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## Novel circuit topologies for repetitive pulsed power and plasma applications

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**Abstract:** This paper discusses novel circuit topologies for repetitive ultra-short and microsecond pulsed power sources, pulsed transient thermal plasma and pulsed corona plasma generations. Critical circuit elements are heavy-duty thyristors, a transmission line transformer, and triggered spark-gap switches.

### 1. Introduction

In the last decade, both thermal and non-thermal plasmas have been widely investigated for pollution control and sustainable development. Several recent publications present the state of the art of thermal [1-3] and non-thermal plasma [4-7] technologies. Lack of cost-efficient plasma generation and processing techniques, however, delay the acceptance by industries. Our R&D activities are related to electrical discharges, pulsed corona plasma for gas and water treatment, plasma assisted gasification, electrical diagnostics, and EMC techniques [8]. The objective is to develop cost-effective pulsed power and plasma systems in order to fill the gap between fundamental investigations and industrial applications.

### 2. Ultra-short pulsed power generation

The most critical component in the development of repetitive ultra-short pulsed power technology is the high-voltage and large-current switch. Available switches can be listed: thyratron, pseudo spark gap, crossatron, ignitron, spark gap (gas, liquid and solid dielectrics), semi-conductor, magnetic, fuse, and plasma opening switches. The difficulty for industrial applications of ultra-short (20-50 ns) pulsed power techniques arises from the simultaneous requirements on power rating, efficiency, lifetime and cost. As an example, Table 1 lists expected specifications of a 100 kW source for corona plasma applications.

Table 1. A 100 kW corona plasma system.

Peak output current (kA)	20
Peak output voltage (kV)	100
Output impedance ( $\Omega$ )	5
Pulse repetition rate (pps)	1000
Voltage rise time (ns)	10
Pulse width (ns)	50
Energy efficiency (%)	>90
Switch lifetime (shots)	> $4 \times 10^{10}$

Based on switching topologies, available pulsed power circuitries can be divided into two groups, namely single- and multiple-switch circuits. For 1-10 kW systems, a single high-pressure triggered gas-filled spark-gap switch is the most cost effective. When scaling up the system from 10 to 100 kW, multiple-switch pulsed power systems, however, become necessary in order to reach the lifetime [9].

Figure 1 shows an example of a DC superimposed multiple-switch circuit topology for pulsed corona plasma applications. Various switched-mode power supplies can be used to charge the two pulse forming networks (PFNs). A three-step capacitive charging unit together with the LCR trigger method is described in [10,11]. Two identical triggered spark-gap switches  $S_1$  and  $S_2$  are used to share the output power. At the input side of the transmission line transformer (TLT), the two cables are interconnected via two switches and two pulse forming networks (PFNs). At the output side, the two cables are connected in parallel. When the two switches are closed, the two cables are also put in parallel at the input side.

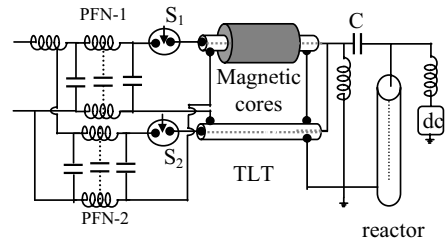


Fig.1. A typical DC superimposed multiple switch circuit topologies.

Whenever one of the switches  $S_1$  or  $S_2$  closes, a step front travels between the two cables, which greatly increases the voltage on the second switch. As a result, the two switches close almost simultaneously. No special synchronization trigger circuits are required. A simple LCR trigger circuit can be used to trigger one of the switches for up to a pulse repetition rate of 1000 pulses per second (pps) [10,11]. In comparison with a single-switch circuit, the switching duty for each switch shown in Fig.1 is reduced by a factor of two. As a result, the switch lifetime can be improved by a factor of four.

TLTs are used for both impedance matching and synchronization of multiple switches. In fact, the circuit principle shown in Fig.1 can be used for any number of switches. Increasing number of switches and reducing the output impedance scale up the output power. At the output side of TLTs, various series and/or parallel connection can be used to match corona plasma reactors. Cost effective industrial systems can be realized. It is anticipated that ultra-short 100 kW pulsed power source specified in Table 1 can be manufactured at a cost of less than 300 k€ for industrial applications.

### 3. Microsecond pulsed power generation

Microsecond (1-200  $\mu$ s) pulsed power systems are usually based on either magnetic compression or solid-state switches. Figure 2 partly shows a circuit topology for microsecond pulsed power generation. An AC/DC/Pulse converter is used to charge the high-voltage capacitor  $C_h$ . The inductor  $L$  is designed to be large enough to allow resonant charging of the HV capacitor  $C_h$ . After that, capacitor  $C_h$  discharges to  $C$  via the inductor  $L$  and the two diodes  $D_1$  and  $D_2$ . The high-voltage capacitor  $C$  is repetitively charged till a designed energy level. Discharging it via a heavy-duty thyristor  $S$  produces output pulses.

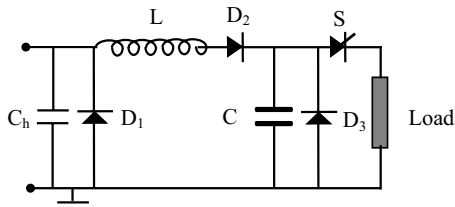


Fig.2. A circuit topology for microsecond pulsed power generation.

In collaboration with Geo-Resources [12], solid-state switch pulsed power sources with up to 10 kJ/pulse, as shown in Fig.3, have been developed by using the above circuit topology. The output current and the pulse duration are around 20 kA and 150-200  $\mu$ s, respectively. The high-voltage capacitor  $C_h$  is charged to 20-30 kV in about 25  $\mu$ s at 1-12 J/pulse and at 1-1000 pps. The high-voltage capacitor  $C$  ranges from 32 to 640  $\mu$ F. According to today's switching technologies, the circuit in Fig.2 can be easily scaled up to a few hundreds kJ/pulse. In comparison with traditional capacitive charging techniques either at constant voltage or at constant current, the capacitor  $C$  in Fig.2 is charged in steps at a constant energy per pulse. The pulsed power systems can be used for various applications, such as to

generate acoustic pulses as seismic source and to energize pulsed thermal plasma reactors.



Fig.3. All solid-state switch pulsed power source (courtesy of Geo-Resource, B.V., Rotterdam, The Netherlands).

### 4. Pulsed corona plasma

Based on the state of the art, a positive streamer can be described as: a highly ionized plasma, called streamer head, propagating from anode to cathode at a velocity of  $10^5 - 3 \times 10^6$  m/s. The size of the plasma region is around 50-100  $\mu$ m during the propagation. Between the plasma and the anode, there is an almost dark streamer channel with a diameter similar to the diameter of the streamer head. After the streamer head has bridged the electrode gap, a current can still flow via the formed streamer channel, the so-called secondary streamer. For a wire-cylinder or wire-plate corona reactor, many parallel streamers propagate from the corona wire towards the ground electrode when the applied voltage becomes higher than the inception voltage.

About 60 years ago, Willey observed that an intermittent discharge (10  $\mu$ s duration) was much more effective in producing acetylene in a mixture of methane and nitrogen than AC and DC discharges under the same conditions [13]. Previous patents awarded to Siemens for gas cleaning by pulsed corona technique can also be dated back in the early 1930's [14]. Unfortunately, pulsed corona plasma technique has, however, not been used in industries [15]. Two

critical issues impeded industrial applications. The first one is the capability of repetitive pulsed power techniques. The second is the total energy consumption. The essential know-how is cost-effective corona plasma generation technique, which is still under investigation. In addition to the simultaneous requirements on the power rating, the efficiency, the lifetime and the cost, the pulsed power source should be immune to repetitive spark breakdowns inside the reactor. To our knowledge, no system reported can meet these requirements. Several recent industrial demonstration systems are based on magnetic compression with pulse duration of around 200-500 ns, which leads to more than five times energy consumption. Based on multiple-switch circuit topologies as shown in Fig.1, ultra-short pulsed power systems have become available for industrial implementations of corona plasma techniques. Two 100 kW pulsed corona plasma systems as specified in Table 1 could be used to simultaneously remove NO<sub>x</sub>, SO<sub>2</sub>, HF, HCl, C<sub>h</sub>H<sub>m</sub>, heavy metals, PCDD/F (polychlorinated dibenzo-dioxins/dibenzofurans), and dust from a 150 t/day municipal waste incinerator.

## 5. Pulsed thermal plasma

Traditional thermal plasmas are high-frequency inductively coupled plasma torches, DC transferred and non-transferred arcs. Those plasmas are usually generated in a small volume and at a very high temperature (the order of 10,000 K) and/or a high heat flux. With regard to environmental applications, the two critical drawbacks of those plasmas are the short lifetime of the electrode and the difficulty of matching the related physical and chemical processes to the plasma specifications. For example, ideal plasma assisted gasification would be performed around 1,000 K in a large reactor volume. Unfortunately, by using the traditional thermal plasma generation techniques, the temperature is much higher than the ideal one. The newly proposed technique for generation of multiple pulsed thermal plasmas [16] could overcome those drawbacks and provide a new methodology for plasma engineering and processing.

As an example, Fig.4 shows a circuit topology for generation of two pulsed thermal plasmas. As discussed for the circuit shown in Fig.2, the high-voltage capacitor C<sub>h</sub> and the transmission line cables are resonantly charged in about 25 μs. Similar to the synchronization of multiple-switches as shown in Fig.1, the two transmission cables synchronize the two transient plasmas. As a general circuit principle, multiple-plasma reactors are interconnected to a set of transmission lines, where they are connected in parallel at the input side (connected to the inductor L as shown in Fig.4). Tests with two, three and four plasma reactors in air have experimentally verified the

circuit topologies for generation of multiple transient plasmas.

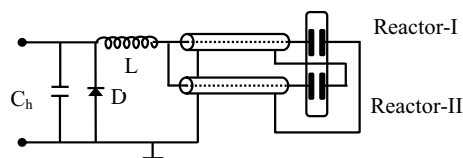


Fig.4. A circuit topology for generation of multiple transient thermal plasmas.

The plasma reactor is energized during three distinguishable stages. During the first stage, the plasma reactor is resonantly charged to a maximum voltage of around 20-30 kV in about 25 μs. In the second stage, an arc discharge occurs inside the reactor. The voltage drops to about 100 V in about 50-100 ns, and at the same time, the reactor is energized with a large peak current. During this stage, the reactor is energized by the stored energy in the cable, where the peak arc current depends on the maximum charging voltage and the characteristic impedance of the cable. After this initial arc plasma generation, the discharge of the high-voltage capacitor via the inductor L generates the third stage, the flame-like plasma, where the peak current depends on the maximum charging voltage on the capacitor and the circuit impedance  $\sqrt{\frac{L}{C_h}}$ . The plasma duration depends

on the plasma impedance and the inductor. The voltage on the reactor is almost constant during about 0.2-1.5 ms with a peak current of around 20-50 A. According to those time resolved energization processes, one may conclude that by changing either the high-voltage capacitor or the transmission line, the energy transfer ratio for the arc and the flame-like plasmas can be easily controlled. Figure 5 shows a plasma photo at 1 kW average power and at a pulse repetition rate of 200 pps in air. Two wire electrodes with a gap distance of 10 mm are used to generate the plasma. The length and diameter of the wire electrode are 70 mm and 5 mm, respectively. With a pulsed power system as shown in Fig.3, thousands of such transient plasmas can be generated simultaneously for a large volume plasma processing.

## 6. Conclusions

Using a solid-state pulsed power source, multiple thermal plasmas can be easily generated in large volume. The plasma can be generated in various kinds of electrode geometries, in various gases and under various temperatures. Industrial demonstrations would further prove their advantages in comparison to a traditional plasma torch. Multiple-switch based ultra-

short pulse generators have become available as the enabling technique for industrial implementations of corona plasma techniques for exhaust or synthetic gas cleaning.

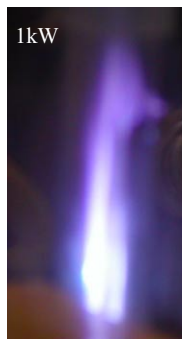


Fig.5. A plasma photo.

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