A 10 kW high-voltage pulse generator for corona plasma generation


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I. INTRODUCTION

Worldwide research and development on corona plasma techniques for pollution control and sustainable development are gradually leading to industrial applications. Investigations range from odor treatment, indoor air cleaning, volatile organic compound (VOCs) abatement, and flue gas cleaning to CO$_2$ conversion and biogas cleaning. To successfully promote these industrial applications, the availability of highly efficient and reliable high-voltage-pulsed power sources is critical. In previous work, we have reported that by using various voltage pulses and/or corona reactors pulsed streamer coronas may develop into two phases, corresponding to primary and secondary streamers. Energy transfer during these two phases depends on the voltage rise rate and the pulse duration. Optimized relationships among the voltage rise time, the peak voltage, the pulse duration, the voltage rise time, the peak voltage, the pulse duration, the pulse repetition rate, and the pulse duration. Optimized relationships among the voltage rise time, the peak voltage, the pulse duration, the energy transfer efficiency of about 80%–90%. At each frequency, the deviation of the energy per pulse is around 1.0%. Moreover, the generator has been tested for more than 100 h for both industrial demonstrations and laboratory investigations at an average output power of 1–10 kW. © 2001 American Institute of Physics.

II. VOLTAGE PULSE GENERATOR

A. Main electrical circuit

Figure 1 shows a schematic diagram of the electrical circuit with a resistor as load. The pulse transformer separates the low- and high-voltage parts of the circuit. The low-voltage part consists of a main filter, a set of rectifiers, a three-step resonant charging circuit that is switched by thyristors, and the primary winding of the pulse transformer TR. The high-voltage part consists of the secondary winding of the pulse transformer TR, a high-voltage diode D, an air coil inductor $L_3$, a high-voltage energy storage capacitor $C_L$, a triggered spark-gap switch S, a transmission line transformer (TLT), and Metglas magnetic cores placed around the TLT cables. The TLT is constructed with four 50 Ω coaxial cables (RG218). At the input side, four cables are connected in series, which gives output impedance of 200 Ω. All electrical parts including the TLT are operated in air. The TLT and the Metglas cores are specially designed to limit energy losses by the secondary mode current and to minimize their effect on the voltage rise time and the voltage gain.

In order to stabilize the switching voltage of the spark-gap switch and the output energy per pulse, the three thyristors, $T_1$, $T_2$, and $T_3$, are switched in series. Detailed discussions of this are given in Refs. 6 and 8. A four-step process generates the voltage pulse. In the first step, the low-voltage capacitor $C_L$, resonant converter $C_0$, thyristor $T_1$, and inductor $L_1$. During the second step, the high-voltage capacitor $C_L$ is resonantly charged in about 20–70 μs via $C_L$, $L_2$, TR, $T_2$, D, and $L_3$. Then the stored energy is transferred to the load via a spark-gap switch S and a TLT. Before low-voltage capacitor $C_L$ is charged again, the third thyristor, $T_3$, is used to correct the voltage...
polarity on \( C_L \) via \( T_3 \) and \( L_1 \). Detailed discussions on the spark-gap switch are presented in Sec. II B. The switching voltage of the spark-gap switch and the voltage gain of the TLT determine the output peak voltage. After the main spark gap breaks down, the voltage on capacitor \( C_h \) decreases with a time constant of \( Z_{\text{in}}C_h \). The generator can produce 30–100 kV peak voltage in a rise time of about 20 ns and pulse duration of 50 to 250 ns.

**B. Spark-gap switch and the trigger method**

The switch for high voltage and large current may be the most critical element in the development of pulsed power techniques. The properties of the switch significantly affect the cost, efficiency, reliability, and capacity of the generator. Although spark-gap switches have been widely used for pulsed power generation, there is not much in the literature in relation to high repetition rate and long lifetime continuous operation.

A newly designed spark-gap switch, shown in Fig. 2, including an inductor \( L \), a capacitor \( C \), and a resistor \( R \) formed \( \sim LCR \) triggering method has been developed to bridge the gap for industrial applications. The arrows indicate the gas flow. Both the main electrode gap and the trigger electrode gap are flushed by a forced gas flow. The gas flows into the spark-gap switch around the trigger electrode, and then flows out via six symmetrical exits under atmospheric pressure. In terms of the pulse repetition rate and the flush gas flow rate, the triggered spark-gap switch may run in a prefire or a normal switching mode.

The inductor \( L \), capacitor \( C \), and resistor \( R \) form the LCR triggering circuit, where we always have \( R \gg 2\sqrt{L/C} \) and \( C_h \gg C \). After the thyristor \( T_2 \) is switched on, the voltage on the high-voltage capacitor \( C_h \) will rise as

\[
V(t) = \frac{V_{\text{max}}}{2} \left[ 1 - \cos(\omega t) \right],
\]

where

\[
\omega = \sqrt{\frac{C_L + n^2 C_h}{n^2 C_h C_L \left( L_2 + \frac{L_3}{n^2} \right)}}
\]

is the resonant frequency determined by \( C_L \), \( L_2 \), \( TR \), \( L_3 \), and \( C_h \), and \( V_{\text{max}} \) is the maximum voltage on the high-voltage capacitor after resonant charging. The turns ratio of the pulse transformer \( TR \) is \( n \). The voltage on the trigger electrode rises as

\[
V_T(t) = \frac{V_{\text{max}}}{2} \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2} \left[ \exp \left( -\frac{t}{\tau} \right) - \cos(\omega t) \right] + \frac{V_{\text{max}}}{2} \frac{\omega \tau}{1 + \omega^2 \tau^2} \sin(\omega t),
\]

where \( \tau = RC \) and \( \omega t \leq \pi \). At the end of the charging cycle \( \omega t = \pi \), the ratio of the voltage \( V_T \) on the trigger electrode to that on the high-voltage capacitor \( C_h \) can be expressed approximately as

\[
\frac{V_T}{V_{\text{max}}} = \frac{1}{2} \frac{\beta^2}{1 + \beta^2} \left[ 1 + \exp \left( -\frac{\pi}{\beta} \right) \right],
\]

where \( \beta = \omega \tau \), which is defined as the time coefficient. After resonant charging of \( C_h \), the smaller capacitor \( C \) will be further charged via the LCR circuit by high-voltage capacitor \( C_h \). During this process, the voltage on the trigger electrode decreases exponentially with the time constant \( \tau \). The voltage between the anode and the trigger electrode increases exponentially until the trigger gap breaks down. After that, a high frequency current through inductor \( L \) and capacitor \( C \) brings more energy into the trigger gap. As a result, the main gap is fired also. In order to prevent early firing during the charging period, the voltage ratio \( V_T/V_{\text{max}} \) should be carefully designed. Figure 3 shows the dependence of the voltage ratio on the time coefficient \( \beta \). During our tests, \( \beta \) values in the
range of 10–20 give better performance. To avoid prefiring and misfiring, the average electric field in the main gap is designed to be around 26–33 kV/cm in air.9

III. RESULTS AND DISCUSSIONS

A. Characteristics of the triggered spark-gap switching

In order to demonstrate the switching behavior of the spark-gap switch, Fig. 4 shows a typical voltage waveform appearing on high-voltage capacitor \( C_h \) after switch on of thyristor \( T_2 \). The voltage first increases during the resonant charging process, and then remains almost constant until the main spark gap is fired. The delay between the end of the charging cycle and closure of the spark-gap switch mainly depends on the time coefficient \( \beta \) and the voltage pulse repetition rate [pulses per second (PPS)]. Figure 5(a) shows an averaged time-resolved voltage waveform based on 12 signals. Each fast voltage drop corresponds to one of the moments that the main spark gap breaks down. The time derivative of the averaged voltage obviously demonstrates the switching behavior, indicated in Fig. 5(b). The positive part corresponds to the charging current, while the negative peaks correspond to the switching. Each negative peak corresponds to the fast voltage drop in Fig. 5(a) at the moment when the main spark gap is fired. In these examples, it can also be seen that the spark-gap switch always breaks down after the resonant charging process. With the time derivative of a large number of time-resolved voltage waveforms, the time delay for the spark-gap switching can be evaluated. By sampling 1000–4000 signals, Fig. 6 shows the time-resolved derivatives of the averaged voltage waveforms for pulse repetition
rates of 10, 20, 40, and 500 pps, respectively. By increasing
the pulse repetition rate, the distribution functions move to
earlier times and their half widths decrease. According to our
experimental observations, by optimizing the electrode ge-
ometry, the flush gas flow rate, and the time coefficient \( \beta \),
very stable spark-gap switching can be achieved.

B. Output characteristics of the generator

For corona plasma generation, wire–wire, wire–
cylinder, and wire–plate reactors are under investigation for
various corona-induced plasma applications, such as biogas
cleaning and VOC emission abatement.\(^2\,5\,7\) For example, us-
ing a wire–cylinder reactor with length and inner and outer
diameters of 3000, 3, and 160 mm, respectively, a 2.0 kW
averaged corona plasma can be generated with corona energy
of 2.3 J/pulse at a pulse repetition rate of 860 pps.\(^6\) With
regard to the energy transfer for primary streamer propaga-
tion and matching between the generator and corona
reactors,\(^4\,5\) a wire–plate corona reactor is used to match the
present generator. Successive development of the present
system is a 10–30 kW corona plasma system with a hybrid
pulsed power source, which consists of a high-voltage pulse
generator, as shown in Fig. 1, and a resonant capacitive
charging unit. Sixteen wire–cylinder reactors in parallel with
a total corona wire of 16 m are used to match the source.\(^8\)

Figure 7 shows typical voltage and current output wave
forms with a resistor load. The voltage rise time is about 20
ns, while the pulse duration depends on the time constant of
\( Z_m C_h \). As a function of the pulse repetition rate, Fig. 8
shows the typical averaged output power for three different
energies per pulse. During these tests, the load resistor varied
between 48 and 60 \( \Omega \) because of the heating and the electric
field. Both the pulse repetition rate \( f \) and the energy \( e_p \) per
pulse determine the average power \( P = f e_p \). Figure 9 shows
the standard deviation of the measured power in terms of the
pulse repetition rate. After optimizing the spark-gap switch
and its triggering circuit, the deviation is around 1.0% within
the pulse repetition rate from 1 to 900 pps. Moreover, the
high-voltage pulse generator could also maintain very stable
outputs even if the main spark-gap switch is prefired.\(^9\)

Previous investigations have indicated that the energy
consumption contributes largely to the operating costs for
industrial applications of pulsed corona techniques. The en-
ergy cost depends on both chemical reactions and the energy
conversion efficiency from the main power line to the plasma
reactor. The energy conversion efficiency of the system has
been investigated for each step of the circuit. The total en-
ergy conversion efficiency from the main power line to a
corona reactor can be divided into two subefficiencies. The
first one \( \eta_1 \) is for charging high-voltage capacitor \( C_h \), while
the second, \( \eta_2 \), is the efficiency of transferring the stored
energy in \( C_h \) to the corona reactor. For the first one, the main
losses are because of the thyristor snubber and the pulse
transformer. The energy conversion efficiency of the present
pulse transformer is around 98%, while the losses on snub-
bers mainly depend on the capacitance ratio of the snubber
capacitor over low-voltage capacitor \( C_L \). As shown in Fig.
1, three air coil inductors are used for resonant charging
and/or discharging process.\(^5\) Subefficiency \( \eta_1 \) increases with
increasing energy per pulse. For an energy output of around
10 J/pulse, \( \eta_1 \) is around 95%.

For the second subefficiency, \( \eta_2 \), the triggered spark-
gap switch, the transmission line transformer, and the match-
ing between the generator and the reactor mainly cause the
losses. We found that, for each corona reactor, there is a
minimum peak voltage required for achieving the maximum energy transfer from the pulse generator to the corona reactor. By increasing the peak voltage beyond the minimum voltage, the equivalent impedance of the corona reactor, $R_{\text{reactor}}$, defined as the ratio of the peak voltage over the peak current, approaches the output impedance of the generator. Subenergy conversion efficiency $\eta_2$ can be generally approximated by

$$\eta_2 \approx \frac{4 \theta}{(1 + \theta)^2},$$

where $\theta = R_{\text{reactor}}/Z_{\text{out}}$. The resistor ratio $\theta$ mainly depends on the peak voltage, while the maximum energy transfer efficiency $\eta_{2\text{max}}$ mainly depends on the TLT design. When the TLT, constructed with a ring core ferrite, is connected in series at the output side ($Z_{\text{out}} = 200 \Omega$), $\eta_{2\text{max}}$ is about 80%. This lower energy conversion efficiency is caused by ferrite saturation. For the present design, larger size micro-gapped Metglas cores are used to prevent saturation and to increase the secondary mode impedance, which gives $\eta_{2\text{max}}$ of around 96%. When the peak voltage on the reactor becomes larger than the minimum voltage, we have $\theta = R_{\text{reactor}}/Z_{\text{out}} \approx 1$, and the efficiency $\eta_2$ approaches the maximum energy transfer efficiency, $\eta_{2\text{max}}$, which is obtained with a matched resistor as the load. As a result, the total energy efficiency $\eta = \eta_1 \eta_2$ for the present system is of the order of 80%–90%.

Moreover, the generator has been tested for more than 100 h for both industrial demonstrations, such as testing on styrene and odor removal from air, and laboratory investigations at an average output power of 1–10 kW. The electrodes are slightly eroded; detailed discussions on the reliability, lifetime, and industrial testing on VOC removal, odor control, and biogas cleaning will be reported in separate papers.

IV. DISCUSSION

An energy efficient repetitive high-voltage pulse generator has been developed for both laboratory investigation and industrial applications. The following features have been obtained.

1. A three-step resonant charging circuit can automatically adapt to a triggered spark-gap switch and a TLT for generating nanosecond high-voltage pulses. The pulse to pulse deviation of the output pulsed energy can be controlled to be less than 1.0% for a pulse repetition rate of 1–900 pps. The system has been tested for more than 100 h without any trouble.

2. According to achieved results, a pulsed power source with average power of up to 30 kW is also under investigation with a matched corona reactor. Detailed results will be reported in the near future.

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