Breakdown in mm-sized discharges : discharge formation under high-frequency AC voltage

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High-frequency AC breakdown covers a broad range of frequencies. The breakdown process in not the same in the whole frequency range, and the most attention has historically been given to low-frequency end where there is at least one breakdown per half voltage cycle, and to the high-frequency end, where the electron energy cannot follow the changes in electric field. The mid-range, although it has been proven as technologically important, has not been extensively studied. The aim of this project was to examine the breakdown process in near-atmospheric pressure argon and xenon in an enclosed pin-pin geometry. The work was focused on 0.3 and 0.7 bar discharges in 4 mm and 7 mm gas gaps. The driving frequency was varied between 60 kHz and 1 MHz. We present several key features of breakdown in this combination of pressure, gap length and voltage frequency.

1. Introduction

Formation of micro- and millimeter sized discharges under the influence of high-frequency AC voltage is of interest for a growing number of applications. In the design of circuit boards and similar systems employing high-power semiconductors, HF (High-Frequency) AC surface discharges are of importance because they cause damage to the dielectric substrates. Partial discharges in partial vacuum are sources of danger in aerospace technology. On the bright side, high-frequency AC discharges are used in material processing to create glow discharges at atmospheric pressures and in lighting industry for easier lamp ignition.

The research of high-frequency AC discharges that are still under the MHz range has been neglected over the years, as being the transitional stage between the AC regime where a discharge is formed in every voltage cycle and the regime where the electrons cannot follow the rate at which the electric field changes. Both of these extremes have been well researched, but the transitional frequency range is still rather unknown. Yet, there have been reports of significant lowering of the minimum breakdown voltage when AC voltage of this frequency range was used, which is an important feature to keep control over. There have been attempts of explaining this observation, however they were insufficient in many cases.

This research deals precisely with this type of breakdown. The frequency of the voltage is low enough to ensure that electron energy can follow its change, which is not true for the heavy charged particles. The electrode gap is such that is ensures that the average drift distance of electrons in one half voltage cycle is significantly greater than the electrode gap, and therefore the electron losses are drift-dominated. The drift distance of the ions is much smaller than the electrode gap.

The project consisted of two parts. The experiments were done in the frequency range between 60 kHz and 1 MHz in argon and xenon at near-atmospheric pressure. The electrode gaps in the experiments were either 4 or 7 mm, and this particular combination of gas pressure, electrode gap and driving frequency positioned our experimental conditions in the high-frequency range where the electron losses were high and drift-dominated. The experiments were done in two ways - by monitoring the breakdown voltage and by the imaging of the process, using an iCCD camera. Numerical simulations were also performed, using a 2-D fluid model, to help explain the effects observed in the experiments. The work brings observations, results of the numerical model and a detailed analysis that leads to the interpretation of the main processes in breakdown processes in this frequency range.

2. Results and discussion

The experimental setup was fully described in [1], and the model in [2].

This research had several goals - to measure the effect of high-frequency AC voltage on the breakdown process and to explain the observed with the help of numerical simulations. In particular, we addressed the timing of the discharge, its appearance, the fact that it needs more than one voltage cycle to form, the influence of the voltage frequency, and perhaps most importantly, the reason why AC breakdown in this frequency range is possible at such low voltages.

The timing of the discharge was found to be quite long - the visible part of the breakdown process took up to 100 μs, which translates to about 100 voltage cycles. Not all the discharges took such a long time to form, and the number of cycles depends on the voltage frequency. The general rule is that the increase in the driving frequency requires more voltage cycles and more time.

The appearance of the breakdown process changed with the driving frequency. At 60 kHz, the breakdown process featured streamer-like structures, which crossed the electrode gap in a fraction of a voltage cycle, most often at the local extreme of the driving voltage. Already at 400 kHz, the discharge was completely diffuse and it took multiple voltage cycles to cross the electrode gap, for the same gap length and gas pressure.

The measurements of breakdown voltage revealed that 0.3 bar discharges ignite at lower voltage than the 0.7 bar discharges, which is well known already from pulsed breakdown, and easy to explain. Also, breakdown in argon was shown to be possible at lower voltage than in xenon and the minimum voltage needed for breakdown decreases with the increase of the driving frequency.

We have found that the differences between the minimum breakdown voltage for discharges in the two different gasses are for the most part caused by the difference in size of the two gas atoms. Xenon, being much larger than argon, has roughly twice as big collision frequency with the free electrons in the gas, at the same pressure. This causes the electrons to lose energy more efficiently in xenon. Consequently, the mean electron energy is lower in xenon than in argon for the same pressure and electric field, which makes up for the fact that xenon has lower lying metastable and ionization level.

With the help of numerical simulations of 0.7 bar discharges in argon, we were able to reproduce the observed in experiments - the low breakdown voltage when AC signal is used, the long formation time, the formation over several voltage cycles and the decrease of the breakdown voltage with the increase of the driving frequency.

The reason for the very low minimum breakdown voltage when discharges in this frequency range are concerned was shown to be different than what was previously suggested. The previously existing theory about high frequency-limited electron drift losses proved to be insignificant in our case. The drift distance of electrons in one half voltage cycle was significantly bigger than the electrode gap in every pressure, gap length and frequency we used. Therefore, changing the frequency could not limit the electron drift losses in a measure so large that it could change the breakdown voltage with the changing of frequency.

Another theory was that due to the polarity oscillations, there is ion density build-up in the electrode gap, that ultimately grows to such a value to be able to start a streamer-like discharge that crosses the electrode gap. Streamers were not observed in high frequencies, no light emission was observed from the electrode gap that would suggest piling up of charge and the simulations have not shown anything resembling this. Therefore, this was not a relevant effect in our discharges.

An important aspect of AC breakdown in this frequency range is that there is indeed charge build-up over several voltage cycles, but this takes place at the electrode tips, where the charge is originally produced. As most electrons can drift away during one half-period, this charge mainly consists of ions that are too heavy to drift away before the polarity changes. In fact, the polarity change is the key feature of AC breakdown, because it causes the ions to oscillate around the electrode tips. The ions created in one half cycle at the electrode tips strike the same electrode during the next half-period, causing secondary electron emission, effectively rising the source term for the electrons to the level above the one conditioned by collisional processes. The secondary electron emission by molecular ion impact was identified as the most important, and the coefficient was set to 0.04.

This means that the minimum breakdown voltage is governed by electron drift losses, the electron source term coming from the secondary electron emission from electrode surface and the source term coming from the collisional processes. For a bigger source term coming from the secondary electron emission, a lower source term coming from the collisional processes is required for the same net electron production. This source term depends on the local electric field, which is at the beginning stages of the breakdown process completely governed by the electrodes. Therefore, the fact that fast enough polarity changes allow for efficient secondary electron emission causes the necessary voltage across the electrodes to be lower. This is why the minimum breakdown voltage is lower for high-frequency AC discharges when compared to pulsed, DC or low-frequency discharges.

This research was done in a specific, enclosed pin-pin geometry, in near-atmospheric pressure noble gasses. The analysis of the experimental and numerical results show that this is indeed a type of breakdown process that marks the transition from pulse-like and low-frequency AC, which features streamers and single polarity discharges, to a regime where ions start playing an important role in the process and can to a large degree determine the characteristics of the discharge. For a much more complete analysis and discussion, we would like to refer you to the full experimental [1] and modelling [2] paper.

References

[1] A Sobota, J H M Kanters, F Manders, M F Gendre, J Hendriks, E M van Veldhuizen and M Haverlag, J. Phys. D: Appl. Phys. 44 (2011) 224002

[2] A Sobota, J van Dijk and M Haverlag, J. Phys. D: Appl. Phys. 44 (2011) 224003