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A High-Voltage Pulse Generator for Corona Plasma Generation

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***Abstract*—This paper discusses a high-voltage pulse generator for producing corona plasma. The generator consists of three resonant charging circuits, a transmission line transformer, and a triggered spark-gap switch. Voltage pulses in the order of 30–100 kV with a rise time of 10–20 ns, a pulse duration of 100–200 ns, a pulse repetition rate of 1–900 pps, an energy per pulse of 0.5–12 J, and the average power of up to 10 kW have been achieved with total energy conversion efficiency of 80%–90%. Moreover, the system has been used in four industrial demonstrations on volatile organic compounds removal, odor emission control, and biogas conditioning.**

***Index Terms*—Corona, high-voltage pulse generator, nonthermal plasma, transmission-line transformer, triggered spark-gap switch.**

I. Introduction

IN THE LAST 15 years, nonthermal corona plasma techniques have been widely investigated for pollution control and sustainable development because of the Clean Air Act. Investigations have extended from odor treatment, indoor air cleaning, volatile organic compounds (VOC) abatement, and flue gas cleaning to CO_2 conversion and biogas cleaning [1]–[4]. According to available literature, more than 50 types of pollutants have been investigated for their emission control [5].

Two critical issues should be solved for corona plasma industrial applications. The first one is the capacity of repetitive pulse power techniques, and the second is the total energy consumption. Worldwide research and development on industrial corona plasma systems, so far, were very much dependent on individual empirical experience. Pilot plant industrial demonstrations become very important for optimizing the processing. A general principle for optimizing corona plasma energization was proposed in order to improve the initial radical production yield and to increase the energy transfer efficiency. Optimized relationships between the voltage rise time, the peak voltage, the size of a corona reactor, the output impedance of a voltage pulse generator, the stray capacitance of the corona reactor, and the corona energy density per unit length of the reactor were also discussed [6], [7]. Our recent research and development includes tar removal from biogas, odor treatment from air, and NO_x removal from engine exhaust gases by using corona plasma techniques. Very efficient heavy-duty high repetition rate generators and efficient corona plasma systems would lead to bridge the gap between fundamental research and industrial applications [8]. As part of the development of 1–10-kW high-voltage pulse generators [9], [10], this paper discusses some critical elements of the system. The final objective of this work is to develop circuit models to design industrial corona plasma systems.

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II. High-Voltage Pulse Generator

A. Main Circuit

Fig. 1 shows the circuit diagram of the high-voltage pulse generator. The pulse transformer *TR* separates the low- and high-voltage parts. The low-voltage part consists of a mains filter, a set of rectifiers or a dc power source, three air coil inductors L_1, L_2, and L_3, three thyristors Th_1, Th_2, and Th_3, two energy-storage capacitors C_0 and C_L, and the primary windings of the pulse transformer *TR*. The high-voltage part mainly consists of the secondary windings of the pulse transformer *TR*, two high-voltage diodes D_1 and D_2, two damping resistors R_4 and R_5, an air coil inductor L_4, a high-voltage energy-storage capacitor C_h, a triggered spark-gap switch S, an *LCR* trigger circuit [10], a transmission line transformer (TLT), and magnetic cores placed around the TLT cables.

The TLT is constructed with four 50-Ω coaxial cables (RG218) connected in parallel at the input side ($Z_{\rm in} = 12.5\ \Omega$) and in series at the output side ($Z_{\rm out} = 200\ \Omega$). At the output side, four cables can also be divided into two sets, and in each set the two cables are connected in parallel. Then, the two sets are connected in series ($Z_{\rm out} = 50\ \Omega$). All electrical parts including the TLT are operated in air. The physical construction of the TLT is specially designed in order to limit the energy loss caused by secondary-mode currents, to protect the spark-gap switch from unmatched operations, and to minimize its effects on the voltage rise time and the voltage gain. The high-voltage capacitor C_h is resonantly charged in about 25 μs, then the stored energy is transferred to a corona reactor via the spark-gap switch and the TLT. The generator can produce 30–100-kV peak voltage with 10–20-ns rise time and 100–200-ns pulse duration.

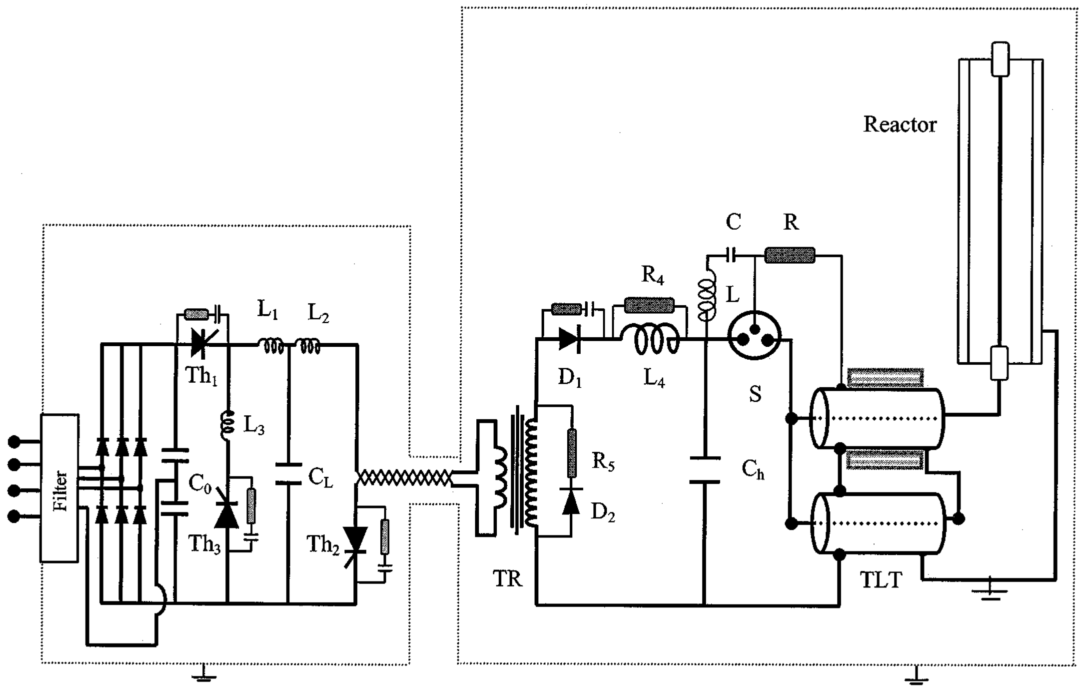

Fig. 1. Schematic diagram of the high-voltage pulse generator and a wire–cylinder reactor.

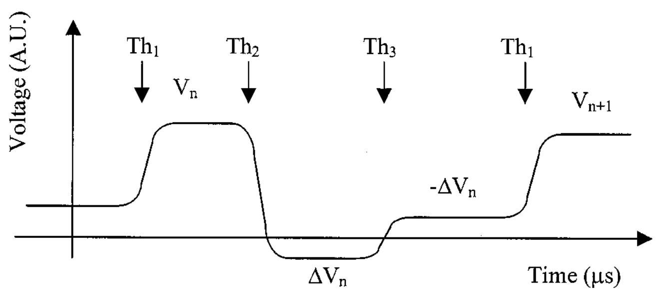

Fig. 2. Schematic diagram of the voltage waveform on the low-voltage capacitor C_L.

In order to explain the circuit principle, Fig. 2 shows a schematic voltage waveform on the low-voltage energy-storage capacitor C_L, where arrows Th_1, Th_2, and Th_3 refer to the moments at which the corresponding thyristors are closed. V_n and V_{n+1} refer to the nth and $(n + 1)$th voltage levels, respectively. The n is the pulse sequence number. With the *LCR* trigger method, the main spark-gap switch is fired after resonantly charging C_h by switching on the thyristor Th_2 [10]. Ignoring losses during the resonant charging and discharging processes, one may derive the following relations between the nth and $(n+1)$th voltage pulses, where N is the turn ratio of the pulse transformer and V_0 is the voltage on the energy-storage capacitor C_0.

$$\Delta V_n = k_c \cdot V_n \tag{1}$$

$$V_{n+1} = 2V_0 + k_c \cdot V_n \tag{2}$$

where

$$k_c = \frac{C_L - N^2 C_h}{C_L + N^2 C_h} \leq 0.$$

If letting

$$V_s = \frac{C_L + N^2 C_h}{N^2 C_h} V_0$$

and

$$\Delta V = \frac{C_L - N^2 C_h}{N^2 C_h} V_0$$

we have the following series equations for solving V_n and ΔV_n:

$$V_{n+1} - V_s = k_c(V_n - V_s) = \cdots = k_c^n(V_1 - V_s). \tag{3}$$

Because $|k_c| < 1$, with increasing the series number n, the voltage V_n will approach the constant value V_s as expressed by the following equation, while ΔV_n will stabilize at the value ΔV

$$\lim_{n\to\infty} V_{n+1} = V_s + (V_1 - V_s) \lim_{n\to\infty} k^n = V_s \tag{4}$$

$$\lim_{n\to\infty} \Delta V_n = k_c \lim_{n\to\infty} V_n = \Delta V. \tag{5}$$

Regarding (4) and (5), one may also conclude that the high-voltage pulse generator remains in very stable operation even if the main spark-gap switch is prefiring or misfiring. Experiments indicated that for up to 10-kW average output, at each pulse repetition rate, the standard deviation in the pulse energy is around 1.0% [10]. The output energy per pulse $\varepsilon_{\text{pulse}}$, the energy transfer efficiency η_{charging} from C_L to C_h, and the maximum charging voltage $V_{\max}$ on C_h can be expressed as

$$\varepsilon_{pulse} = \frac{1}{2 \cdot \theta} \cdot (2V_0)^2 \cdot C_L \tag{6}$$

$$\eta_{ch\arg ing} = \frac{2 \cdot \varepsilon_{pulse}}{C_L \cdot V_s^2} = \frac{4 \cdot \theta}{(1+\theta)^2} \tag{7}$$

$$V_{\max} = \frac{2N \cdot V_0}{\theta} \tag{8}$$

where

$$\theta = \frac{N^2 C_h}{C_L}.$$

For achieving a maximum energy transfer, the two capacitors are designed to satisfy the relation of $\theta = 1$. As a result, according to (6), the energy per pulse linearly depends on the low-voltage capacitor C_L [7]. Within the present work, the energy conversion efficiency, charging rate, pulse repetition rate, energy per pulse, and the deviation of the energy output per pulse are around 95%, 400 kJ/s, 1–900 pps, 1–12 J/pulse, and 1%, respectively. Moreover, the control electronic system was designed with proper EMC techniques to avoid electromagnetic interference and to increase system reliability [9], [11]. Following the same circuit as shown in Fig. 1, a 100-kW average power and 100-J/pulse ac–dc pulse conversion would also be achievable.

B. Spark-Gap Switch

Streamer corona plasma may last a few tens of nanoseconds. Thus, to generate corona plasma of 10-kW average 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 should be around 50 Ω and 200 MW, respectively. At the moment, solid-state switches are still too expensive, and magnetic compression techniques do not have the energy efficiency for such kind of high-voltage pulsed power and corona plasma applications. Because of the higher holdoff voltage, larger possible currents, and smaller forward voltage drop, a high-pressure triggered spark-gap switch is one of the most cost-effective switches for 1–10-kW corona plasma applications, provided the lifetime and the repetition rate can be improved. Moreover, to reliably produce corona plasmas, the high-voltage pulse generator should be immune to spark breakdown inside the reactor or any other kind of short circuit. The triggered spark-gap switches indeed allow a very robust design of the corona circuitry [7]. Fig. 3 shows the schematic diagram of a homemade triggered spark-gap switch. The switch is flushed with air under atmospheric pressure. The flush gas flows into the triggered spark-gap switch from both the trigger gap and the center of the trigger electrode, and then flows out via six symmetrical exits. The anode is a 40.0-mm cup with a hole of 21.0 mm in diameter, which results in an anode width of 9.5 mm. The inner and outer diameters of the cylindrical trigger electrode are 9.0 and 18.0 mm, respectively. The trigger-gap distance and the diameter of the cathode disk are 1.5 and 40.0 mm, respectively. The electrodes are designed to allow 5.0 mm in depth erosion. The main spark-gap distance is from 8.5 to 12.5 mm. All three electrodes are made of copper/tungsten alloy. Injecting high-frequency arc plasma into the gap triggers the main spark gap. The switch could run up to 1000 pps under average switch power of up to 10 kW. After more than 300 h of testing, the specific electrode erosion rate is around 5×10^{-10} cm^3/shot. For a high-pressure spark-gap switch, more than 8 mm in depth electrode erosion is allowable to maintain very stable switching, which leads to a lifetime of around one year. We also noticed that the matching between the pulsed power generator and corona reactors significantly affects the electrode erosion rate. When the generator is not very well matched to the reactor, a large amount of energy can be reflected back into the switch. As a result, tungsten is evaporated from the Cu/W alloy and visible damage on the electrode occurs after about 10^6 shots. A good matching between a pulsed power generator and a corona reactor not only increases the total energy efficiency but also improves the switch lifetime [7].

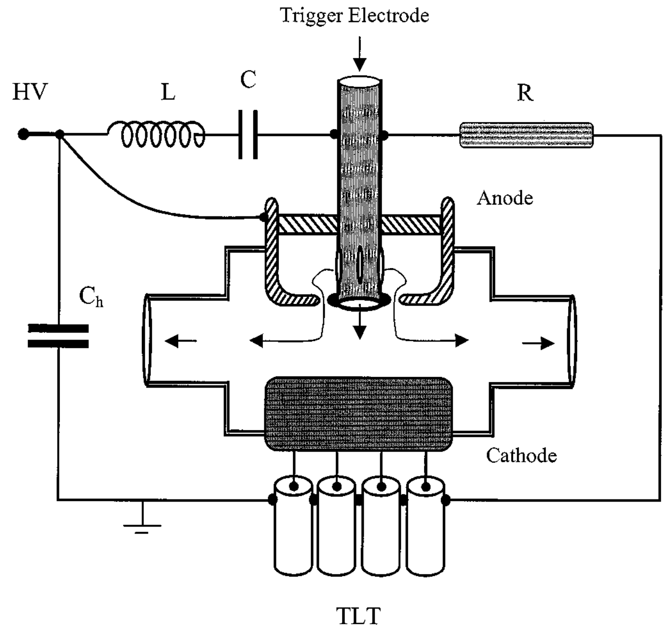

Fig. 3. Triggered spark-gap switch.

C. TLT

In contrast to a magnetically coupled pulse transformer, a high-voltage pulse in the order of 100 kV with a rise time of 10–20 ns and a high repetition rate can be easily generated by discharging a high-voltage capacitor to a TLT via a high-voltage switch [9]. Guanella's work may be one of the earliest works on TLT [12], where four 240-Ω transmission lines in a series-parallel arrangement were used to get an impedance ratio of 16 : 1. Sevick gave a very comprehensive review on classical theories and applications of transmission line transformers [13]. Graneau *et al.* reports more recent work on a physical model and development of TLT for high-voltage pulse generation [14], [15]. For the four- and five-cable TLTs, the voltage gains are around 3.4 and 4.5, which correspond to energy transfer efficiency of around 72% and 81%, respectively. The ten-stage TLT constructed with ten 110-m-long coaxial cables and ferrite cores gives a better performance on the voltage gain of around 10. Pecastaing *et al.* discussed a compact TLT constructed with up to ten cables and ferrite beads [16]. They also experimentally investigated the effects of ferrite beds on the voltage gain. However, the system cannot be used near a grounded structure.

When designing a TLT for larger power corona plasma applications, the following aspects must be taken into account simultaneously: the input and output impedance, the voltage or current gain, and the energy conversion efficiency [7]. To generate a large volume of corona plasma needs a very compact TLT with smaller output impedance. However, there is no model available

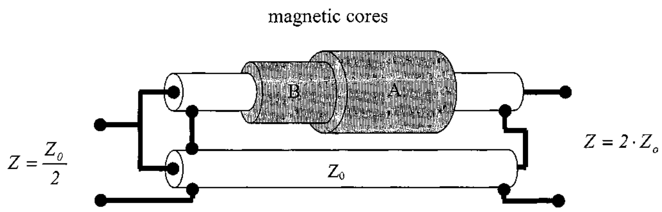

Fig. 4. Two-cable transmission-line transformer.

yet for designing such kind of TLT and a corona reactor in relation to such pulsed power applications.

After firing the triggered spark-gap switch, the high-voltage pulse propagates via the transmission line to the corona reactor. The peak power and/or peak current mainly depend on the switching voltage and the input impedance $Z_{\rm in}$ as shown in Fig. 1. By using a TLT as shown in Fig. 4 to match a reactor, either high output peak voltage or large output peak current could be realized for a given peak output power. For multiplying the output voltage, the two cables with impedance of Z_0 are connected in parallel at the input side, which is connected to the switch as shown in Fig. 1. At the output side, which is connected to the reactor, the two cables are connected in series. Then, the impedance ratio is $Z_{\rm out}/Z_{\rm in} = 4$. For multiplying the output current, the input and output sides of the TLT are connected in series and in parallel, respectively. Then, the impedance ratio becomes $Z_{\rm out}/Z_{\rm in} = 1/4$. Moreover, with a TLT, a high-voltage pulse could be easily superimposed on a dc bias for corona plasma energization [7], [8]. In order to design a very efficient pulsed power generator, our TLT is usually constructed with two types of magnetic cores A and B as shown in Fig. 4. The magnetic core A is designed for achieving large secondary-mode impedance. The magnetic core B is designed to absorb the reflected energy under unmatched operations. Generally speaking, microgap ferrite and/or Metglas are used for the A-type core. Iron powder magnetic materials are used for the B-type core [7]. In the following, we mainly discuss the energy conversion efficiency and the A-type magnetic core.

In order to evaluate the energy conversion efficiency from the high-voltage capacitor C_h to a load and to optimize the cable number of a TLT, we suppose that all cables have identical physical construction and the TLT perfectly matches the load. The secondary-mode current or the related impedance Z_s mainly causes the energy loss. Then, for an m-cable TLT, we have the following relation to estimate the relative energy loss $W_{\rm TLT}$:

$$W_{\rm TLT} \propto \sum_{k=1}^{m-1} \left(\frac{k}{m}\right)^2 \cdot \frac{V^2}{Z_s}. \tag{9}$$

The energy loss depends on the secondary-mode impedance Z_s, the cable number m, and the output peak voltage V. Fig. 5 shows an example of the loss in comparison to a four-cable TLT at a matched load and 100-kV output. For a 10–30-kW hybrid pulse power source, we usually use a two-cable TLT as shown in Fig. 4 [7].

D. Magnetic Cores

As indicated by (9), one technique to reduce the loss in the TLT caused by the secondary-mode current is to increase the secondary-mode impedance by placing magnetic cores between the outside conductor of the cable and ground structure. In the following, we use a very simple model to evaluate how to design the magnetic core for constructing very compact TLTs.

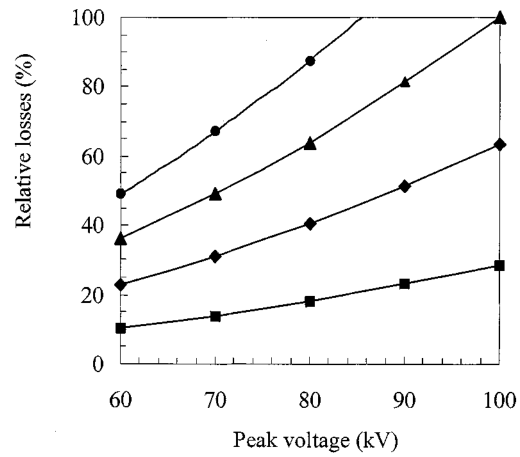

Fig. 5. Relative losses in TLT in comparison with a four-cable TLT at 100-kV output. ●: five-cable TLT; ▲: four-cable TLT; ◆: three-cable TLT; ■: two-cable TLT.

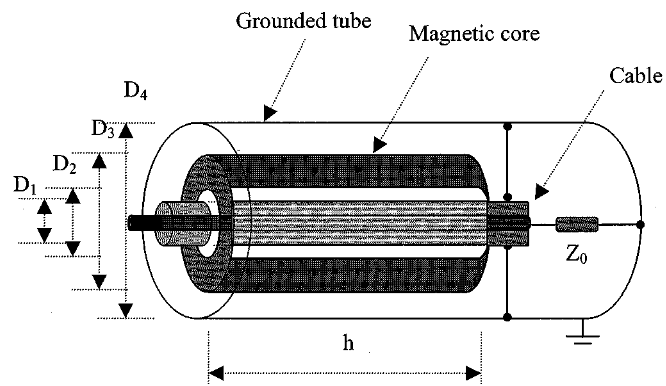

Fig. 6. Schematics of the A-type magnetic core, a cable, and a grounded tube.

If the upper cable of the two-stage TLT in Fig. 1 is placed around a grounded structure, a high-voltage pulse would propagate between the outside conductor of the upper cable and the ground after the high-voltage pulse reaches the output side. In order to evaluate the physical shape of the magnetic core for blocking the current flow, it is supposed that a cable is placed at the center of a grounded tube and the magnetic core is uniformly placed between the outside of the cable and the tube. Fig. 6 shows a schematic diagram. The outer diameters of the cable, the inner and outer diameters of the core, and the inner diameter of the tube are D_1, D_2, D_3, and D_4, respectively. All components are placed in air. At the right-hand side, the cable is terminated with a matched resistive load. At the left side (the input side), the inner conductor of the cable is grounded to the tube. A high-voltage pulse with pulse duration of ΔT is applied between the outside conductor of the cable and the tube. The pulse will propagate toward the end of the cable, both in and outside the cable. The ratio of the energy flows in and outside the cable depends on the corresponding impedance ratio.

To avoid multiple high-voltage pulse reflection inside the core, the transient time inside the core must be longer than 50%

of the pulse duration ΔT. Therefore, the core length h should be designed according to the following relation:

$$h \geq \frac{1}{2} \cdot \frac{0.3\Delta T}{\sqrt{\mu_r \cdot \varepsilon_r}} \quad (10)$$

where μ_r and ε_r are the effective permeability and dielectric constant of the magnetic core, respectively. The values of ΔT and h are in the units of nanoseconds and meters, respectively.

For a practical compact TLT, (10) actually determines the minimum length h of the TLT. For an example, the minimum cable length is about 2 m if using a core with $\mu_r = 245$ and $\varepsilon_r = 1$ for a 100-ns voltage pulse. For a 50-ns voltage pulse generator, 1-m-long cables should be long enough for building the TLT. For our present high-voltage pulse generators, the length of TLT cable ranges from 1 to 4 m [7]. The characteristic transfer impedance between the outside of the cable and the grounded tube can be expressed as

$$Z_s = 60 \ln\left(\frac{D_4}{D_1}\right) + 60\left(\sqrt{\frac{\mu_r}{\varepsilon_r}} - 1\right)\ln\left(\frac{D_3}{D_2}\right) \quad (11)$$

where the first term is the impedance without using the core, while the second term is the added impedance by the core.

To significantly reduce the energy flow between the outside of the cable and the tube, the impedance should be designed so that

$$Z_s \gg Z_0. \quad (12)$$

It can also be easily derived that for the two stage TLT, the maximum energy transfer efficiency with a matched load can be approximated by Eq. (13).

$$\eta_{\mathrm{TLT}} = 1 - \frac{Z_0}{2 \cdot Z_s}. \quad (13)$$

According to the above discussions, the magnetic core is a critical element for development of a compact TLT. As an example, if 50-Ω cable with outside diameter D_1 of 18.5 mm is used, and a ratio of $Z_s : Z_0$ of $10:1$ ($500\,\Omega : 50\,\Omega$) is required, i.e., $\eta_{\mathrm{TLT}} = 95\%$, the value of D_4 reaches 77 m without the use of magnetic cores. Generally speaking, when $Z_s \gg Z_0$, the maximum energy transfer efficiency for a TLT with n identical cables can be approximated by

$$\eta_{\mathrm{TLT}} = 1 - \frac{\sum_{1}^{n-1} k^2}{n} \frac{Z_0}{Z_s}. \quad (14)$$

To compare the losses with and without magnetic cores, the energy loss ratio caused by secondary-mode impedance during the voltage propagation time ΔT can be evaluated by

$$\varphi = \frac{Z_{s0}}{Z_s} \quad (15)$$

where

$$Z_{s0} = 60 \ln\left(\frac{D_4}{D_1}\right)$$

is the impedance without using magnetic cores. Substituting (11) into (15), one obtains

$$\varphi = \frac{\ln\left(\frac{D_4}{D_1}\right)}{\ln\left(\frac{D_4}{D_1}\right) + \left(\sqrt{\frac{\mu_r}{\varepsilon_r}} - 1\right)\ln\left(\frac{D_3}{D_2}\right)}. \quad (16)$$

Therefore, if the magnetic cores can significantly reduce the loss, one needs $\varphi \ll 1$. According to (16), this means

$$\left(\frac{D_3}{D_2}\right)^{\sqrt{\mu_r/\varepsilon_r}-1} \gg \frac{D_4}{D_1}. \quad (17)$$

For practical setups, because of the physical size limitation, the energy efficiency improvements by using magnetic cores can be evaluated by using (14). Although there are no standard methods to design the core, and μ_r and ε_r nonlinearly depend on the H field, (10) and (17) are the basic criteria for designing the magnetic core, where the distance between a cable and the grounded cabinet can be used as the D_4. Both physical size and the magnetic characteristics of the core play significant roles for affecting the energy transfer efficiency [7].

For a given cable and grounded structure, according to (16), the loss decreases by increasing either μ_r or the ratio of D_3/D_2. However, the length of the core does not affect the efficiency once it satisfies (10). Moreover, because the energy efficiency mainly depends on the impedance ratio (Z_0/Z_s), it increases by reducing the impedance Z_0. As a result, for a given output peak voltage, by reducing the TLT impedance, both the efficiency and average corona power increase, which is one of advantages of using a TLT.

E. Corona Plasma Reactor

As shown in Fig. 1, corona reactors are placed perpendicularly on the top of the cabinet of the pulsed power source. In order to improve the matching between the power source and corona reactors, wire-wire, wire-cylinder, and wire–plate-type corona reactors have been investigated. Optimal corona plasma energization or matching between a generator and a reactor can be achieved by considering the following three distinctive energization periods: before, during, and after corona plasma generation. After optimizing the energization, a corona plasma reactor behaves like a matched resistive load. The corona energy per pulse and/or the average output power do not significantly depend on the electrode geometry [7]. For generating uniform corona plasma inside a reactor, the high-voltage pulse propagation time inside the reactor should be much shorter than the propagation time for primary streamer to bridge the electrode gap. The duration may last a few tens of nanoseconds. The effective length of the corona wire is usually around 1 m. For an example, our 10–30-kW corona plasma reactor consists of 16 in-parallel wire–cylinder-type reactors. The length, inner, and outer diameters of each reactor are 1000, 3, and 160 mm, respectively. The reactor is energized with a hybrid pulse power source to simultaneously induce chemical reaction and realize electrostatic precipitation [7].

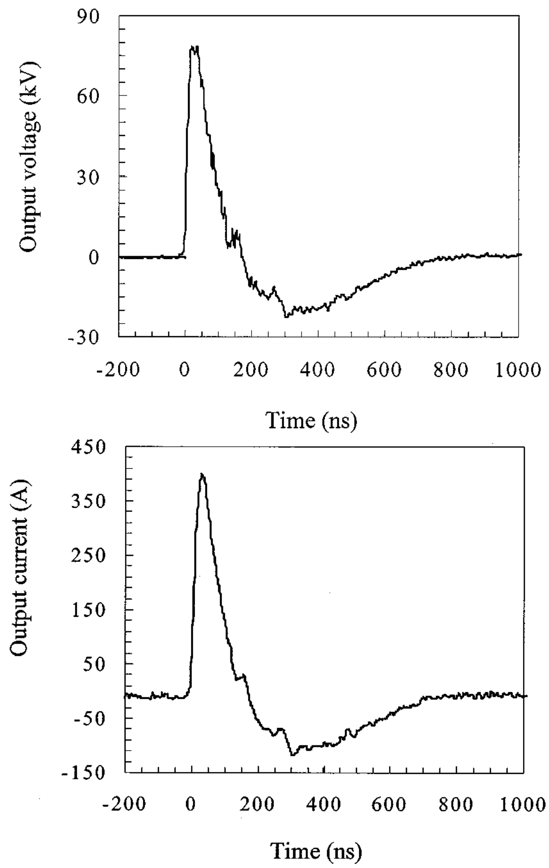

Fig. 7. Typical voltage and current outputs with a matched resistor load.

III. Experimental Results

Within the last two years, the high-voltage pulse generator has been used for both laboratory experiments and four times pilot plant industrial investigations on odor emission control, VOCs abatement [6], and biogas conditioning [17]. As an example, Fig. 7 shows typical voltage and current output with a 200-Ω matched resistive load. Fig. 8 shows the average power in terms of the pulse repetition rate, where the output impedance $Z_{\rm out}$ is 50 Ω. Both the pulse repetition rate and the energy per pulse determine the average power. After optimizing the spark-gap switch and its triggering circuit, the deviation from pulse to pulse is around 1.0% within the pulse repetition rate from 1 to 900 pps [10]. The energy conversion efficiency has also been investigated for each step of the circuit. The main losses are caused by the thyristor snubber, the pulse transformer, the spark-gap switch, and the TLT. According to the proposed method to design a TLT, the total energy conversion efficiency of the high-voltage pulse generator is around 80%–90% [7].

IV. Conclusion

A high-voltage pulse generator has been developed for both laboratory experiments and industrial demonstrations. The main elements of the power source were discussed, and the following remarks have been obtained. A three-step resonant charging circuit can automatically adapt to a triggered spark-gap switch and a TLT for producing pulsed streamer corona plasma. The total

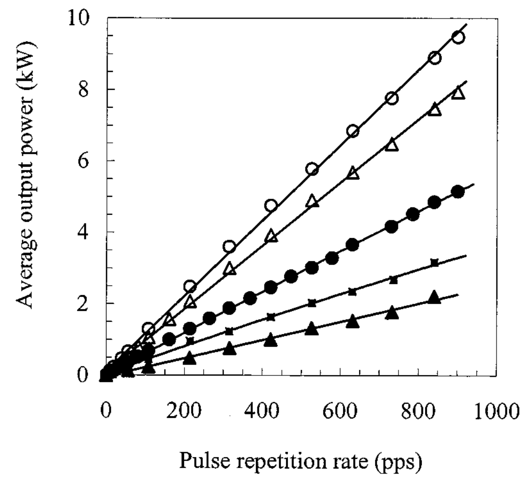

Fig. 8. Typical output of average power in terms of the pulse repetition rate and the energy per pulse.

energy efficiency significantly depends on TLT and corona reactor. The length of TLT cable should be designed by considering the magnetic cores. Based on the present system development, a new corona plasma system with average corona power on the order of 10–30 kW is also under investigation.

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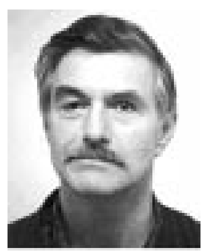

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