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Total Variation Diminishing technique in numerical simulation of Trichel corona in air

Kazimierz Adamiak*, Anatoly Malevanets

Department of Electrical and Computer Engineering, Western University, London, Ontario, Canada

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ABSTRACT

This paper deals with the numerical simulation of the Trichel pulse corona discharge in air under the room temperature and atmospheric pressure in the pin-plane configuration. A simplified drift-diffusion model of the discharge is considered with three species: electrons, positive and negative ions. The Total Variation Diminishing algorithm is used to stabilize the charge transport equations. The effect of the voltage level and the external circuit parameters on the average corona current, pulse frequency and pulse parameters are presented. The results of numerical predictions are compared with the experimental data.

1. Introduction

The Trichel pulse mode of the corona discharge can be observed in some electronegative gases only (for example air or oxygen) and it consists of a regular train of very steep and very short pulses followed by much longer inter-pulse period. While the practical significance of this kind of discharge is limited, it has attracted attention of many researchers, who have tried to clarify the intriguing mechanism of this phenomenon.

The first observation of these pulses dated back to the works of L.B. Loeb's research group [1] – it earned its discoverer, G.W. Trichel, not only a doctorate, but also a permanent name in the history of gas discharges. Obtained by him oscillograms of the discharge current revealed discrete pulses in the discharge current with the magnitude and frequency related to the average current, the discharge electrode curvature and the gas pressure [1]. On the other side, the pulse frequency was apparently independent on the gap length, if the corona current was kept constant, and on the parameters of the external electric circuit. At increased voltages the pulse shape remained constant, but the trailing edge of the pulses was interrupted at higher and higher values, as the impulses approach each other. Because the pulse frequency was not a function of the air gap length, the author speculated, that the pulses resulted from the transport of positive ions near the discharge electrode. At voltages just above the onset level, but below some critical value, the pulses were random and irregular.

Subsequent experimental data reported by Loeb et al. [2] confirmed that the pulse frequency rapidly increases with the supply voltage, rising up to a few hundred kHz. Moreover, the details of the original explanation of the discharge mechanism had been slightly revised. The new model stressed the importance of the slow negative ions, which can quench the discharge – this is why the pulse mode was observed in electronegative gases only. This problem was also thoroughly studied in the early works of Weissler, who investigated both positive and negative discharges in pure gases and their mixtures [3]. Trichel pulses were not observed in pure hydrogen, nitrogen or argon. However, small traces of oxygen in any of these gases resulted in the pulse corona generation.

The negative ions don't need to be completely removed from the air gap – it is sufficient if they become "ineffective", which means that they should move sufficiently far from the discharge point. Therefore at high frequencies, many clouds of the negative space charge can be present in the air gap at the same time. It has also been noticed that the regular pulses were not observed for extremely sharp electrodes and for very clean gases; regular pulses were obtained if the radius of curvature of the sharp electrode was bigger than 20 μm; below this value the current waveform was irregular, without a clearly defined fundamental frequency. The authors also hypothesised that small surface imperfections are necessary for the regular pulses to occur, as the discharge needs to be initialized from a single active spot, smaller than 0.2 μm in diameter. For larger discharge areas, a few discharge spots can exist, each producing independent pulses. It has also been discovered that the electrode material has no effect on the pulse formation,

* Corresponding author.
E-mail address: kadamiak@eng.uwo.ca (K. Adamiak).

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which apparently contradicted Trichel's hypothesis that the secondary emission of electrons, caused by the impact of positive ions, triggers subsequent pulses. Loeb and his co-authors concluded that there must be more than just one means for generating triggering electrons: field emission, UV light and other effects.

Even more surprising results were obtained in clean dry air. The Trichel pulses were still formed, but they were irregular both in terms of magnitude and frequency. A detailed study of the surface smoothness and the presence of particles clearly proved that “the presence of fine particles on the tip of the point is a necessary condition for the appearance of Trichel pulses” [2].

English was the first one to be able to record the pulse waveform [4]. He noticed that the Trichel pulses at different voltage levels preserve their shape, but change the amplitude. The corona current in his experiments was sometimes erratic: at the same voltage level it would suddenly decrease or increase. These changes, or “modes”, were always accompanied by frequency and amplitude change, but also by relocation of the corona discharge point.

All these preliminary observations have been confirmed later by Asinovskii et al. [5]. While at lower voltages the corona discharge is localized near one point on the discharge electrode, at higher voltages a few different points appear. One of Asinovskii's experiments identified seven discharge points with seven series of Trichel pulses: each of them having a stable amplitude and frequency.

A systematic experimental investigation of Trichel pulses in air was carried out by Lama and Gallo [6], who aimed to find a relationship between the pulse parameters (frequency, average current and charge per pulse) and the supply voltage for different point radii and air gap lengths. The pulse details (rise time, width and fall time) were not determined. The relationship between the average current and the pulse frequency was linear regardless on the electrode radius, which proved that charge per pulse is always constant. Numerical interpolation of the experimental points led the authors to a conclusion that the pulse frequency is inversely proportional to the square of the electrode spacing and the sharp electrode radius of curvature, and proportional to $V(V-V_0)$, where V is the supply voltage and V_0 – corona onset level. On the other side, the average corona current is inversely proportional to the square of the electrode spacing, but practically independent on the corona point radius.

The experimental observations also allowed Lama and Gallo to do an interesting analysis of the transit time (time required by the negative ions to drift across the air gap), the number of ion clouds simultaneously present in the air gap, the total electric charge in the air gap and the relationship between the pulse frequency and the clearing length (a distance which the negative ions have to move before the next pulse may be generated). Near the corona onset, the negative charges must be completely removed from the air gap before the next pulse can be triggered, so only one ion cloud can be present. At higher voltages, the Trichel pulse period is much shorter that the transit time and many ion clouds are present in the air gap. The cloud separations are non-uniform: they have the maximum value near the corona electrode and decrease moving towards the ground plane.

While earlier works on the Trichel pulse formation didn't consider any chemistry of ionic reactions, Gardiner and Craggs [7,8] have shown that the ion conversion should be taken into account in calculation the drift time of the negative ion cloud, which affects the pulse frequency. By sampling of ions from the discharge area and evaluating their mass in a quadrupole mass filter, Gravendeel and de Hoog showed that the negative ions cluster with water molecules [9].

At higher gas pressures the Trichel pulses have a relatively simple form. However, depending on the gas pressure and the pin sharpness the pulses may be much more complicated, with additional humps on the leading and trailing edges of a pulse. Scott and Haddad investigated these humps for different tip diameters, gas pressures and voltages [10]. Experiments with gas mixtures involving oxygen, nitrogen and argon revealed that the gas composition also affects the pulse shape. However, while argon plays just a passive role, nitrogen actively participates in the process affecting the pulse shape [11]. The experiments of Cernak and Hosokawa, carried out in carbon monoxide at 13.33 kPa, lead them to a theory that the hump on the leading edge is caused by the cathode photoemission enhanced by the formation of the ionization wave towards the cathode. The second hump on the current waveform is due to the secondary electron emission caused by the impact of positive ions [12].

Earlier experiments with the Trichel corona discharge seem to indicate that at increased voltages the pulses are followed by a spark discharge. However, Akishev et al. showed that in some situations a glow discharge can be observed [13,14]. Under normal conditions, an increased electric field reaches a critical value when the ionization layer extends to the entire air gap. Any ionization instability at these conditions triggers the spark discharge. Some special techniques, for example external gas flow, allow for preventing the ionization instability. The same authors also suggested some techniques for controlling the pulse shape and magnitude, for example, by using different shapes of the discharge point or different dielectric shields near the discharge area. The negative glow discharge was also reported in Ref. [15].

Recent years have brought another series of experimental studies related to different aspects of Trichel pulses – they were carried out mostly at reduced air pressures, when the pulse dynamics is much slower. The results published in Ref. [16] indicated that for low pressures (8–12 Torr) three different modes can be identified: the pulseless pre-charge, the Trichel pulse and the glow modes. A relatively long rise time of the pulse allowed recording discharge images and emission spectra at different stages of the pulse formation, which contributed to a better understanding of the process [17].

Statistical fluctuations of the Trichel pulses in air for just one electrode spacing and variable voltages were discussed in Ref. [18]. An apparent mode transition for the pulse frequency and magnitude may be related to relocation of the discharge port, previously reported by English [4] and Asinovskii et al. [5]. A detailed investigation of this problem was presented by Amirov et al. [19], who observed that the discharge pin topography may have a dramatic effect on the pulse characteristics. After many experiments with different cathode materials and radii of curvature, they concluded that the pulse frequency and amplitude remains the same, if the discharge spot is fixed. The pulse amplitude depends on the cathode local radii of curvature, but jumping of the discharge spot from one point to another is not a sufficient condition for changing the pulse parameters. They may remain the same, if the surface properties in a new position are the same. A local variation of the surface properties caused by oxidation or erosion, which varies more often for the cathodes with a larger radii of curvature, affect the secondary emission coefficient, so when the discharge spot wanders to such a point, the pulse parameters may vary.

The results reported in Ref. [20] mostly concentrate of electromagnetic radiation generated by the Trichel pulses, which may be a significant source of the electromagnetic interference. In addition, characteristics of the corona discharge in the point-plane and wire-plate configurations were studied. While the pulse frequency and magnitude strongly depend on the voltage and the gap configuration, the pulse rise time is very similar regardless of the gas pressure, voltage or gap length. However, after changing the point diameter from 100 to 400 μm, the rise time changes from 17 to 36 ns Similar results were obtained by Zhang et al., who noticed