J	100 J
Pulse repetition rate	1000 pps	1000 pps
Voltage rise-time	10 ns	10 ns
Pulse width	150 ns	50 ns
Energy conversion efficiency (mains to load)	80 %	>90 %
Switch lifetime	10 <sup>9</sup> shots	>4.10 <sup>10</sup> shots

### 2. Principle of the DSRD based high-voltage pulsed power generator

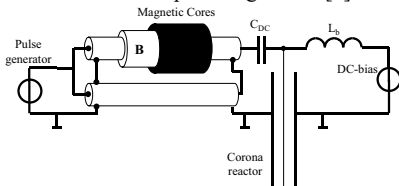
Work started in 1983 in the Ioffe Institute in St. Petersburg led to the development of pulsed power generators combining inductive energy storage and a

special semiconductor opening switch, the so called drift step recovery diode, DSRD. The diode utilizes the super fast voltage recovery in high-voltage silicon p-n junctions during forward to reverse conduction of high currents. Blocking occurs when the charge injected during forward conduction equals the charge extracted during reverse operation [7]. The DSRD is claimed to have unlimited life time, and can operate at high pulse repetition rates, up to kHz. The diodes can be stacked to obtain high hold-off voltages (100 kV). The basic principle is shown in Fig. 1.



**Figure 1:** Principle of the diode based pulsed power generator

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 the second 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  $L_2$ . A detailed circuit description is given in [8].



**Figure 2:** A corona system, energized by the diode-based pulse generator, and connected via a TLT. Also, a DC-bias can be used.

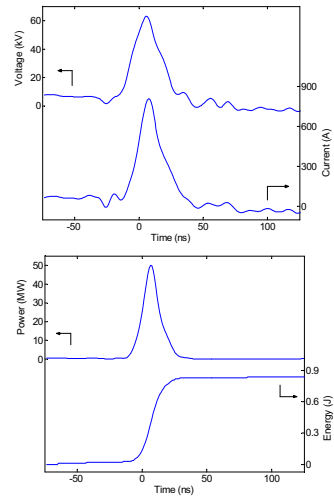
A generator of this type can easily be connected to a matched TLT [2], as is shown in Fig. 2. At the generator-side, both transmission-lines are connected in parallel, thus providing a low impedance for the generator (25 ohm). At the reactor-side, the lines are connected in series. This output impedance of 100 ohm, provides a better matching with the reactor. In addition, the output voltage will be doubled. The main functions of the TLT in this work are: (i) increase the output voltage, (ii) achieve a higher output impedance

for better matching with the reactor, (iii) protection of the switch, and (iv) easy coupling with a DC-bias.

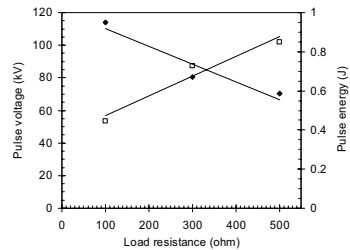
The pulse voltage can be superimposed on a DC-bias voltage. Advantages are: (i) simultaneous corona processing and electrostatic precipitation, (ii) increased average corona power, while both the energy in the coupling capacitor  $C_{dc}$  and the energy delivered by the pulse generator are transferred to the reactor, and (iii) better matching between pulse generator and reactor (see next Sections).

### 3. 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 ohm are given in Fig. 3. The pulse voltage is about 60 kV with a risetime of 9 ns and a pulse-width of 22 ns. The peak power is about 50 MW and the energy-per-pulse is 0.95 J, giving an average output power of 950 W at 1000 pps. For a higher load resistance, the output voltage increases to over 100 kV at 500 ohm (Fig. 4). However, the energy per pulse drops with increasing load resistance due to impedance mismatch.



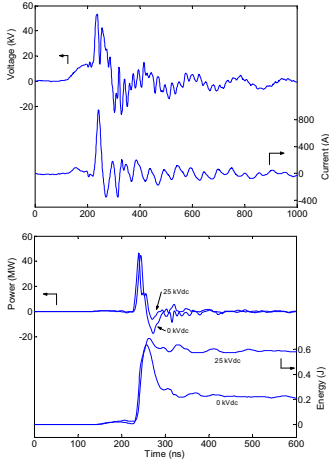
**Figure 3:** Pulse voltage, current, power and energy, measured at the TLT-output for a resistive load of 100 ohm.



**Figure 4:** Pulse voltage and pulse energy for various resistive loads.

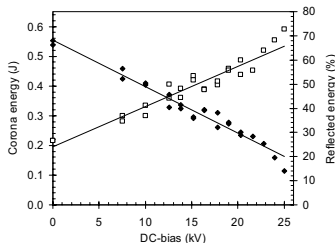
#### 4. Tests on a corona reactor

The system has been tested on a wire-plate corona reactor. Waveforms can be seen in Fig. 5. Due to improper impedance matching between the generator and the corona reactor, part of the energy reflects back towards the generator (Fig. 5b). Also oscillations occur on the waveshapes.



**Figure 5:** (a) Voltage and current waveform. (b) Power and energy-per-pulse at 0 and 25 kV DC-bias. The reactor is a wire-plate type with 116 mm plate-plate distance, 12 m wire length and 1mm wire diameter

Proper 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 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, the total peak-voltage can be set by a DC-bias voltage. This significantly improves the matching (Fig. 5b). 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.



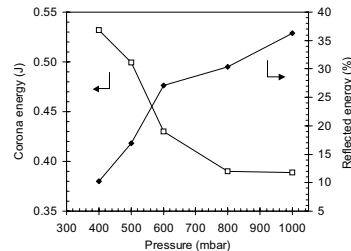
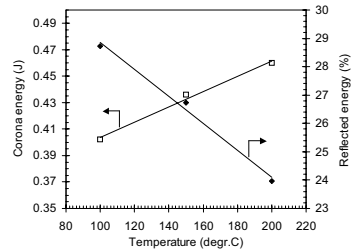
**Figure 6:** Corona and reflected energy versus the DC-bias voltage. The reactor is a wire-plate type with 116 mm plate-plate distance, 12 m wire length and 1mm wire diameter.

The effect of the DC-bias voltage is also shown in Fig. 6. 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 increases; from 0.2 J without DC-bias to 0.6 J at 25 kV DC-bias.

#### 5. Energizing a pulsed corona tar cracker

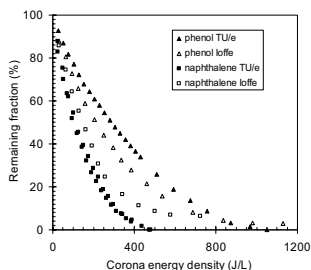
To supply combustion engines or gasturbines with fuel gas obtained from biomass gasification, it is necessary to remove heavy hydrocarbons (tars) from the biogas. We are investigating pulsed corona as an alternative method for catalytic and thermal tar removal [9]. We coupled the DSRD-based pulse generator to the wire-cylinder reactor of our tar removal system. No DC-bias voltage could be used, so other ways to optimize matching must be found.

Streamer properties depend mainly on E/n values inside the reactor. 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. 7a). 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. 7b). The reflected energy can be reduced to about 10 % at 400 mbar.



**Figure 7:** Corona and reflected energy versus (a) the reactor temperature, and (b) the pressure inside the reactor. The reactor is a wire-cylinder type with 250 mm diameter and 3 m length.

Results for the removal of the tar components naphthalene and phenol in biogas are shown in Fig. 8. The results obtained with the diode-based pulsed power supply (closed markers) are compared with previous results with the spark-gap based generator as described in Table I (open markers). There are no significant differences between the results of both generators; both generators perform well and allow efficient corona processing of tars in biogas.



**Figure 8:** Tar removal from biogas by means of the diode-based pulse generator (closed markers) and a spark-gap based pulse generator (open markers). The gas temperature was 220 degr.C at atmospheric pressure. The reactor is a wire-cylinder type with 250 mm diameter and 3 m length.

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

## 6. Conclusions

This paper describes a high-voltage pulsed power generator, based on inductive energy storage combined with a diode-based opening switch:

- In a matched resistive load, the specifications of the generator are: pulse voltage 60 kV, pulse power 50 MW, energy-per-pulse 0.95 J, pulse rise time 9 ns and pulse width 22 ns. At higher resistances, the voltage can increase upto 100 kV, but the pulse energy drops due to impedance mismatch.
- Using a DC-bias significantly improves the matching between generator and corona reactor. 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 reactor. More effective is to reduce the reactor pressure.

- The generator allows efficient tar removal in biogas by means of corona processing.
- No problems with the generator were observed during duration tests. Operation was stable and temperatures of various components of the generator remained within acceptable values. Various breakdowns in the reactor occurred, which did not hamper the generator.

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**Acknowledgements** - The authors greatly acknowledge the support of the Dutch Technology foundation STW and the Dutch foundation for sustainable energy SDE.

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