

Corona plasma energization techniques: ultra-short and DC/AC power sources

Citation for published version (APA):

Yan, K., Winands, G. J. J., Liu, Z., Heesch, van, E. J. M., & Pemen, A. J. M. (2005). Corona plasma energization techniques: ultra-short and DC/AC power sources. In *Proc. XIVth International Symposium on High Voltage Engineering, Beijing, China, August 2005* (pp. C33-1/6)

Document status and date:

Published: 01/01/2005

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Corona plasma energization techniques: ultra-short and DC/AC power sources

K. Yan, G.J.J. Winands, Z. Liu, E. J. M. van Heesch, and A.J.M. Pemen,

EPS Group, Department of Electrical Engineering
Eindhoven University of Technology
5600 MB, Eindhoven
The Netherlands
e-mail: k.yan@tue.nl

Abstract: This paper discusses some critical issues when developing industrial corona plasma systems. Based on streamer generation and interaction between power sources and reactors, the power conditions for streamer corona plasma generation can be divided into two groups, namely ultra-short and DC/AC pulsed-power sources. Today, single- and multiple-switch circuit topologies become available to scale the ultra-short pulsed-power system up. DC/AC sources are being introduced into the market. Industrial pilot investigations have demonstrated their advantages and drawbacks. The data available would be sufficient enough for commercial-scale design for either odour emission control and/or exhaust gas cleaning.

1. Introduction

With regard to pollution control and electrical discharges in gases, the most popular techniques used to be electrostatic precipitation and ozone generation. Both of them have a history of over a century. In the last 20 years, corona plasma techniques have been widely investigated for pollution control and sustainable development. Investigations have extended from odour treatment, indoor air cleaning, VOCs abatement, flue gas cleaning to methane reforming, hydrogen production and fuel gas cleaning. Corona plasmas are often used together with additional techniques in order to control by-products and to increase the efficiency. For examples, NO_x and SO_2 can be converted to NH_4NO_3 and $(\text{NH}_4)_2\text{SO}_4$ salts with NH_3 addition; VOCs can be decomposed to CO_2 and H_2O with catalyst; Dioxin/furans and Hg can be removed with a corona plasma scrubber; hydrogen sulphide can be converted to hydrogen and sulphur; under plasma enhanced catalysis soot and NO_x can be oxidized to CO_2 and reduced to nitrogen, respectively. According to available literature, more than 50 types of pollutants have been investigated for their emission control by using corona plasma techniques. Table 1 summarizes the state of the art of corona plasma applications.

Although the technique has not been widely used in industries, it is anticipated that in coming years the technique will play a very significant role for large volume exhaust gas cleaning. Two critical issues that should be solved for industrial applications are the capacity and cost of repetitive pulse power techniques, and the total energy consumption. Today, unfortunately, lack of cost effective corona plasma generation and processing techniques discouraged industries to promote those applications. Nevertheless, three industrial corona plasma demonstration systems with up to 50-100 kW in average power were recently reported in Japan, Korea and China. All of them are based on the magnetic compression technique with pulse duration of 200–500 ns. The main technical difficulty for applying such pulsed corona plasmas arises from simultaneous requirements on power rating, energy conversion efficiency, lifetime and cost. Moreover, industrial systems also bring up the main issue of the matching between the source and the reactor. It seems that the recently reported semi-wet DC/AC corona plasma system is one of the most cost effective techniques due to it does not need short pulsed-power sources but a DC/AC one.

In the first place, it is worth to note that by applying a positive voltage pulse in non-uniform electrode configurations, such as point-plate, wire-plate, and wire-cylinder, streamer corona plasma is absolutely generated once the applied voltage is beyond the inception; generation of streamer corona plasma, however, does not always need a pulsed-power source; DC and DC/AC ones can also be used. At the moment, we are developing two kinds of power systems for corona plasma applications: namely an ultra-short (20-50 ns) hybrid pulsed-power system (HPPS) and DC/AC modulator. This paper discusses basic characteristics of streamer corona plasmas, presents the two energization methods, and reviews our recent research and development on various critical issues in order to bridge the gap between fundamental investigations and industrial applications [1].

Table 1. List of potential applications of corona plasma techniques for pollution control and sustainable development

<i>Applications</i>	Main functions	Status
Indoor	Bacterial, virus and odour removal	Mature
Exhaust gas cleaning	To convert NO _x and SO ₂ to NH ₄ NO ₃ and (NH ₄) ₂ SO ₄ under NH ₃ addition	Industrial demonstration
	To remove gaseous, heavy metals and particles simultaneously	Industrial demonstration
	NO _x reduction from mobile sources	Concept proof
	Dioxin/furans and Hg removal	Industrial demonstration
Air cleaning	Odour, VOCs and micro-organisms removal	Industrial demonstration and close to mature
Synthesis gas cleaning	Tar cracking, CO to CO ₂ conversion, gaseous and heavy metals removal	Industrial demonstration
Methane reforming	To convert CH ₄ to higher hydrocarbons or methanol	Concept proof
Hydrogen	To produce H ₂ from fossil fuels	Concept proof
Oil reforming	To upgrade heavy oil to light ones	Concept proof
Soil cleaning	To remove organic pollutants and micro-organisms	Concept proof
Water cleaning	To remove organic pollutants and micro-organisms	Demonstration

2. Characteristics of corona plasmas

2.1 Simultaneous streamer generation

In a non-uniform electrode arrangement, electron avalanche can lead to streamer formation. Discharge channels in the form of streamers appear in the electrode gap. Generally speaking, there are two types of streamers: positive and negative ones. They are similar to the so-called cathode and anode directed streamers in a uniform electric field. By taking ICCD pictures with high resolution in space and in time, it was observed that inside a wire-cylinder or a wire-plate corona reactor, many parallel streamers propagate almost simultaneously from the corona wire towards the ground electrode. The time delay between individual streamers generated at different locations is close to the time required for voltage pulse to propagate from the one location to the other. As a consequence of many streamers in parallel, a large current pulse is needed for the generation. In this paper, we call this kind of plasma generation technique, which is obviously based on pulsed-power technologies, as simultaneous streamer generation.

A positive streamer can be described as: in a non-uniform electric field, highly ionized plasma, called streamer head, propagates from anode to cathode with a velocity of $10^5 - 3 \times 10^6$ m/s. The size of the plasma region is around 100 μ 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 bridges the electrode gap, a current may keep flow via the formed channel, which is called secondary streamer.

During the primary streamer propagation, a single streamer may branch to several. The average electric field in the channel is about 5–7 kV/cm in air and 8 kV/cm in flue gas, respectively. It approximately equals to the streamer stability field, the minimum field for streamer propagation in a uniform electrical field. If the applied voltage is insufficient to supply the field for a streamer channel to bridge the electrode gap, the streamer head stops propagation before reaching the cathode. Thus, in order to generate corona plasma with a maximum streamer length inside the reactor, a minimum voltage for building up the streamer channel is required. The voltage can be a DC bias or a voltage pulse. As a result, a HPPS system has been considered as the most cost effective for pulsed streamer corona plasma applications. Figure 1 shows a mobile HPPS system. Sixteen wire-cylinder reactors in-parallel are used to match a 10-30 kW HPPS source. The length and inner and outer diameters of each reactor are 1000, 3, and 160 mm, respectively.

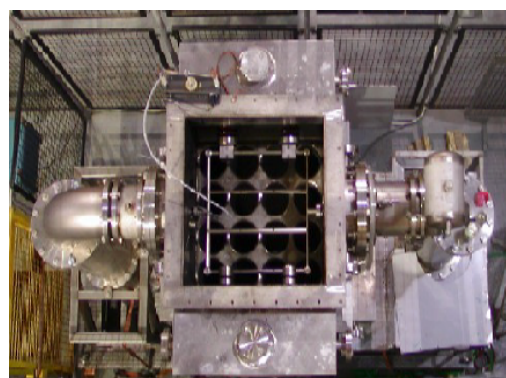


Fig.1. A mobile HPPS system.

2.2 Random streamer generation

In contrast to using pulsed-power technologies, it is well known that for a point-plate electrode arrangement in air, a positive DC electrical discharge may change from onset streamer to glow, pre-breakdown streamer and then to spark breakdown when increasing the applied voltage. The discharge patterns are dependent on electrode geometry, gas flow rate and compositions. The glow and streamer coronas can be distinguished by means of optical and electrical measurements. Unfortunately, generation of a large volume streamer corona with a DC source can face two technical problems. The first one is related to the effects of gaseous composition on the corona discharge pattern. The second is related to the sensitivity to electrode miss-arrangements. Non-uniform gas distribution and mis-arrangements of electrode configurations can cause the transition from streamer corona to glow discharge. As a result, glow and streamer may be generated simultaneously. With regard to the relationship between the corona modes (glow and streamer) and chemical reactions, systematic experiments on NO to NO₂ conversion in gaseous mixtures of N₂+O₂+CO₂+H₂O+NO_x demonstrated that a glow discharge induces negligible chemical reactions in contrast to a streamer corona. A pre-breakdown streamer is less efficient than an onset streamer.

In order to overcome the above technical problems and generate large volume corona plasma with a simple power source, a DC/AC energization technique was introduced: DC bias with superimposed high-frequency AC (10-60 kHz). Electrical, optical and chemical characteristics of DC/AC energized corona plasmas were investigated for nozzle-plate, saw-plate and wire-plate corona reactors. In contrast to a corona discharge with a DC power source, DC/AC (10-60 kHz) energized corona plasmas are less sensitive to gaseous compositions and electrode miss-arrangements provided the AC peak-peak voltage is larger than 1.0 kV. Optical and electrical measurements show that streamers are produced randomly along the high-voltage electrode, and the peak current and the energy transfer differ per streamer. With a DC/AC source, streamers are not generated at the same time; thus, it becomes unnecessary to use a pulsed-power source for the plasma generation. In this paper, we call this kind of plasma generation technique as random streamer generation.

At the moment, an industrial DC/AC system is under investigation for flue gas cleaning with gas flow rate of 10,000 Nm³/h. Much more detailed investigations on odour and VOCs emission abatement will also be carried out in the near future with multi-channels wire-plate reactors as shown in Fig.2. The DC/AC source is

around 1-2 kW. The length, height, and plate-plate distance are 1000, 1000 and 150 mm, respectively.

With regard to the two reactors shown in Fig. 1 and Fig.2, they are indeed as the same as two electrostatic precipitators. In fact, available ESP can be retrofitted for corona plasma applications. Details between simultaneous and random streamers are listed in Table 2.



Fig.2. A mobile DC/AC system

3. Power sources

Matching a high-voltage pulse generator to a corona plasma reactor becomes more important when scaling the system up. Optimizing the energy transfer increases the initial radical production; and improving the energy conversion efficiency reduces both investment and operational costs. Earlier reported technique for improving the matching is to use a DC bias in addition to a voltage pulse. Detailed guideline was just proposed to optimize peak voltage, rise time, output impedance, pulse duration, average power, corona reactor and also processing. Figure 3 shows an example of proposed ultra-short pulsed power circuit topology used for the plasma reactor shown in Fig.1. Our recent R&D activities are mainly focused on multiple switch topologies in order to reduce the switch duty of individual switch and at the same time to increase the total switching current or output power [2,3,4].

For a corona plasma reactor, a minimum peak voltage is required in order to achieve the maximum energy transfer from the generator to the reactor. The total peak voltage V_t is obtained by superimposing the voltage pulse V_p to the DC bias V_{dc} . When the applied voltage is below the minimum, there is always oscillation between the power source and the reactor. For almost all available pulsed-power circuit topologies, the oscillation not only leads to reduce the energy efficiency, but also could cause serious damage to their high-voltage switches. On the other hand, if the oscillating energy can be recovered, the energization technique shifts from

pulse to DC/AC. Both capacitive and inductive coupling circuit topologies as shown in Fig. 4 can be adopted for design of a DC/AC power source. These two are the most common circuits for generation of

DC/AC voltage. All kinds of switch mode techniques may be adopted for both AC and DC parts. A direct DC/AC generation is also possible with a limited peak-peak AC voltage at a repetition rate of 100 – 5000 pps.

Table 2: Comparison of pulsed power and DC/AC energized streamer coronas

Specifications	Simultaneous streamer	Random streamer
Power conditions	HPPS	DC/AC
Circuit topologies	Single or multiple switches topologies	Oscillators
Recommended switches	Spark-gap switch, Magnetic compression, thyristor, IGBT, IGCT	IGCT and IGBT
Pulse repetition rate	50-1500 pps	1 –130 kHz
Electron energy of streamer heads	~ 10 eV	~ 10 eV
Peak current (per unit length of reactor)	≤ 600 A/m	10-200 mA/streamer
Peak power (per unit length of reactor)	≤ 600 MW/m	~ 3 kW/streamer
EMC (di/dt) max	≤ 30 A/ns/m	~ 30 mA/ns/streamer
Average streamer velocity	5.0×10^5 - 3.5×10^6 m/s	~ 2.0×10^5 m/s
Energy for primary streamer	≤ 3 J/m/pulse or 3mJ/streamer	~ 0.3 mJ/streamer
Streamer diameter	~ 100 - 200 μm	~ 20 – 50 μm
Ions current/total current		~ 20 %
Time delay between streamers	Simultaneous (1-3ns for a 50 mm length wire)	Random (200 ns-1ms for a 100 mm length wire)
Main advantages	Flexibilities in either plasma power density or size of reactor	Less expensive power sources with a maximum voltage
Main drawbacks	Expensive power sources with a minimum peak voltage and a maximum pulse duration	Limited power density per unit volume of reactor.

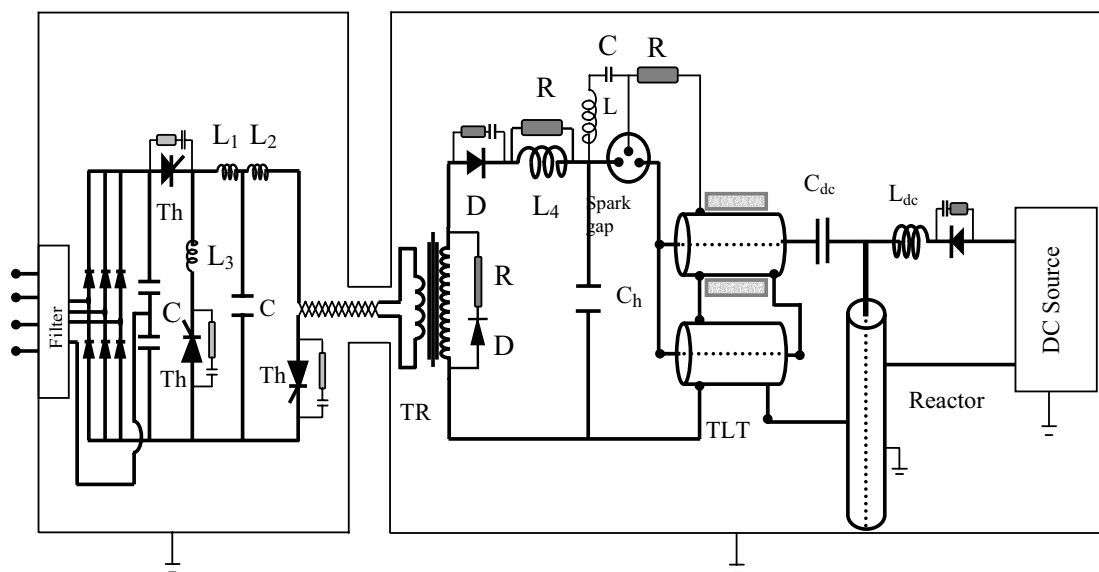


Fig.3. A HPPS circuit topology.

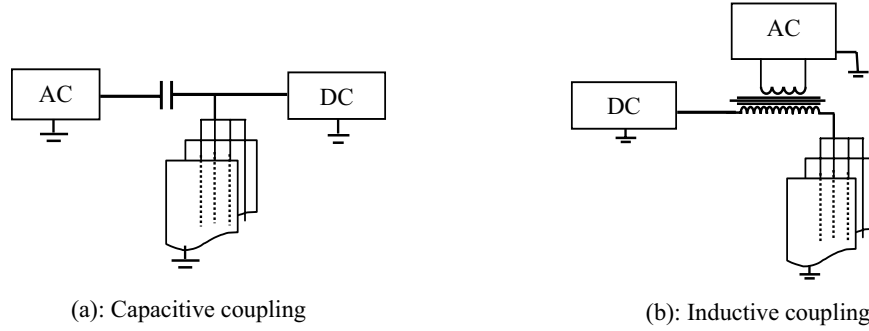


Fig.4. Typical circuit topologies for DC/AC energization.

For a HPPS system, the pulse duration should be designed in accordance with the primary streamer duration ΔT . Thus, a minimum peak voltage and a maximum duration ΔT become important to obtain the maximum energy transfer and at the same time to avoid secondary streamer development. Otherwise, the interaction between the power source and the reactor leads to either high-frequency oscillation or large energy transfer via secondary streamers. The total peak voltage V_t , the duration ΔT , the output voltage pulse V_p , and the impedance Z_{out} of the high-voltage pulse generator can be evaluated via the following equation.

$$P_{pulse} = f \cdot \frac{V_p \cdot V_t}{Z_{out}} \cdot \Delta T \quad (1)$$

where P_{pulse} and f are the average pulsed-power and the pulse repetition rate, respectively. For example, the output impedance Z_{out} and the V_p and V_t for the reactor shown in Fig.1 are designed to be around 20 Ω , 80 kV, and 110 kV, respectively.

With regard to the circuit in Fig.3, one may derive the following equations to evaluate the output energy per pulse, where V_{res} is the so-called residual voltage on the reactor after corona plasma quenching, V_{max} and V_{min} are the maximum and minimum voltages on C_h before and after pulsed-energization.

$$\frac{V_{min}}{V_{max}} = \frac{C_h}{8C_{dc} + C_h} + \frac{2C_{dc}}{8C_{dc} + C_h} \cdot \frac{V_{res} - V_{dc}}{V_{max}} \quad (2)$$

$$\varepsilon = \frac{C_h}{2} \cdot (V_{max}^2 - V_{min}^2) + \frac{C_h}{2} \cdot (V_{max} - V_{min}) \cdot V_{dc} - \frac{C_h^2}{8C_{dc}} \cdot (V_{max} - V_{min})^2 \quad (3)$$

Increasing the DC bias leads to reduce the minimum voltage V_{min} , and then increase the total output energy ε .

For the HPPS system in Fig.1, the voltage ratio of $\frac{V_{min}}{V_{max}}$ is designed to be about 7% - 12% for 10-30 kW average power at a pulse repetition rate of 1000 pps and a DC bias of 35 kV. Thus the total corona plasma power can be approximated as:

$$p = p_{dc} + p_{pulse} = \kappa \cdot V_{dc} \cdot (V_{dc} - V_c) + f \cdot \left[\frac{C_h}{2} \cdot (V_{max}^2 - V_{min}^2) + \frac{C_h}{2} \cdot (V_{max} - V_{min}) \cdot V_{dc} - \frac{C_h^2}{8C_{dc}} \cdot (V_{max} - V_{min})^2 \right] \quad (4)$$

where V_c is the DC corona onset voltage. In contrast to a conventional DC corona, in this case, the coefficient constant κ is also dependent on the pulsed energy transfer. The total power of the HPPS system consists of two parts. The first one is contributed by the DC corona; and the second is due to the pulsed energization. The DC bias source shown in Fig.3 is used to charge the coupling capacitor C_{dc} and to generate a DC corona plasma between pulses. Previous publications suggested that the DC bias should be below the onset voltage in order to avoid DC corona. In a HPPS system, however, the DC bias can be much higher than the onset but below the spark breakdown voltage. Our criteria are not to generate DC glow, but to generate DC onset streamer. In fact, when the first term dominates the total power, the system tends to a DC/AC corona plasma; when the second term becomes the dominant one, the system tends to be a pulsed corona plasma.

Bridging the electrode gap by a streamer does not necessarily lead to full spark breakdown. However, spark breakdown occurs only after streamer bridging the gap and a streamer channel, or Townsend like glow discharge, is formed. The time delay for the streamer-glow-spark transition ranges from 0.2 to 25 μs . When a pulsed corona plasma system is designed according to the proposed logical steps, full spark breakdown never

occur inside the reactor because no secondary streamers can be generated during first primary streamer propagation.

In contrast to the above ultra-short pulse, a DC/AC source may keep a long current flow when the streamer channel bridges the gap, and then lead to full spark breakdown. It seems that there is only one way to avoid the transition is that DC/AC plasma is generated below a maximum voltage, which can be approximated by the minimum voltage for streamer to bridge the gap. The plasma is indeed onset streamer discharge. The resulted drawback is limited plasma density per unit volume of the reactor. Fortunately, it is still high enough for air, flue and fuel gas cleaning.

4. Conclusions

Two types of corona plasma energization techniques have been developed for simultaneous and random streamer generations. For a HPPS system, a minimum peak voltage and maximum pulse duration should be applied for improving both the matching and the efficiency. For a DC/AC system, the applied voltage must be below a maximum for streamer not to bridge the gap. Either secondary streamer or full spark-breakdown will not occur due to a low applied voltage. The power source and the reactor can be designed as a single oscillator. Today, the data available are sufficient enough to scale both HPPS and DC/AC up for industrial applications, and at the same time, much more R&D activities are called of for industrial applications.

5. References

1. K. Yan, "Corona plasma generation", PhD Thesis, Technische Universiteit Eindhoven, The Netherlands, 2001, <http://alexandria.tue.nl/extra2/200142096.pdf>.
2. K. Yan, H.W.M. Smulders, P.A.A.F. Wouters, S. Kapora, S.A. Nair, E.J.M. van Heesch, P.C.T. van der Laan, and A.J.M. Pemen, "A novel circuit topology for pulsed power generation", *Journal of Electrostatics*, 58, (2003), 221-228.
3. G.J.J. Winands, K. Yan, S. A. Nair, A.J.M. Pemen, and E.J.M. van Heesch, "Evaluation of corona plasma techniques for industrial applications: HPPS and DC/AC systems", *Plasma Processes and Polymers*, Vol 2 (2005) 232-237.
4. Z.Liu, K. Yan, A.J.M. Pemen, S.A. Nair, G.J.J. Winands and E.J.M Van Heesch, "Synchronization of multiple spark-gap switches", submitted to *Journal of Electrostatics*, 2004.