Matching Repetitive Pulsed Power to Industrial Processes

E.J.M. van Heesch^{*} Non-member

Keping Yan^{*} Non-member

A.J.M. Pemen^{*} Non-member

S.A. Nair^{*} Non-member

G.J.J. Winands^{*} Non-member

I. de Jong^{**} Non-member

Repetitive pulsed power techniques have enormous potential for a wide range of applications, such as nano-particle and hydrogen production, gas and water processing and sterilization, and generation of X-ray, EUV, and high-power acoustics. This paper presents the state of the art of our activities on repetitive ultra-short and microsecond pulsed power sources, pulsed thermal and streamer corona plasmas. Critical circuit elements are heavy-duty thyristors, transmission line transformers, and triggered spark-gap switches.

Keywords : plasma catalysis, pulsed power, streamer corona, seafloor mapping

1. Introduction

In the last decade, our research and development activities on pulsed power and plasma technologies are mainly related to fundamental investigations on physical and chemical processes of electrical discharges, system development of pulsed corona plasma for gas and water treatment, pulsed plasma torch, electrical diagnostics, and EMC techniques⁽¹⁾⁽²⁾. The objective is to develop cost-effective pulsed plasma systems for industrial applications. Table 1 summarizes main current activities and their status. This paper reviews the state of the art of our activities on repetitive pulsed power and plasma technologies and their applications.

2. Ultra-short Pulsed Power Source

The most critical component in the development of repetitive

ultra-short (20-50ns) pulsed power technology is a high-voltage and large-current switch. Available switches can be listed as: thyatron, crossatron, ignitron, spark gap (gas, liquid and solid dielectrics), solid-state, magnetic, fuse, and plasma opening switches. The difficulty for industrial applications of the pulsed power technologies arises from simultaneous requirements on power rating, energy conversion efficiency, lifetime and cost. Available pulsed power circuitries are classified into two groups⁽³⁾, namely single-switch circuits for less than 10 kW output power, and multiple-switch circuits for high power (100 kW range) generators.

Figure 1 shows a typical circuit topology with multiple-switches. The primary repetitive low-voltage circuit is based on three step resonant charging and discharging. It consists of three thyristors, two inductors and an intermediate storage

Table 1. Applications of pulsed power and thermal and non-thermal plasmas

Applications	Main functions	Status
Indoor	Odor removal and bacterial and virus cleaning	Mature
Exhaust gas	Conversion of NO _x and SO ₂ to NH ₄ NO ₃ and (NH ₄) ₂ SO ₄ under NH ₃ addition; removal of dioxin/furans, HCl, heavy metals and dusts; NO _x reduction from mobile sources	Demonstration
Air	Odor and VOCs removal and micro-organisms cleaning	Demonstration
Fuel gas	Heavy hydrocarbons (tars) cracking and particles removal, plasma assisted gasification and combustion	Concept proof
Methane	Conversion of CH ₄ either to acetylene or hydrogen	Concept proof
H ₂	H ₂ generation from fossil fuels	Concept proof
Oil	Cracking heavy oil to light ones, plasma assisted pyrolysis	Concept proof
Soil	Decomposition of hydrocarbons (oils) and clean of micro-organisms	Concept proof
Liquid	Oxidation of VOCs and clean of micro-organisms	Concept proof
Material	Surface treatment, nano-particles production	Concept proof
Acoustics	High-pressure wave generation	Mature

^{*} Department of Electrical Engineering, Eindhoven University of Technology

Eindhoven, The Netherlands

^{**} Geo-Resources B.V.

Heemraadsingel 235, Rotterdam, The Netherlands

Fig. 1. Typical multiple-switch circuit topology for ultra-short pulsed power generation

Fig. 2. Coaxial gas-triode switch

Table 2. A 100 kW corona plasma system

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

capacitor (C_2). Thyristor number one and two respectively charge and discharge the capacitor C_2 during each pulse cycle. The third thyristor reverses the polarity of the remaining voltage on C_2 after each cycle. The high-voltage part mainly consists of a step-up transformer, four high-voltage capacitors, four spark-gap switches and a transmission line transformer (TLT), which is made of four rigid cables. At the input side of the TLT, the four cables are interconnected via the four switches and the four identical high-voltage capacitors. At the output side, the four cables are connected in a parallel/series configuration. When the four switches are closed, the four capacitors are also put in parallel. As a result, the input and output impedances of the TLT are $0.25Z_0$ and Z_0 , respectively, where Z_0 is the characteristic impedance of the cable. The four capacitors are charged simultaneously in about 20 μ s, and the four switches are used to share the output power.

Whenever one of the switches closes, a fast step front travels between the two related cables, that leads to overcharging of the other three switches. As a result, all switches close almost simultaneously. No special synchronization trigger circuit is 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)⁽⁴⁾. In comparison with a single-switch circuit, the switching duty or switching current for each switch shown in Fig.1 is reduced by a factor of four. As a result, the switch lifetime can be improved by a factor of about 16. Moreover, the coaxial type electrode geometry, as shown in Fig.2, increases its lifetime up to the order of around 4×10^{10} shots.

For these novel multiple-switch circuit topologies, TLTs are used for impedance matching and synchronization of the multiple switches⁽³⁾. In fact, the circuit principle can be applied to any number of switches. An increasing number of switches and a

Fig. 3. A circuit topology for microseconds pulsed power generation

Fig. 4. All solid-state switch pulsed power source

lower output impedance are needed to scale up the output power. At the output side of a TLT, various in series and/or in parallel connections can be applied to match all kinds of loads. It is anticipated that a 100 kW ultra-short pulsed power source with specifications as listed in Table 2 can be manufactured at a cost of less than 300 k€.

3. Microsecond Pulsed Power Source

Microseconds (1-200 μ s) pulsed power sources are usually based on magnetic compression and solid-state switches. Figure 3 shows the main part of a novel circuit topology for microsecond pulsed power generation. An AC/DC/Pulse converter is used to resonantly charge a high-voltage capacitor C_h , which then discharges to a high-voltage pulse forming capacitor C via an inductor L and two diodes D_1 and D_2 . The high-voltage capacitor C is repetitively charged till a designed voltage or energy level. Discharging it via a heavy-duty thyristor S generates output pulses. In comparison with traditional capacitive charging techniques either at a constant voltage or at a constant current, the capacitor C is charged in steps at a constant energy per pulse. Figure 4 shows a photo of such an all solid-state switch pulsed power source⁽⁵⁾. The output energy, peak current and the pulse duration are up to 10 kJ/pulse, 20 kA, and 150-200 μ s, respectively. Applying presently

available switches, the circuit can generate up to a few hundred kJ/pulse. The systems can be used for various purposes, such as to generate acoustics as seismic sources, to generate pulsed plasma for wastewater treatment, and to energize pulsed thermal plasmas.

4. Pulsed Corona Plasma

Two critical issues for industrial applications of pulsed corona plasma techniques are the cost of repetitive pulsed power source and the total energy consumption. Development of industrial systems also brings up the following specific issues: specifications of the pulsed power source; size of the corona reactor; matching between the source and the reactor; energy conversion efficiency; radical production efficiency; by-products, and cost effectiveness. In addition to the investigations on fundamental physical and chemical processes⁽⁶⁾, we also proposed and applied a general principle for development of industrial pulsed corona plasma systems⁽⁷⁾⁽⁸⁾.

As an example, Fig. 5 shows a photo of our 10-30 kW hybrid pulsed power source (HPPS) and corona plasma system. 16 wire-cylinder type reactors are used in parallel. The length and the inner and outer diameter of each reactor are 1000, 3 and 160 mm, respectively. The reactor and gas temperatures can be

Fig. 5. A mobile pulsed corona system (see reference 7 for circuit diagram and details)

Fig. 6. Bio-gas cleaning. The conditions are: 1 J/pulse, 80 kV, 200 ns pulse length, 20 ns pulse rise time, 25 cm diameter 3 m long reactor, 200 deg.C, 1 bar, bulk gas composition 50 % N₂, 20 % CO, 17 % H₂, 12 % CO₂, 1 % CH₄, initial concentrations: naphthalene 5 gr/m³, toluene 1 gr/m³, phenol 1 gr/m³

independently controlled up to 200 °C. The HPPS mainly consists of two parts: a high-voltage pulse generator and a DC power source. Before applying a high-voltage pulse on the reactors, all of them are first charged to a bias voltage V_{dc} . By firing the main switch S, the energies stored in a coupling capacitor and in a high-voltage capacitor are transferred into the reactor simultaneously. In comparison with available magnetic compression techniques, the HPPS technique allows the pulse duration to be reduced by a factor of ten without affecting the energy conversion efficiency.

To our knowledge, several current industrial pulsed corona plasma systems are based on magnetic compression techniques with pulse duration of around 200-500 ns. The HPPS corona system may be the only industrial system with the ultra-short pulse duration. A series of industrial demonstrations are anticipated to evaluate its technical and economical feasibilities. Based on our previous industrial experiments under gas flow rates of up to 5000 Nm³/h, we anticipate that for industries, such as animal farmers and meat producers, the system shown in Fig.5 can be used for industrial deodorization in the range of 20,000-50,000 Nm³/h. The corona energy density and the treatment time range from 0.2 to 0.4 Wh/Nm³, and from a few ms to a few seconds, respectively.

In addition to exhaust gases and/or air cleaning⁽⁹⁾, plasma assisted fuel processing and/or cleaning also become emerging techniques for sustainable energy development⁽¹⁰⁾⁻⁽¹³⁾. Here we discuss one such application, dust and tar removal from biomass derived fuel gas⁽¹⁴⁾⁽¹⁵⁾. Experiments have demonstrated that corona plasma converts heavier hydrocarbons (or tar) to lighter ones, and both tar and dust can be removed simultaneously. In comparison with traditional techniques of catalytic and thermal cracking and scrubbing, it has been considered that ultra-short pulsed corona plasma is one of the most competitive techniques for fuel gas cleaning. Figure 6 shows an example of tar (naphthalene, toluene, and phenol) removal in terms of corona plasma energy density. With regard to the heating value of 4-5 MJ/Nm³ of the fuel gas, further detailed investigations are needed in order to reduce the energy consumption.

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 temperature in the order of 10,000 K⁽¹³⁾⁽¹⁶⁾. Their main functions are to generate a very high heat flux. With regard to environmental applications, two critical drawbacks of those plasmas are a short lifetime of electrodes and difficulties of matching related physical and chemical processes to the plasma specifications. For example, an ideal plasma assisted gasification should be performed around 1,000 K in a large reactor volume. Unfortunately, by using the traditional thermal plasma techniques, the temperature is far above the ideal one. The newly proposed technique for generation of multiple pulsed thermal plasmas can overcome the drawbacks and provide a new methodology for plasma engineering and processing⁽¹⁷⁾.

As an example, Fig.7 shows a circuit topology for generation of two pulsed thermal plasmas. Similar to the synchronization of multiple-switches as discussed for the circuit of Fig.1, the two transmission cables synchronize the two transient plasmas.

As a general circuit principle, multiple-plasma reactors are

Fig. 7. A circuit topology for generation of two pulsed thermal plasmas

Fig. 8. Schematic diagrams of two typical multiple pulsed thermal plasma reactors

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. 7). Various kinds of electrode geometries, such as, point-to-plate, wire-to-wire, wire-to-tube, wire-to-plate, plate-to-plate, and tube-to-tube, can be used to construct the plasma reactor. The reactor volume or the electrode-gap distance can be estimated according to the criteria of streamer-glow-spark transition⁽¹⁸⁾. Figure 8 shows two examples of wire-to-wire and tube-to-tube reactors. Tests with two, three and four plasma reactors in air have experimentally verified the circuit topologies for generation of multiple transient plasmas.

The plasma reactors are energized in three distinguishable stages. During the first stage, they are resonantly charged to a maximum voltage of around 20-30 kV in about 20 μ s. In the second stage, arc discharges occur in the reactors. The voltage drops to about 100 V in 50-100 ns, and at the same time, all reactors are energized with a large peak current. During this stage, the reactors are energized by the stored energy in the cables. The peak arc current depends on the maximum charging voltage and the characteristic impedance of the cable. Multiple plasmas are synchronized at the beginning of this stage. Figure 9 shows typical plasma current waveforms with two reactors. Thus, one can conclude that the two plasmas are synchronized with 2-4 ns.

After the arc plasma generation, the discharge of the high-voltage capacitor C_h via the inductor L generates the third stage flame-like plasmas. The maximum current depends on the maximum charging voltage on the capacitor and the circuit impedance $\sqrt{L/C_h}$. It is around 20-50 A. The plasma duration depends on the plasma impedance and the inductor. Within this stage, the voltage on the reactors is almost constant during about 0.2-1.5 ms.

Analyzing the time resolved energization processes, one can

Fig. 9. Typical current waveforms for two pulsed arc plasmas

Fig. 10. Photograph of a pulsed thermal plasma

conclude that by changing either the high-voltage capacitor or the transmission lines, the energy transfer ratio for the arc and the flame-like plasmas can be easily controlled. Figure 10 shows a plasma photo at 1 kW average power and at a pulse repetition rate of 200 pps in air. A wire-to-wire reactor with a gap distance of 10 mm is 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.4, thousands of such transient plasmas can be generated simultaneously.

6. Future Prospects

According to their electron and ion temperatures, plasmas for processing technologies can be divided into two groups, namely thermal and non-thermal ones. In the last decade, both of them have been widely investigated for pollution control and sustainable development. Several recent reviews present the state of the art for thermal⁽¹¹⁾⁻⁽¹³⁾⁽¹⁶⁾⁽¹⁹⁾⁽²⁰⁾ and non-thermal plasma⁽⁹⁾⁽²¹⁾⁻⁽²⁵⁾ technologies. With regard to solid-waste treatment, pollution emission control and sustainable energy, Fig.11 shows a logical diagram for plasma assisted processing. Both pulsed thermal and non-thermal (or streamer corona) plasmas can be used to improve gasification and pyrolysis. Ultra-short pulsed corona plasma will further prove its advantages for both fuel and exhaust gas cleaning. Integrating pulsed corona plasma techniques with other available techniques, such as chemical catalysis, electrostatic precipitation and scrubbing, will lead to development of a zero

Fig. 11. Schematic diagram for pulsed power and plasma applications

emission system for low concentration emission abatement.

7. Conclusions

A general principle has been proposed and used for design of industrial corona plasma systems. Based on multiple-switch circuit topologies, up to 100 kW ultra-short pulsed power sources (20-50 ns) can be manufactured at a cost of less than 300 k€. A streamer corona plasma system can be applied at the cost of an electrostatic precipitator. Using a single all solid-state switch pulsed power source, multiple thermal plasmas can be easily generated in a large volume. For various kinds of electrode geometries, in various gases and under various temperatures, one can generate the plasma by adapting the system to each specific situation. Industrial demonstrations will further prove the advantages in comparison with traditional plasma torches. All solid-state switch pulsed-power systems are becoming available for wastewater treatment and generation of high-power acoustics.

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E. J. M. (Bert) van Heesch (Non-member) was born in Utrecht, The Netherlands, in 1951. He received the Master's degree in physics from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1975 and the Ph.D. degree in plasma physics and fusion-related research from Utrecht University, The Netherlands, in 1982. Since 1986, he has been leading Eindhoven Corona and Pulsed Power Research Group. Prior to that, he was occupied with fusion technology in Jutphaas, The Netherlands; in Suchumi, Russia; and in Saskatoon, Canada. Among his designs are a toroidal fusion experiment (5-GW pulse power), a particle beam diagnostic, a substation high-voltage measuring system, and a unit for continuous pulsed power corona.

Keping Yan

(Non-member) was born in China. He received the B.Sc. and M.Sc. degrees from 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. Since 1988, his research activities have been in pulsed power and applied plasma science with applications to pollution control and sustainable development. He has co-authored about 40 papers in Journals, about 70 papers in conferences and co-invented 6 patents.

A.J.M. (Guus) Pemen

(Non-member) was born in Breda, The Netherlands, in 1961. He received the B.Sc. degree in electrical engineering from the College of Advanced Technology, Breda, in 1986, and the Ph.D degree in electrical engineering from Eindhoven University of Technology, The Netherlands, in 2000. He worked for KEMA T&D Power in Arnhem, The Netherlands. He joined TU/e in 1998 as assistant professor, and his research interest includes high-voltage engineering, pulsed power and pulsed plasmas. Among his achievements are the development of an on-line monitoring system for partial discharges in turbine generators and a pulsed-corona tar cracker. He is the founder of the Dutch Generator Expertise-Centre.

S.A. (Sreejit) Nair (Non-member) was born on 22nd April, 1978 and graduated in chemical engineering from the University of Mumbai, Institute of Chemical technology, Mumbai, India. Presently he is pursuing his PhD at the Eindhoven University of Technology, The Netherlands in the area of tar removal by non-thermal plasma techniques.

G.J.J. (Hans) Winands (Non-member) was born in Kerkrade, The Netherlands, on March 27, 1978. He received the M.Sc. degree in Applied Physics from Eindhoven University of Technology, The Netherlands, in 2002. In 2002 he joined the faculty of Electrical Engineering at the Eindhoven University of Technology to perform a PhD study.

I.B. (Ivan) de Jong (Non-member), was born in 1948 in Merano, Italy. In 1979, he received M.Sc. degree in Geophysics and Structural Geology with the State University of Leiden. In his academic and professional career, as a geophysicist and geologist, he worked with a number of companies and organization, such as the World Bank and United Nation. In 1990, he co-funded Geo-Resource, and has been the technical director of the company. He has supervised a number of projects related to high-resolution seismic survey and instruments, such as sparker, boomer, streamer, and multi-channel data acquisition system.