Heavy-duty high-repetition-rate generators

Citation for published version (APA):

DOI:
10.1109/TPS.2002.805321

Document status and date:
Published: 01/01/2002

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.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 08. Jan. 2021
Heavy-Duty High-Repetition-Rate Generators
E. J. M. van Heesch, K. Yan, and A. J. M. Pemen, Member, IEEE

Abstract—We present our recent results on high-power repetitive pulse sources for continuous operation. Two 1–10-kW systems using advanced spark gap technology and a transmission line transformer have been tested for several hundred hours at a 60-MW pulse level. High reliability and above 90% overall efficiency are realized. Introducing a dc-bias, we designed a 30-kW hybrid system for industrial corona applications. The dc bias allows better matching, faster spark gap recovery, and higher power.

Index Terms—Diode opening switch, gas triode, plasma processing, pulse generator, pulsed processing, repetitive pulsed power, transmission line transformer, VOC removal.

I. INTRODUCTION

WORLDWIDE research and development on industrial nonthermal plasma techniques is approaching industrial applications. Investigations extend from flue gas cleaning, and odor treatment, to VOC abatement [1]. High-voltage pulsed power techniques become the enabling know-how for industrial applications. The work presented here is part of our program on fundamental and industrial research on pulsed corona generation and electromagnetic compatibility (EMC). Two 1–10-kW high-voltage pulsed power sources have been developed [2], [3]. Up to 100-kW systems will be built in near future.

By applying high-voltage pulses to a nonuniform electrode geometry, such as wire-cylinder or wire-plate, transient streamer coronas can be generated. In air and flue gases, streamers cross the electrode structure (reactor) within a few tens of nanoseconds. The electrical pulse energy is transferred to a large number of streamer channels. Streamer corona may last a few tens of nanoseconds. Thus, for generating 10-kW coronas at 1000 pps, 50-ns pulse duration, and 100-kV peak voltage, the output impedance and the peak power of the high-voltage pulse generator are around 50 Ω and 200 MW, respectively. High-voltage and large-current switches are needed to generate such nonthermal plasmas. Solid-state switches are expensive, and magnetic compression techniques are less energy efficient. Because of the higher hold-off voltage, larger current conduction, and small forward voltage drop, the high-pressure triggered spark-gap switch may be one of the most cost effective switches for 10-kW corona applications, provided the lifetime and the repetition rate can be improved. Fig. 1 shows a general schematic diagram of a hybrid pulsed power system (HPPS) for corona energization [4]. It includes a transmission line transformer and a dc-bias provision.

II. PULSE GENERATION

The most common circuit is based on the discharge of a high-voltage capacitor \( C_h \) into a low-inductance circuit through a switching device as shown in Fig. 1. As the first step for generating nanosecond high-voltage pulses, the storage capacitor \( C_h \) (or a pulse forming line) is repetitively charged via resonant circuitry and discharged via a high-voltage switch. Solid-state switches and LC-circuits together with a pulse transformer are the components of the resonant circuitry. In our pulse generator, the high-voltage capacitor is usually charged in about 25 μs, and discharged in about 100 ns. The most critical aspects of this part are the energy conversion efficiency, charging and discharging rates, pulse repetition rate, energy per pulse, stability of the output, and the EMC properties of the system. With high-performance thyristors, a three-step resonant charging circuit has been developed for combination with a triggered spark-gap switch. The charging circuit recycles the surplus energy of the previous charging cycle to reach high stability and efficiency (see Fig. 2). After the discharge into the load some energy returns to the capacitor \( C_L \) (see Fig. 1) and results in a negative residual voltage. Before the next pulse starts, the polarity of this voltage is resonantly reversed. This reduces the energy needed to recharge \( C_L \) in the next pulse. After a number of pulses the voltage \( V_n \) at \( C_L \) and the surplus \( \Delta V_n \) automatically reach a stable value. Measured at the input of the spark gap, the energy conversion efficiency of the resonant charging system during corona operation reaches 95%. The charging rate, pulse repetition rate, energy per pulse, and the deviation of energy per pulse are near 400 kJ/s, 1000 pps, 1–12 J/pulse, and 1%, respectively. By the inclusion of proper EMC principles, the system reliability is high and electromagnetic interference is well avoided. These principles, described in [5] are based on the design of EMC walls, differentiating/integrating (D/I) signal transfer [2] and layout of local common mode current paths. Interference problems within the pulse source and with external electronics are solved; sensitive equipment can be placed on the source’s enclosure or at any close distance. Along the same lines 100-kW average power and 100-J/pulse systems will be achievable.

After resonantly charging the high-voltage energy storage capacitor (or a pulse forming line), the stored energy is discharged into a transmission line transformer (TLT) [2] via the high-voltage, large current switch. The pulse duration depends on the high-voltage capacitance and the input impedance of the TLT, while the rise time mainly depends on the switch-on time and/or the switch inductance. In order to have a small switch inductance the energy storage capacitor is constructed in a coaxial configuration around the switch. At the output of a 50-Ω TLT, high-voltage pulses of 30–100 kV with a rise time of about 20 ns, a pulse duration of 50–250 ns, a pulse...
Fig. 1. Basic layout of a hybrid generator connected to a pulsed corona plasma system. The resonant charging system of $C_0$, $L_1$, and $T_1$ charges $C_L$. The system of $C_L$, $L_2$ transformer, and $T_2$ charges $C_3$, $T_3$ and $L_1$ reverse the polarity of the voltage that remains on $C_L$ after the discharge of $C_h$ into the load. The spark gap discharges $C_h$ into the corona load via a transmission line transformer. Matching is achieved by the TLT and by the capacitors $C_{in}$ and $C_{end}$. The dc source supplies the dc-bias energy.

Fig. 2. Voltage on $C_L$ during charging ($T_1$), discharging ($T_2$) and polarity reversal ($T_3$). The sequence shown here displays one pulse and the start of the next one. The amount $\Delta V_n$ corresponds to the surplus energy that remains on $C_L$ after the end of the discharge into the corona load. By polarity reversal this energy is efficiently used for the next pulse.

repetition rate of 1–900 pps, an energy of up to 12 J/pulse, and an average power of up to 10 kW (Fig. 3) have been achieved with a total (wall plug to load) energy transfer efficiency of about 90%. The generator has been tested for several hundred hours.

III. SPARK-GAP SWITCH

Switching is triggered by a high-frequency discharge in the annular gap between the trigger rod and the surrounding main electrode. The resonant charging voltage itself energizes the oscillatory (LCR) trigger circuit. To stabilize and clean the gap it is purged by a gas flow applied via the gap between central trigger rod and main electrode. The design of the switch is intended to minimize the required gas flow rate, to increase the pulse repetition rate, to improve the lifetime, and to switch large power. Fig. 4 shows the layout of the switch. Depending on the gas flow rate of the switch and the pulse repetition rate, a prefire or normal switching mode is observed (see Fig. 5). To avoid prefire the flow rate must be more than $10\,m^3/h$ per 150 Hz of repetition rate. With growing operating time, the spark-gap distance will increase because of electrode erosion. In terms of the averaged charging waveform on the storage capacitor, and its time derivative. The voltage first increases during the resonant charging process, and then remains almost constant until the main gap is fired. The positive part of the time derivative corresponds to the charging current, while the negative part corresponds to the (switching) time-delay distribution. Prefiring of the spark-gap switch occurs when the gap distance is 9.5 mm and below. For a gap distance of 12.0 mm and up, very late firing

3.0 kW, respectively. The voltage first increases during the resonant charging process, and then remains almost constant until the main gap is fired. The positive part of the time derivative corresponds to the charging current, while the negative part corresponds to the (switching) time-delay distribution. Prefiring of the spark-gap switch occurs when the gap distance is 9.5 mm and below. For a gap distance of 12.0 mm and up, very late firing
Fig. 5. Maximum allowable repetition rate of the spark gap as a function of the airflow rate (flow via gap around trigger rod in main electrode). The normal mode occurs if the flow rate is sufficiently high (tests at 526 Hz, 3 kW power, and 1 atmosphere of air in the gap).

Fig. 6. Averaged high-voltage waveform on the capacitor $C_k$ (upper graph) and the time derivative of this waveform (lower graph) for three gap distances. The time derivative gives a clear picture of the switching delay distribution.

Fig. 7. Addition of dc bias to a corona load improves matching. The oscillations of the voltage on $C_k$ decrease with increasing bias level (0, 10, 20, 27 kV). Dissipation and current duration in the switch can be further minimized to improve interpulse recovery and lifetime of the spark gap.

IV. PULSED POWER TRANSMISSION

The high-voltage pulse propagates via the transmission line to the load (corona reactor). By using a transmission line transformer (Fig. 1) to match a reactor at a given peak output power, either higher output peak voltage or larger peak current can be realized. For multiplying the output voltage two lines with impedance $Z_0$ are connected in parallel at the input side, which is connected to the switch as shown in Fig. 1, while at the output side, which is connected to the reactor, the two cables are connected in series. The impedance ratio is $Z_{out}/Z_{in} = 4$. By reversing in and output of the TLT we would obtain an impedance ratio of 1/4. Moreover, with a TLT, a high-voltage pulse can easily be superimposed on a dc bias to enhance corona energization. Important aspects for the construction of a TLT are the peak power level and the energy losses due to the secondary mode current. The secondary mode is a wave traveling back from the cable end to the switch in the space between cable braid and surrounding metal. In our previous work, the TLT was constructed with four 50-$\Omega$ coaxial cables (RG218). To have a larger output current the four cables are divided into two sets, and in each set the two cables are connected in parallel. The two sets
are connected in series at the output ($Z_{\text{out}} = 50$ Ω). All electrical parts including the TLT are operated in air. Depending on high-voltage pulse duration and magnetic core material, a minimum length of the TLT is required to achieve a high energy-transfer efficiency [3]. Results of matching the generator to a resistive and to a corona load by application of this transmission line transformer are shown in Fig. 8. Currently we are constructing a new compact TLT with in/output impedances of 5 and 20 $\Omega$ for 10–30-kW average power and 320 MW peak power.

V. MATCHING SOURCE AND REACTOR

Considering total energy conversion efficiency, corona radical production and system reliability, matching between a corona reactor and a high-voltage pulse generator becomes increasingly important when scaling up the system. Unfortunately, almost no literature or techniques have been reported for improving the matching. Generally speaking, the reactor is energized in three phases, before, during, and after corona. Before corona, perfect matching is not well possible. During this phase reflection is minimal if the output impedance of the high-voltage pulse generator, the time to reach corona and the capacitance of the reactor are designed according to (1). For a small-size laboratory corona plasma system, this criterion can be easily realized. For a larger corona system it is more complicated. Hereafter, we discuss some practical techniques to satisfy (1).

\[
\tau = 2Z_{\text{out}}C_{\text{r}}
\]  

In the first place, apart from (1) the stray inductance between generator output and reactor input is to be minimized, i.e., a compact layout is needed. Secondly we consider (1) and the reactor itself. Electrically, a reactor can be described in terms of a vacuum (geometrical) transfer impedance $Z_r$ and a capacitance $C_r$. As a function of the effective length $l$ of the corona reactor from one end to the other, we define the following equation to evaluate these two parameters:

\[
Z_r [\Omega] C_r \text{ nF} = 3.3l \text{ m},
\]

At the end the reactor is an open end for high-voltage pulse propagation. As a result, energy would be reflected back to the generator. In order to solve this problem and to satisfy the previously proposed criteria to achieve good matching, two matching capacitors $C_{\text{in}}$ and $C_{\text{end}}$ (Fig. 1) are proposed. Insertion of the extra capacitors minimizes reflections that occur before inception. The capacitance seen by the output impedance $Z_{\text{out}}$ increases from its original value $C_r$ to the new value $C_{\text{in}} + C_r + C_{\text{end}}$. With these extra capacitors (1) changes into

\[
\tau = 2Z_{\text{out}}(C_{\text{in}} + C_r + C_{\text{end}}).
\]  

In case $Z_r = Z_{\text{out}}$ we should omit in (3) the capacitances $C_{\text{in}}$ (not needed) and $C_r$ (part of the matched line $Z_r$). In most practical cases, however, $Z_r \geq Z_{\text{out}}$.

Next we describe the matching during and after corona. Corona starts at the corona inception voltage $V_i$ and stops again when the voltage drops below the level ($V_k$) needed to maintain the streamer stability field. One reported practical technique to improve matching is to use dc superimposed on the high-voltage pulse [6]. During corona, the reactor impedance tends to automatically match the source impedance if the voltage is sufficiently high (Fig. 9). Instead of increasing the pulse voltage we can add a dc-bias voltage to accomplish automatic matching during this phase. During the next phase, after corona, the pulse voltage decays to zero. The energy contained in this last part of the pulse is not used for corona production. It will be lost to dissipation in the switch and leads to unnecessary erosion. By decreasing the duration of the tail or by raising the tail of the pulse to a level closer to the required minimum voltage $V_k$ to sustain streamers we can avoid this loss. DC bias is a way to realize the latter option.

VI. FURTHER DEVELOPMENTS

To improve matching and to increase output power a 10–30 kW hybrid pulsed power generator is in development. It has two parts, a high-voltage pulse generator and a resonant capacitor-charging unit (dc source), which are coupled via a capacitor (Fig. 1). Before applying the high-voltage pulse, the reactor is resonantly charged in 100 μs to $V_{ke}$ via a high-voltage diode, an inductor, the coupling capacitor and the TLT. By firing the main spark-gap switch, the energies stored in the coupling capacitor and in the high-voltage capacitor $C_h$ are transferred to the reactor simultaneously. Corona is generated during the pulse, while electrostatic precipitation is realized.
in between the pulses by the dc voltage. The dc bias not only reduces the spark-gap switch duty but also improves the energy transfer efficiency from the pulsed power generator to the corona reactor. Examples of peak power as a function of dc-bias voltage are shown in Fig. 10.

**REFERENCES**


---

**E. J. M. (Bert) van Heesch** was born in 1951 in Utrecht, The Netherlands. He received the Master’s degree in physics from Eindhoven University of Technology, 1975, and the Ph.D. degree in plasma physics and fusion related research from the University of Utrecht, 1982.

He is currently an Assistant Professor with Eindhoven University of Technology, where he has been leading the pulsed power research group since 1986. Before that, he was occupied with shock-tube gas dynamics (Eindhoven, 1975) and with fusion technology (Jutphaas, The Netherlands, 1975–1984, Suchumi former U.S.S.R., 1978 and Saskatoon, Canada, 1974–1986). Among his designs are various plasma diagnostics, a toroidal fusion experiment, a particle beam diagnostic, substation high-voltage measuring systems, and systems for pulsed corona treatment of gases and fluids. Currently, he is supervising the work on pulsed power development and application. His research is the basis for teaching and coaching university students and Ph.D. students. He is a co-inventor for three patents.

---

**K. Yan** was born in China. He received the B.Sc. and M.Sc. degrees from the Beijing Institute of Technology (BIT), Beijing, China, and the Ph.D. degree from Eindhoven University of Technology (TU/e), The Netherlands. From 1986 to 1997, he was with BIT as Researcher and Associate Professor. He joined TU/e in December 1998, and is currently a Researcher at TU/e. Research activities are in pulsed power and applied plasma science with applications to pollution control and sustainable development. He has coauthored 26 papers in journals, approximately 50 papers in conferences, and three patents.

---


Before joining the Electrical Power Systems group of Eindhoven University of Technology, he worked for KEMA T&D Power in Arnhem, The Netherlands. He is leading the Eindhoven Pulsed Corona and Pulsed Power work on tar cracking in thermally generated biogas. His research interest includes high-voltage engineering and pulsed power. Among his achievements are the development of an on-line monitoring system for partial discharges in turbine generators and a 30-kW pulsed-corona reactor for industrial applications. He is the founder of the Dutch Generator Expertise Center.