Power dissipation and time of breakdown in AC discharge of argon at a low pressure in the frequency range 5-10 kHz

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Abstract

The influence of 5-10 kHz audio frequency on the power dissipation in ac discharge of argon gas was studied experimentally, at pressures 50-80 mTorr and electrodes separation 10 cm (pd range 0.5-0.8 Torr. cm). The measurements have shown that the discharge behavior in the ac circuit is equivalent to a series RC circuit. It is observed that the variation curve of discharge power P with the frequency f is approximately has a Gaussian shape. It is also observed that the curve of P_m- pd is the inverse of Paschen curve, where P_m is the maximum power in the frequency range. The time of breakdown is estimated from the curve of P- f.

Key words

time of breakdown, low pressure ac discharge, argon ac discharge،
Power dissipation in ac discharge.

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القدرة المبددة وزمن الانهيار الكهربائي عند التفريغ بالتيار المتناوب في غاز الاركون عند ضغط واطئ وضمن الترددات 5-10 kHz

احمد يونس عويد

قسم التقنيات الالكترونية ، المعهد التقني الموصل

الخلاصة

تناولت هذه الدراسة التجريبية تأثير الترددات الصوتية 5-10 kHz للتيار المتناوب في القدرة المبددة خلال التفريغ بالتيار المتناوب في غاز الاركون، عند الضغوط 50-80 mTorr والمسافة الفاصلة بين القطبين 10 cm (عند مدى pd 0.5-0.8 Torr. cm). كشفت القياسات أن منظومة التفريغ تتصرف في دائرة التيار المتناوب بشكل مكافئي لدائرة مقاومة ومتسعة على التوالي. لقد لوحظ بان منحني تغير قدرة التفريغ P مع التردد f مقارب للشكل الكاوسي. لقد لوحظ أيضا أن منحني P_m- pd هو معكوس منحني باشن (Paschen curve)، حيث أن P_m هي أعظم قدرة للتفريغ خلال مدى الترددات المذكورة. إن زمن التفريغ الكهربائي تم تخمينه من خلال منحني P - f.

Introduction

The study of electrical breakdown in gases provides useful information about discharge parameters, which are very significant in plasma applications. From the previous recent studies of discharges, there are well known facts available. The most important breakdown characteristic is the electrical breakdown time delay, which can be expressed as the sum of the statistical time delay and the formative time delay [1, 2]. During breakdown process, most of the positive ions are produced near the anode [3,4]. The transit time of the positive ions between discharge electrodes can be used to estimate the time needed to sustain the discharge [4]. The drift velocity of electrons and ions depend, on the value of the reduced electric field E/p [4,5]. There are different spatial regions present in dc glow discharges at low pressures [6]. These regions have a characteristic value of electric field and potential.

For audio frequency ac discharge, the breakdown voltage of a gas is a function of ac frequency [7-10]. It has been also found that ac breakdown depends on the transit time of the ions, T/2 of the ac potential, and the dark current [7,8]. The micro processes (collisions of particles) of audio frequency ac discharges have been assumed to be almost similar to those of dc discharges[1,4]. This has hindered the studding of these discharges in a view of the fact that such discharges need special experimental equipment. The aim of the present work is to further demonstrate the behavior of low pressure argon discharge excited by ac frequency of the range 5-10 kHz.

Experimental details

The experimental arrangement is shown in Fig.1. The discharge chamber is a 10 cm length and 8 cm diameter glass tube. O-rings are fitted to the two aluminum disk electrodes at the two ends of the chamber. The sinusoidal high discharge voltage waveform is initiated by a sinusoidal audio frequency oscillator. The output of the oscillator is applied to an audio frequency power amplifier (Tellewatt E120). The amplified output is then fed into a custom made step-up transformer capable of supplying up to 750 V_p and 20 mA_p from the first secondary coil L2 and up to 10 V_p, and 50 mA_p from the second secondary coil L3 in the frequency range of 0.1 kHz to 20 kHz. L3 is used for voltage sampling. The transformer turns ratio is $N_{L1}/N_{L2} \approx 2500/10000$ and $NL1/N_{L3} \approx 2500/50$. The discharge current sampling is measured through the voltage measurement across the series resistance R1 (510 Ω). The ac discharge I-V loop shown on the oscilloscope screen was captured using an accurately aligned digital camera. The captured pictures are used in the further analysis.

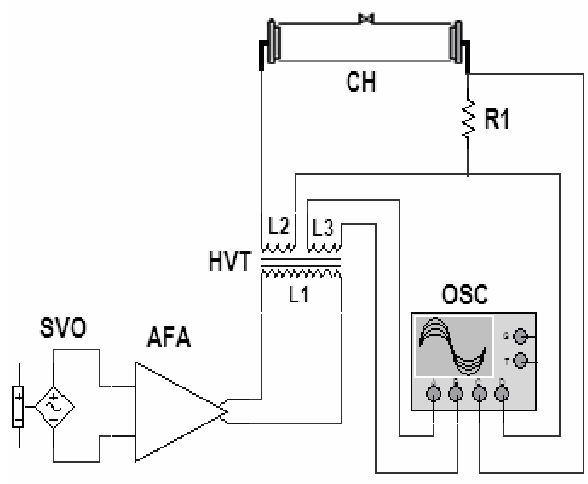

Fig.1: Schematic of the experimental set-up. where (SVO), sine voltage oscillator, (AFA), audio frequency amplifier, (HVT), high voltage transformer, (CH), discharge chamber and (OSC), dual-channel oscilloscope.

Measurements are carried out at four discharge pressures near the Paschen minimum [11]. These pressures are 50, 60, 70, and 80 mTorr. The voltage applied to the discharge tube is fixed at 400 V_p. The ac discharge I-V loops signals are applied to the oscilloscope. Digital pictures of these loops at 11 frequency values in the range of 5-10 kHz are taken. These digital pictures are converted to numerical data using a Matlab image processing program [12, 13].

Results and discussion

1-Changing the time of discharge with ac frequency

The root mean square value of ac voltage (V_{rms}) which is needed to cause breakdown of the argon gas at pressures 50-80 mTorr with 10 cm electrodes separation is on average $V_{rms}=V_{bk}\times1.414 \approx 260$V (where V_{bk} is the DC breakdown voltage and V_{bk}=180 V) [9-11]. This voltage value can be considered for frequencies from 5 to 10 kHz due to the fact that the change in ac breakdown voltage with frequency in this range is small and can be eliminated [7]. The ac peak voltage (V_o) used in this study is 400V. Thus, during each half cycle, we have specified time interval tg during which glow discharge or at least breakdown may take place. This correspond to situations when the applied voltage is $V>V_{bk}$. The time interval td during which $V<V_{bk}$ is associated with dark discharge.

The time at which the breakdown process is starting (t_s) is given by;

$$V = V_o \sin(2\pi ft) \rightarrow t_s = \frac{\sin^{-1}\left(\frac{V_{rms}}{V_o}\right)}{2\pi f} \qquad (1)$$

The relation between the time of a half period $T_{1/2}$ and the frequency f of a sine wave voltage is $T_{1/2}=1/2f$. Therefore, the time tg is given by [9]:

$$t_g = 2\left(\frac{T}{4} - t_s\right) \rightarrow t_g = \frac{\left(\frac{1}{2} - \frac{\sin^{-1}\left(\frac{V_{rms}}{V_o}\right)}{\pi}\right)}{f} \rightarrow t_g \approx 0.27/f \qquad (2)$$

and the remaining time is:

$$t_d = \frac{T}{2} - t_g \rightarrow t_d = \frac{\sin^{-1}\left(\frac{V_{rms}}{V_o}\right)}{\pi f} \rightarrow t_d \approx 0.23/f \qquad (3)$$

It is clear that $T_{1/2}$=tg+td, and there are two discharge modes (high and low current modes) at each half period of the discharge sine voltage.

2-Changing the carnal parameters of the discharge with ac frequency

The full breakdown process of gases takes typically 0.01 msec or more at low pressures [4,5]. For the frequency range 5-10 kHz, the range of the time tg is 27 - 54 μsec and that of the time td is 23-46 μsec. Thus, it is expected that there is enough time to breakdown the argon gas at all frequencies in the range 5-10 kHz.

In argon plasma the loss of the charge particles afterglow is due to the volume recombination and diffusion decay [4,5]. The diffusion loss depends on the characteristic size of the chamber and takes much more than 1 msec for 8 cm characteristic size [1,4,5]. The valuable loss of volume recombination needs at least 1 msec [4,5]. Therefore, these mechanisms have long time compared to the time td of the frequency range. Thus, the loss of charge particles can be ignored during the time td.

At $V_{rms}\approx260$ V and pd≈0.5-0.8 Torr.cm, the reduced electric field (V_{rms}/pd) range is 322-516 $V.Torr^{-1}.cm^{-1}$. The corresponding range of drift speed of ions and electrons is 150-175 $m.sec^{-1}$ and $(2\text{-}3)\times10^5$ $m.sec^{-1}$ respectively [5]. Therefore, the range of transit time of charge particles between the discharge electrodes is 570-670 μsec for ions and 0.33-0.5 μsec for electrons. The electrons have very short transit time and can be transferred between the electrodes during the time tg at all frequencies in the range. The positive ions have long transit time compared to the time tg. Therefore, the ions can not be transferred between the electrodes during the time tg of the working frequency range.

3-Changing the waveform of discharge current with ac frequency

In the frequency range 5-10 kHz, it is clear that $tg \ll t_{id}$, where t_{id} is the positive ions transit time between discharge electrodes. Therefore, most of the positive ions which produced during breakdown process stay near the anode during the short time td, when the electrodes changed their polarities. During the time tg of the second half of ac voltage the ions drift to the adjacent cathode and released electrons (secondary electrons emission). At the same time the secondary electrons drift to the anode to produce new positive ions. Therefore, consequently there is charge to the space near the anode and discharge at the cathode during each cycle of the discharge ac voltage. Fig.2 shows the images of the discharge current waveforms at pressure 50 mTorr for frequencies from 5 to 10 kHz.

It is fairly evident that the shape of the sine waveform of the discharge current is unaffected by the varying of ac frequency, while the amplitude is changed. This means that the discharge behavior is equivalent to a series RC circuit because of, consequently there is charge and discharge near the electrodes during each cycle of the discharge ac voltage (i.e. the space near the electrodes equivalent to a capacitance while the discharge bulk equivalent to a resistance).

4-Changing the discharge power with ac frequency

In the frequency range 5-10 kHz, when the time tg is greater than the time of breakdown t_B, the positive ions have short time $(tg-t_B)<<t_{id}$ to drift to a short distance S away from the anode. The distance S is given by:

$$S=(t_g-t_B)\times v_{id}\approx(\frac{0.27}{f}-t_B)\times v_{id} \qquad (4)$$

where v_{id} is the positive ions drift velocity. The charge particles when drift to the electrodes will confront electric resistance (collisions) that depends on the distance S which depends in turn on the frequency of ac voltage.

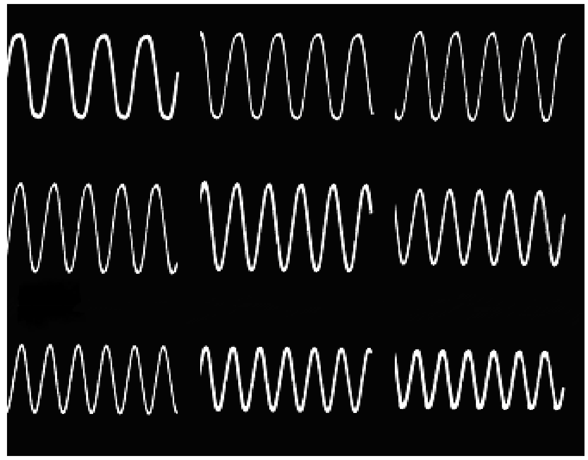

Fig.2: Discharge current waveforms for frequencies 5,5.5,….,9.5 kHz, at pressure 50 mTorr.

The drift velocity of ions and the distance S are also changed with gas pressure. The discharge current amplitude will increase when the time $(tg-t_B>0)$ is decreased. Therefore, it can be deduced that:

1- There is a specific frequency f_{mp} which has $tg=t_B$, minimum discharge resistance and maximum discharge current and power.

2- Concerning the frequencies $f<f_{mp}$, $tg>t_B$, the discharge current, and power, they increase as the frequency is increased.

3- For frequencies $f>f_{mp}$, $tg<t_B$, the discharge current, and power, they decrease as the frequency is increased.

This means that the power-frequency curve of the discharge in the frequency range f_1 - f_{mp}- f_2 has approximately a Gaussian shape, where $f_1 < f_{mp}< f_2$. Therefore, the time t_B can be estimated experimentally from equation (1) when the frequency of maximum power f_{mp} is specified.

The power dissipation per cycle in ac discharge of argon in the range 5-10 kHz has experimentally calculated from the area of ac I-V loop images which displayed in Fig.3, by using a special Matlab program [12, 13].

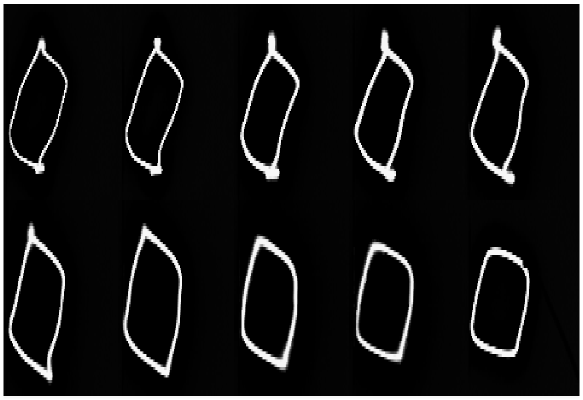

Fig.3: AC I-V loop images for frequencies 5,5.5,…9.5 kHz respectively ,at pressure 50 mTorr.

The resulting numerical data have plotted with the corresponding fitted curves in Fig.4.

From Fig.4, the frequency of the maximum power f_{mp} (the time of breakdown t_B) and maximum power P_m can be estimated as shown in table 1. It is clear that the time of breakdown t_B is in agreement with that which is stated in [4, 5].

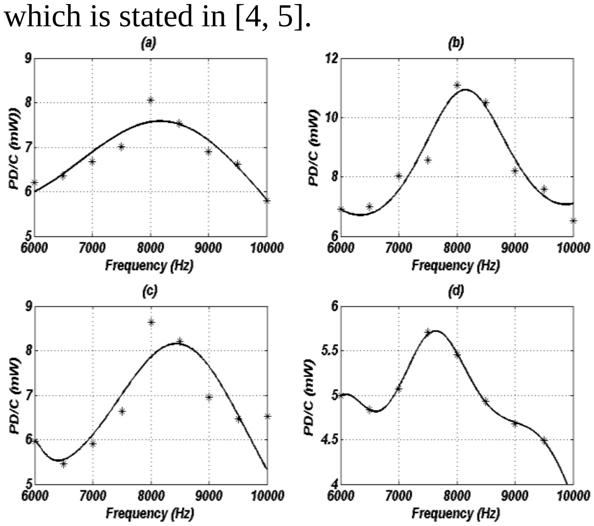

Fig.4: The power dissipation per cycle (PD/C) in ac discharge of argon gas at pressures (a) 50,(b) 60,(c) 70 and (d) 80 mTorr

Table 1: Maximum Power dissipation and time of breakdown of the discharge at different values of pd.

pd (Torr. cm)	P_m(mW)	t_B(msec)
0. 5	7.580	0.03296
0. 6	10.93	0.03316
0. 7	8.153	0.03202
0. 8	5.719	0.03528

5-Changing the maximum power dissipation with pd value

Fig.5 shows that the maximum power dissipation is obtained at pd value of Paschen minimum 0.6 Torr.cm [11]. Moreover, the value of maximum power increases with the increasing values of pd<0.6 Torr.cm and decreases with the increasing values of pd>0.6 Torr cm. These results can be explained as to be due to the well known physical facts. For pd<0.6 Torr.cm, the density of atoms in the chamber is increased with the increase of gas pressure. Thus, the number of positive ions which can be produced by the accelerated electrons during breakdown process will increase [1,4,14]. For pd>0.6 Torr.cm, more increase in atoms density with gas pressure will deaccelerate the electrons and decrease the number of positive ions which produced during breakdown process. Maximum density of positive ions is obtained at pressure of Paschen minimum which has optimum values for energy of electrons and density of atoms. Figure 5 shows that the P_m- pd curve is the inverse of Paschen curve.

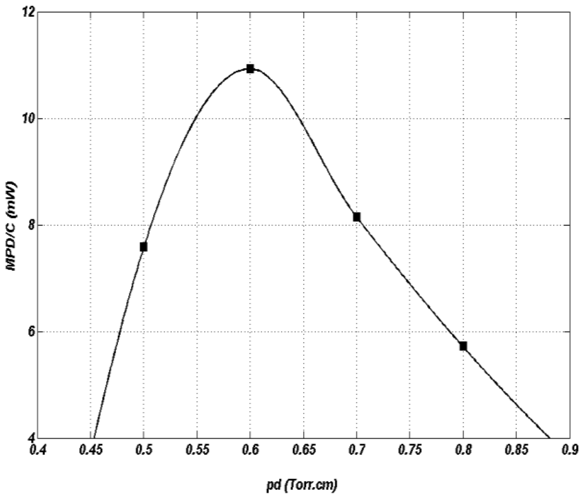

Fig.5: The maximum power dissipation per cycle (MPD/C) in the frequency range 5-10 kHz of ac discharge of argon gas at different values of pd.

Conclusions

In the range of frequency 5-10 kHz and pd value 0.5-0.8 Torr.cm, the sinusoidal waveform of discharge current is unaffected by the breakdown of the argon gas, While the amplitude is changed with frequency and pressure. In this frequency range the discharge behavior is equivalent to a series RC circuit. The variation of the power of a low pressure ac discharge with frequency in the range 5-10 kHz is approximately Gaussian in nature. The time of breakdown of argon gas can be estimated from frequency of maximum power dissipation. The variation of maximum power dissipation with pd values 0.5-0.8 Torr.cm is the inverse of Paschen curve.

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