SIMULATION STUDY OF A PULSED CORONA DISCHARGE BY MEANS AN ELECTRICAL MODEL

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Abstract

A model, structured as an equivalent electric circuit and its application in the simulation study of a pulsed corona discharge in the pre-arcing regime are presented. The discharge is actually produced within a coaxial cylinder reactor by means of a system based upon 1 kHz plasma discharges intended for water treatment. The proposed computational model takes into consideration the three main mechanisms of the process: (a) the relevant physical characteristics of water, (b) the ionisation and expansion phases in the spark channel, which includes the near-breakdown electric current generated by the change of the effective capacitance and resistance, and (c) the energy associated with this initial spark in the water. Considering this, a coaxial reactor and an inexpensive and compact high voltage pulsed power supply system were designed and constructed with the purpose of producing the pulse corona discharge experimentally. The coaxial reactor is constituted by a cylindrical chamber endowed with a straight central rod, the system operating within the 100-2000 Hz frequency and 0-30 kV amplitude ranges. The experimental outcome is compared with the simulation results in order to validate the model and to approach the evolution of the pulsed discharges experimentally observed. The measurement of the simulated discharge current turns to be fundamental in establishing the external networking requirements. This current value is also particularly useful to determine the design characteristics of water purification system components.

Keywords: Plasma modelling, pulsed corona discharge, streamer, plasma.

Presenting Author's biography

Samuel R. Barocio received his PhD degree in Physics from the University of Manchester, UK, in 1997. He has specialised in Plasma Physics modelling and data interpretation with particular interests in near integrable systems and frequency analysis.

1 Introduction

The removal of all those environmental pollutants which make an impact on the hydrologic cycle demand increasing concern and effort. Such contaminants can be as harmful as acid (SO_x, NO_x) and green house gases (CH_4, CO_2, N_2O), volatile organic compounds (VOCs) or the so called dangerous particles. Moreover, several processes have been specifically developed for microorganism disinfection and organic compound degradation in drinking water [1].

In the treatment of pollutants and in the eradication of microorganisms in water, some methods, such as advanced oxidation processes (AOPs) or electronic irradiation, have been regularly applied. Recent studies point to alternative water purification techniques, in particular, to the use of out of equilibrium plasmas at atmospheric pressure, generated by well regulated electric discharges [2].

Different methods exist to carry out the process of electric discharges in water; a) contact glow discharge electrolysis [3], b) dielectric barrier discharge [4] and c) pulsed corona discharge [5]. In each case, especially when the reactor geometry in non-uniform, it is probable that a streamer occurs which can generate some chemical species [6]. Several researchers report the effects on micro organisms of chemical species and radicals like O_2^- (super oxide), H_2O_2 (hydrogen peroxide), $OH^\bullet$ (hydroxyl radicals) and O_3 (ozone). These species react leading to lipid hyperoxidation, protein degeneration, enzyme inactivation and even DNA damage [4].

It is known that the development of inhomogeneous electric fields, sufficiently high to generate corona discharges in a liquid, acts as a powerful sterilizing agent. More specifically, high voltage pulses are required to this purpose, with a few ns rising times and pulse widths covering a range from ns to µs, to be applied between very close electrodes while avoiding falling into a spark breakdown.

Under laboratory conditions, pulsed corona discharges (PCDs) are able to create large quantities of energetic electrons which prove to be highly effective in destroying a wide range of biological species [7].

The present report deals with a description of the evolution of PCDs in dielectric media. It has been attempted by means of a model structured as an approximated equivalent electric circuit whose elements are identified and deducted from each one of the discharge stages and simulated by MATLAB/Simulink® software. Considering this, the reactor and a pulsed power supply (PPS) was constructed to carry out the PCDs experimentally. The approximation simulation results are compared to the PCDs experimental outcome in order to validate the model analysing the voltage and current waveforms.

2 Basis of the Pulsed Corona Discharge Model

Two main concepts of electrical breakdown in liquids are crucial in corona discharges: bubble and electronic processes. In the first case, a small volume in a liquid reaches the thermal vaporization threshold. A bubble will grow and the electric breakdown will take place. In the electronic process, breakdown is attained when the electrons, accelerated by the applied electric field, collide and ionise the medium [8]. These processes produce more free electrons generating nearly cylindrical channels of conductivity in the water (streamers). The characteristics of streamer depend on the electric field and, inherently, on the reactor configuration.

A coaxial reactor formed by a cylindrical chamber and a straight central rod anode (Fig. 1) has been proposed for the experimental requirements of the present study, as it allows to expose larger water volumes to the discharge while providing a greater homogeneity to it.

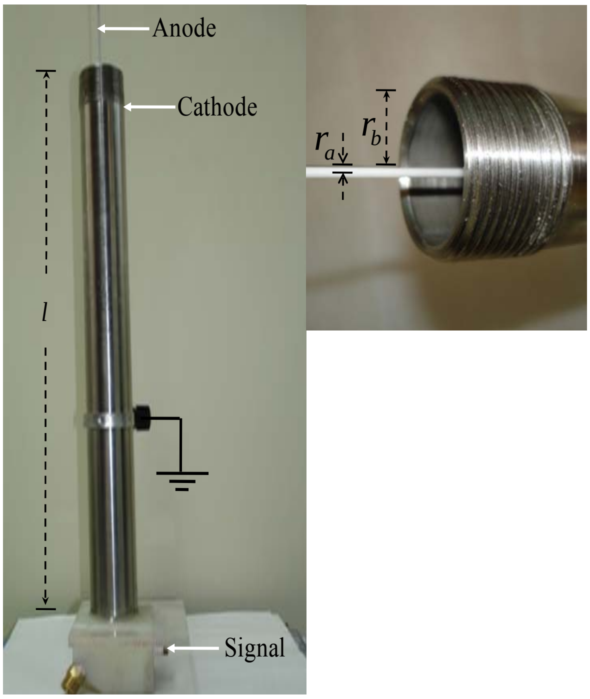

Fig. 1 The pulsed corona discharge reactor

The model evolution started from identifying the main electrical parameters of the discharge in water. These correspond to three basic mechanisms, represented in Fig. 2: (1) the medium electric response characterised by a resistance R_m and a capacitance C_m, (2) the streamer ionisation and expansion that develops into the pre-breakdown current described by resistance $R(t_s)$ and capacitance $C(t_s)$, and (3) the energy associated to the electric breakdown in water characterised by resistance R_b and channel inductance L_b [9].

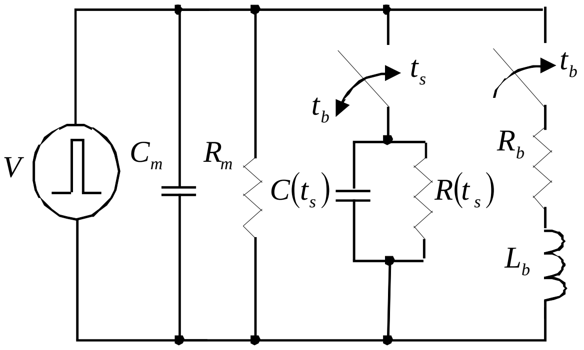

Fig. 2 The model simulating the medium properties, the streamer formation and the breakdown components

The electrode response is included in the nature of the medium, seen as the combination of resistance R_m and capacitance C_m. These elements are, in turn, a function of the conductivity σ_m and are given by [10]:

$$R_m = \frac{\ln(r_b/r_a)}{2\pi\,\sigma_m\, l} \tag{1}$$

$$C_m = \frac{2\pi\varepsilon l}{\ln(r_b/r_a)} \tag{2}$$

where r_a and r_b are the internal and external electrode radii respectively, l the reactor length, and ε is the medium absolute permittivity tantamount to the product of $\varepsilon_0\,\varepsilon_m$. Here ε_m is the water relative permittivity. According to the geometric characteristics of the built reactor, l =30 cm, r_a =0.25 mm and r_b =1.27 cm, and a water conductivity σ_m estimated in ~5µS cm^{-1}, the final values are R_m =4168 Ω and C_m =340 pF.

The second mechanism included is the pre-breakdown phase of the discharge, where, due to the application of high voltage pulses, small streamers cross from the rod electrode to the wall which acts as the outer electrode. The capacitance created between the streamer head and the wall behaves as an impedance limiter current through the initial streamer. The resistance of the gap between electrodes, $R(t_s)$, can be expressed by [11]:

$$R(t_s) = \frac{d_g}{n\,q\,\mu A_s} \tag{3}$$

where d_g, n, q, and μ are the gap, the density, charge and mobility, respectively. Considering that each streamer is a cylindrical conduction channel with constant radius r_s =100 µm [12]. A streamer is most probable to develop [13] when $n \approx n_e \approx 1\times 10^{26}$ m^{-3}, q =1.602×10^{-19} C and $\mu \approx 1\times 10^{-5}$ m^2/Vs. If the gap is d_g =1.245 cm and $A_s = \pi r_s^{\,2}$ then $R(t_s)$ =2474 Ω. Then, in order to avoid the streamer to collapse, the charge in the streamer channel should be $\sim 1\times 10^{-6}$ C m^{-1} [14] so that $C(t_s)$=0.5 pF.

As to the third mechanism, the formation of a broad conductive thermal gas channel can be detected by the occurrence of a spark and represented by the breakdown resistance R_b and inductance L_b. The parameter R_b is small (no greater than a few ohms) so that a high current can flow through the gap; this parameter can be calculated as [15]:

$$R_b = \frac{1}{\sigma_s}\frac{d_g}{\pi r_s^{\,2}} \tag{4}$$

Notice that highly ionised gas conductivity under the prevailing conditions can be approximated by $\sigma_s = 1.5\times 10^{-5}\,T^{3/2}$ [16], σ_s being given expressed in S cm^{-1}, and the gas temperature T in energy units conventionally transformed into K. Meanwhile, T is comparable to the average energy per discharge, in the order of ~ 2 eV [17]. Hence, the streamer temperature can be estimated to be in the order of 20,000 K, whereby we assume R_b =93 Ω.

The inductance L_b is the sum of the electromagnetic energy stored in the conduction channel and that of the electromagnetic field produced by the current that flows along the channel [15]:

$$L_b = \frac{\mu_0 d_g}{2\pi}\left[\frac{1}{4} + \ln\left(\frac{d_f}{r_s}\right)\right] \tag{5}$$

where μ_0 is the vacuum magnetic permeability and d_f is the maximum characteristic distance from the spark to the nearest null electromagnetic field point within the system. In our case d_f is the reactor length, so that L_b =20.5 nH.

Finally, the pre-breakdown lifetime, t_s, can be estimated by $d_g = \upsilon_d\, t_s$ [11] where υ_d is the streamer velocity which can be assumed as constant and in the order of the electron velocity 30×10^3 ms^{-1} [8], so that t_s =400 ns.

3 Main Results and Discussion

Fig. 3 portrays the excitation circuit and the general model of the reactor where each one of the discharge stages is shown. These have been simulated on MATLAB/Simulink® software. The pulse transformer operates in the general circuit at a 1:50 rate and it is biased by a DC power supply adjusted from 0 to 600 V. The latter is powered by means of a three-phase source, while an insulated gate bipolar transistor

(IGBT) excited by a gate driver, was selected for the commutation process implementing a flyback converter. This is associated with a freewheeling (or flyback) diode, and the load is played by the model electrical elements previously calculated. This whole electric system delivers high voltage short pulses whose duration can be adjusted by means of the gate driver of the circuit. The times t_s and t_b are activated sequentially by generators at each discharge stage.

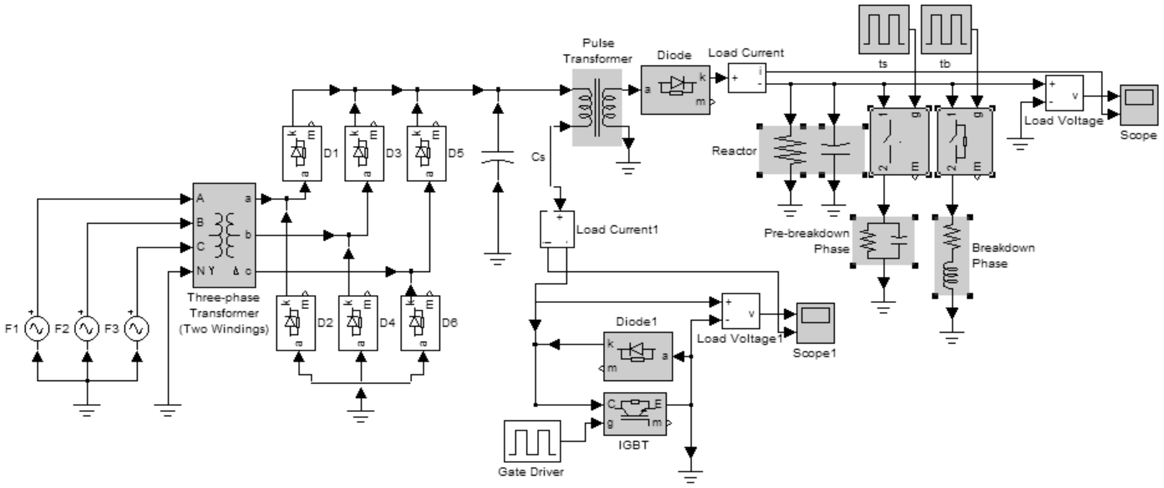

Fig. 3 Proposed circuit for PCD simulation

All in all, we present in the first place the results obtained when considering in the model just the physical parameters of the system (mechanism 1). The respective voltage and current waveforms from the simulation on Simulink™ are presented in Fig. 4. The voltage waveform presents a lag with respect to the current waveform which is a typically capacitive behaviour due the capacitance C_m . Fig. 5 exhibits the voltage and current waveforms, respectively, obtained from the experimental performance. The voltage was measured by means of a TDS 2024 Tektronix oscilloscope and a P6015A HV probe. The current was gauged by a Rogowski coil with a 1 V/1 A resolution.

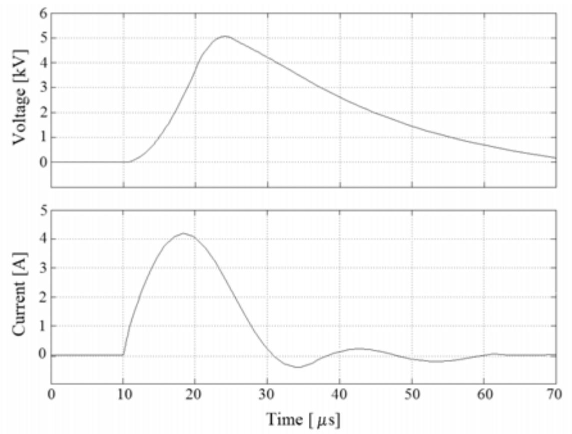

Fig. 4 Waveforms from the load after the application of a pulse when considering just the physical parameters of the system on a Simulink™ recreation

The experimental waveform evolution seen in Fig 5 is closely approximated by the predicted evolution shown in Fig. 4. These initial experiments were carried out without water in the reactor, although in similar conditions to the simulated characteristics. The experimental outcome seems to be in good accordance with the simulation, namely, HV pulses in order of ~5 kV and current ~4 A peak to peak. This concerns not only the shape but also the amplitude of each waveform. However, in order to validate our proposed model, all the calculated parametric data should be consider in the simulations and then the pulsed discharges in water should be carried out.

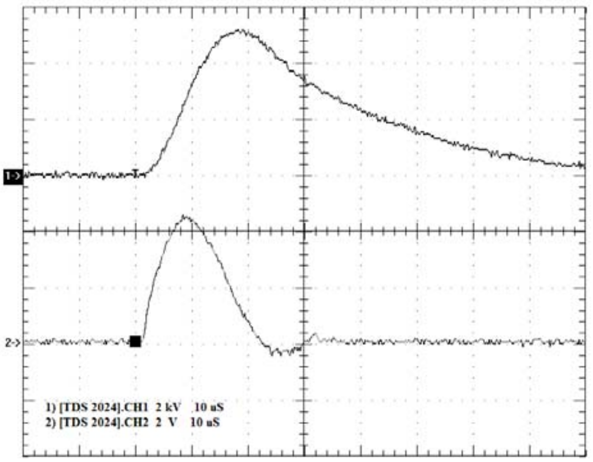

Fig. 5 Typical voltage and current waveforms experimentally measured when a pulse is applied in the reactor

Fig. 6 exhibits the waveforms obtained from the simulation when the full model is applied. These waveforms are generated on the load. The HV pulses are in the order of 15 kV and a ~7 A peak to peak maximum current is reached. Then, Fig. 7 shows the experimental voltage and current traces obtained while the power supply is connected to the discharge reactor.

The voltage presents an ~15 kV amplitude while the current attains an ~7 A peak to peak.

The current is an important parameter because it couples the process inside the discharge volume to the external electric circuit. The current amplitude and its waveform are also important for a first qualification of the discharge, mainly whether it is a full or partial breakdown. It follows from the current waveform that the arc is not generated in the reactor when the pulse is applied, provided that there is no current excess in this waveform. Notice that the current tends to be maximised when the voltage precipitates, until equilibrium is settled.

This simulation study indicates that the discharge properties depend strongly on the input voltage characteristics, i.e., voltage strength, pulse width and rise time. It is also observed that a corona discharge can be created without any accompanying arc breakdown by appropriately selecting the voltage pulse parameters, mainly the pulse duration, for a given reactor geometry.

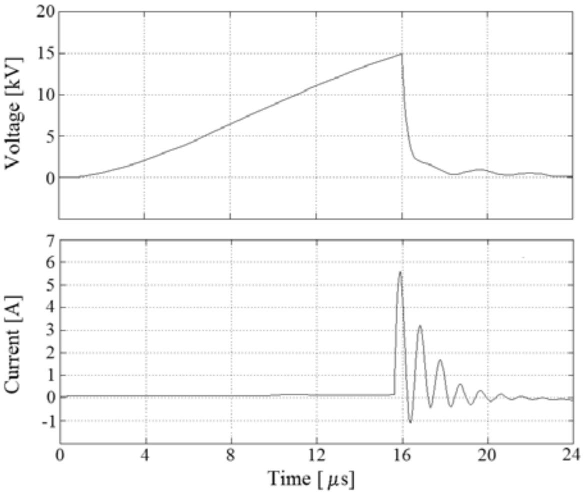

Fig. 6 Full model waveforms from the load in the simulated circuit

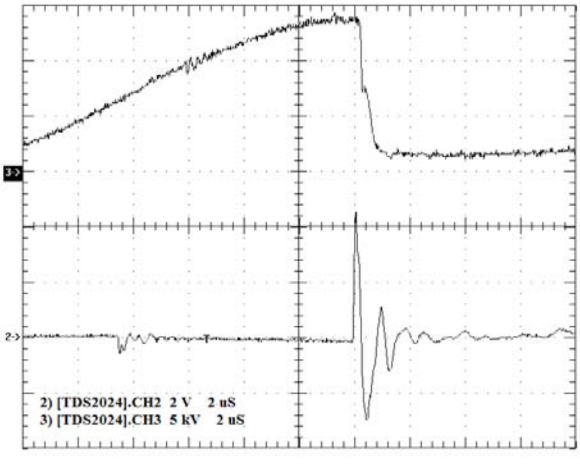

Fig. 7 Typical voltage and current waveforms measured during a corona discharge. A 15 kV breakdown voltage and a peak to peak 7 A top discharge current can be observed

4 Conclusions

An electric circuit which replicates all the main features of a pulsed corona plasma discharge conducted in a cylindrical coaxial reactor has been developed and experimentally validated. Thus, it has been proven that a particular discharge behaviour can be prefigured by the elements of an electric network, provided that the experimental set up operates within the 100-2000 Hz repetition rate range with a 1-30 μs pulse width and 0-30 kV amplitudes.

The considerable accuracy of the simulation predictions of discharge form, structure and propagation can be attributed to the particularisation of each experiment by taking into consideration its own pre-breakdown process and its breakdown mechanisms as well as determining the relevant parameters for each phase.

These achievements can contribute to a better understanding of corona discharge water purification with an emphasis on the generation of chemical species, which have proven to be especially effective both in water and some non homogeneous media.

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