Heavy-Duty High-Repetition-Rate Generators

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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.

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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 μ s, 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 system 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 ΔV_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_h . 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 ΔV_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 m³/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, Fig. 6 shows the switching behavior of the triggered spark gap for three main spark-gap distances (9.5, 11.0, and 12.0 mm) at atmospheric pressure. The pulse repetition rate and the average switched power in these tests are around 526 pps and

Fig. 3. Average output power of the high-voltage pulse generator is a linear function of the repetition rate. The load is a matched resistor. The three lines correspond to three matched values of the storage capacitors C_L and C_h .

Fig. 4. Layout of the spark gap switch. Indicated are the electrodes, the coaxially mounted storage capacitor and the trigger circuit that is powered and timed by the resonant charging voltage itself.

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_h (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.

might occur. When the average electric field across the main gap is between 26 and 33 kV/cm, the spark-gap switch could always be fired within the normal switching region. For gap distances from 10 to 12 mm, the spark-gap switch could recover during the

Fig. 7. Addition of dc bias to a corona load improves matching. The oscillations of the voltage on C_h 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.

inter-pulse duration by controlling the gas flow rate. The electrodes are uniformly eroded, and the switch voltage and output power of the pulse generator are independent of the gap distance in this operational regime. Based on the gap erosion rate during more than 100 h at 200–900 Hz, we estimate a switch lifetime of 3–4 mo (4.10^9 shots). By adjusting the gas pressure and the flow rate, more than 6 mm (in depth) of electrode erosion would become allowable which may increase the lifetime to about one year (10^{10} pulses). The eroded material deposits downstream in the gas flush lines where it poses no problem. Deposits do not reach the insulator surfaces. We further noticed that matching between a pulsed power generator and a corona reactor could significantly affect the electrode erosion rate. When the generator is not well matched to the reactor, energy is reflected back into the switch. Fig. 7 shows that oscillations in the voltage on the main electrode decrease with improved matching (by addition of dc bias voltage).

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- Ω coaxial cables (RG218). To have a larger output current the four cables now are divided into two sets, and in each set the two cables are connected in parallel. The two sets

Fig. 8. The momentarily output power to a resistive load and to a corona load. The quality of matching is high in both cases.

are connected in series at the output ($Z_{\text{out}} = 50 \Omega$). 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 Ω 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 Z_{out} , the time to reach corona τ and the capacitance C_r 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).

$$\tau = 2Z_{\text{out}}C_r. \quad (1)$$

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:

$$Z_r [\Omega] C_r \text{ nF} = 3.3l \text{ m}. \quad (2)$$

At the end the reactor is an open end for high-voltage pulse propagation. As a result, energy would be reflected back to the

Fig. 9. Ratio of source over reactor impedance during corona as a function of the applied peak voltage. At sufficiently high peak voltage the impedance of the discharge automatically matches to the source impedance.

generator. In order to solve this problem and to satisfy the previously proposed criteria to achieve good matching, two matching capacitors C_{in} and C_{end} (Fig. 1) are proposed. Insertion of the extra capacitors minimizes reflections that occur before inception. The capacitance seen by the output impedance Z_{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

$$\tau = 2Z_{\text{out}}(C_{\text{in}} + C_r + C_{\text{end}}). \quad (3)$$

In case $Z_r = Z_{\text{out}}$ we should omit in (3) the capacitances C_{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_s) 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_s 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_{dc} 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

Fig. 10. Improved output power and matching at the corona load during stepwise increase of dc-bias voltage. From lower to upper trace: 0, 10, 20, 27 kV dc bias.

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.

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