A Simple Model of Spark Gap Discharge Phase

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Received on: 30/9/2012 & Accepted on: 31/1/2013

ABSTRACT

A simple computational model is established to simulate the spark gap discharge phase. The proposed computational approach is based on Rompe- Weizel model for the resistive phase of the spark discharge where the plasma resistance decreases dramatically and rapidly during this phase converting the gap from a non-conducting (off) state to a conducting (on) state . Results obtained from this model are compared with some available published data and acceptable agreements are obtained.

Keywords: Electric Discharges, Spark Gaps, Discharge Plasmas, Resistive Phase Modeling.

نموذج مبسط لطور التفريغ الكهربائى لفجوة الشرارة

الخلاصة

تم انشاء نموذج حسابي بسيط لمحاكاة طور التفريغ الكهربائي لفجوة الشرارة. يستند النمط الحسابي المقترح الى نموذج Rompe- Weizel المتعلق بطور المقاومة (Resistive phase) لفجوة الشرارة حيث تتناقص مقاومة البلازما خلال هذا الطور بشكل كبير و سريع، مما يحول الفجوة من حالة اللاتوصيل (دائرة مفتوحة) الى حالة التوصيل (دائرة مغلقة). تمت مقارنة النتائج المستحصلة من النموذج المقترح مع بعض البيانات المنشورة المتوفرة حيث تم الحصول على توافقات مقبولة.

INTRODUCTION

The field of electric discharge in gaseous media has received a great attention both scientifically and technically due to the varieties of applications related to discharge plasmas. Gas electric discharges are involved in many applications like fast switching [1], etching computer chips, production of solar cells, monitors screens, etc. In addition, studying these phenomena may lead to improving the existing discharge applications and possibly to the development of new uses of gas discharges [2].

Electric discharges take place in gases experimentally by applying an electric field (potential difference) of sufficient intensity across a gas confined between two electrodes. The gas under this electric tension may switch from an insulating to a conducting medium due to ionization. The switching of the gas to a conducting state is referred to as "breakdown" [3].

In addition to experimental efforts [4], many theoretical studies were performed in the aim of understanding and modeling the different modes of electric discharges through mathematical modeling of the discharge plasmas [5]. However, experimental and theoretical researches have to be associated to each other in order to aid the progress in this field [1].

Gas discharge plasmas consist mainly of electrons, positive ions, neutral atoms, and molecules. In a discharge tube a gas between the electrodes may be ionized when sufficient electric field intensity is applied [6].

Electric discharges in gases may occur in different modes ranging from non self sustaining to arc discharges depending on experimental factors, like the gas type and pressure, electrodes separation, type of electrodes material and surface condition, in addition to the electric circuit characteristics [2]. The physical phenomena that may take place in the ionized gas (or discharge channel) differ for different discharge modes.

Basically, when an electric field is applied between the electrodes, the pre existent free electrons in the gas (that may be produced by any external energy source, like cosmic ray for example) are accelerated towards the positive electrode (anode). In their drift motion they may ionize neutral gas atoms by collisions, producing more free electrons and positive ions [7]. These positive ions (generated throughout ionizations) accelerate towards the negative electrode (cathode) and may cause secondary electrons to be generated from the cathode surface [3,7].

The secondary electrons so generated are accelerated towards the anode producing more free electrons by collisions throughout their drift motion, and so on. This mechanism of free electrons population enhancement through collisions and secondary emissions is referred to as "avalanche"[3]. The avalanche process was mathematically formulated by Townsend and Paschen [2, 3].

It is appropriate here to mention that other mechanisms may contribute in secondary emission of electrons like photoemission, thermionic and field emissions [8].

The avalanche theory assumes homogenous electric field throughout the ionized gas between the electrodes. However, in situations of high pressures and/or long distances between electrodes, the space charge of electrons and ions formed due to ionizations and secondary emissions may distort the local electric field in the gaseous medium and another mechanism will contribute in the breakdown process, this mechanism is the "streamer", which is a fast growing conducting channel formed between the electrodes [1].

In this paper, the breakdown process in spark gaps is considered through a simple calculation procedure. The mode of electrical discharge here is referred as "spark discharge" or simply "spark". The spark is a rapid transient discharge, often characterized by high electric currents. It is characterized by streamers formation that constitutes conducting paths between the electrodes [8].

Spark discharges may be thought of as being primary stages of arc discharges, where a spark collapses before it may develop into an arc due to its short period [8].
One of the interesting usages of spark gaps is their employment as fast switches devices (FSDs) due to their ability to switch rapidly from a non-conducting to a conducting state in addition to the high amounts of currents that may be involved [1].
Spark gap discharges are characterized by high currents and low voltages since they are essentially arc discharges. This means that the discharge (plasma) resistance decreases substantially during the period of the discharge process.

As an FSD the spark gap is considered as an open switch (Off) before breakdown where the voltage across it is high and the current is practically zero, whereas after breakdown the gap is regarded as a closed switch (On) where the voltage is low and the current passing through is high [8].

TIME HISTORY OF BREAKDOWN BEHAVIOR

Figure (1) illustrates the time intervals associated with a pulsed discharge spark gap as follows [8]:

1- The charging time (t_c): is the time required to rise the gap voltage to the self Breakdown value (V_{sb}).
2- The statistical delay time (t_{st}) which is the time lapse between the self Breakdown voltage (V_{sb}) and the application of the over voltage (V_{ov}). It is due to the appearance of a suitably located initiatory electron in the gas.
3- The streamer formation interval (t_s) which is the interval between the statistical delay time and the onset of breakdown due to the formation of streamers.
4- The column heating time (t_{ch}), which is the time required for the gap closurethrough heating of electrons in the discharge column.

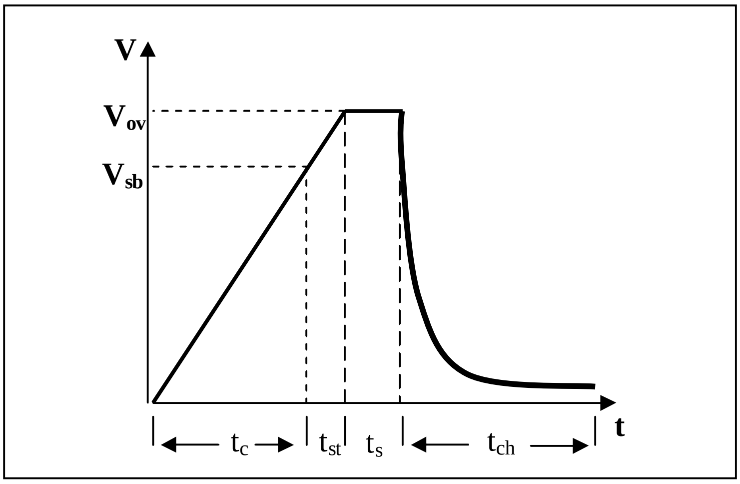


Figure (1) Characteristic time intervals associated with a spark gap discharge.

THE RESISTIVE PHASE OF AN ELECTRICAL DISCHARGE

The heating time (t_{ch}) in Figure (1) is considered as the breakdown interval (or breakdown phase) of the spark gap, where the resistance of the plasma drops dramatically from several tens of mega ohms to a few millions and it is known as the dynamic resistance [8]. For this reason this phase is also referred to as the ***resistive** phase* and it is considered as the switching period of a spark gap since it represents the period through which the gap transfers from none conducting to a conducting state. When spark gaps are to be employed as fast switching devices (FSDs), the resistive phase period becomes an important factor in determining the efficiency of an FSD where the amount of energy deposited in the gas and electrodes during the closure phase affects the durability of the switch when repetitive breakdown is required [1]. It is usually desired to reduce the resistive phase (or dynamic resistance) period to achieve better FSD performance [8].

A PRESENTATION OF SOME IMPORTANT MODELS FOR THE DYNAMIC RESISTANCE PHASE

Several calculation models have been established concerning time dependent plasma resistance during the resistive phase in a spark discharge where theoretical and empirical relations were employed.

Some of the important models that determine the time dependent plasma resistance during the closure phase of the spark gap switch are Toipler model, Rompe and Weizel model, Vlastos and Branginski model, in addition to Sorensen and Ristic formula [8]. The present algorithm is based on equations resulted from Romp and Weizel model which includes the energy balance consideration of the discharge channel.

In Rompe model, the plasma conductivity variation during the resistive phase is taken into account, whereas the discharge channel radius is not included in consideration. However, compared with the other two important models, namely Toipler's and Branginski models, it is believed here that Rompe model is suitable in the present simple formulation. As the Toipler's model depends mainly on the avalanche processes for free electrons enhancement between electrodes, it does not take into consideration both the conductivity variation and energy balance in the discharge. On the other hand, the Branginski model takes into account energy considerations in addition to the discharge channel radius temporal variation throughout the resistive phase, but the plasma conductivity is considered as a constant quantity. However, it was stated that the results obtained from Branginski model rarely fit with experimental data, where the discrepancy was related to the assumption of a constant plasma conductivity of the discharge in Branginski model [8].

It is appropriate in what follows to give a brief presentation of the main equations governing the Rompe- Weizel model.

A BRIEF DESCRIPTION OF GOVERNING EQUATIONS IN ROMPE- WEIZEL MODEL

In a spark discharge an approximate formulation of the power balance is given as [8]:

$$i(t).E(t) = \frac{dU}{dt} \qquad \dots (1)$$

Where U(t) is the internal energy of the discharge plasma (Joules per meter), i(t) and E(t) are respectively the discharge current and electric field intensity between the electrodes.

The plasma conductivity was set proportional to the internal energy as [8]:

$$\sigma(t) = \frac{K_R}{P}U(t) \qquad \dots (2)$$

The unit of σ in eq.(2) is Siemens. meter (S.m).

Here (K_R) is a constant that depends on experimental conditions , P is the pressure of the gas between the electrodes and σ is the plasma conductivity which is defined here as [8]:

$$\sigma = i/E \qquad \dots (3)$$

Defining E as E=V/d, with (V) is the potential difference between electrodes separated by a distance (d), the following form of the plasma resistance [R(t)] may be deduced from eq.(3) as:

$$R(t) = \frac{d}{\sigma(t)} \qquad \dots (4)$$

Substituting for (E) from eq.(3) in eq.(1) gives:

$$\frac{i^2}{\sigma} = \frac{dU}{dt} \qquad \dots (5)$$

Substituting for (U) from eq.(2) in eq.(5) gives after rearranging:

$$i^2 = \frac{P}{2K_R}\frac{d\sigma^2}{dt}$$

Integrating over time yields:

$$\sigma^2(t) = \frac{2K_R}{P}\int_0^t i^2 dt \qquad \dots (6)$$

Now, substituting eq. (6) in eq.(4) we get an expression of the plasma resistance as an implicit function of time through the relation:

$$R(t) = \frac{d}{\sqrt{\frac{2K_R}{P}\int_0^t i^2 dt}} \quad \dots (7)$$

The above equation is the form of the discharge resistance as a function of time in the Rompe- Weizel model.

THE PRESENT CALCULATION PROCEDURE

The aim of the present calculations is to determine some important electrical properties throughout the resistive phase period of a spark gap, namely, the discharge voltage, current, electric field intensity, resistance, and conductivity. A computer program is written to determine and monitor the variations of those quantities with time.

Use is made of some relations generated in the Rompe- Weizel model with the help of two auxiliary empirical equations stated by Sorensen and Ristic for the resistive phase time (τ_R) and the spark gap resistance for gaseous nitrogen given as:

$$\tau_R = \frac{44\, P^{1/2}}{E\, Z^{1/3}} \quad \text{(ns)} \quad \dots (8)$$

and

$$R(t) = 0.23\, Z\, (\tau_R / t)^3 \quad \dots (9)$$

Where the gas pressure (P) is in atmospheric units, the electric field intensity between the electrodes (E) in kV/mm and Z is the impedance if the electric circuit (in ohms).

For the sake of simplicity equation (9) will be written in the form:

$$R(t) = A / t^3 \quad \dots (10)$$

where $A=0.23\times Z\times \tau_R^{\,3}$.

Using eqs. (4) and (10) in eq.(6) and differentiating with respect of time yields:

$$i = \frac{d}{A}\, t^2 \sqrt{\frac{3P}{K_R} t} \quad \dots (11)$$

The instantaneous potential difference between the electrodes is V(t) = i(t) × R(t), using eqs. (10) and (11) this becomes:

$$V(t) = d\sqrt{\frac{3P}{K_R\, t}} \qquad \ldots (12)$$

The instantaneous conductivity can be found from eq. (4), and the electric field intensity may be obtained by the definition: E(t) = V(t) / d.

At an initial time of zero, both the empirical formulae for R(t) [eqn.(9) or (10)] and V(t) [eqn.(12] lead to infinite values. However, it is required here to assign a breakdown voltage value (V_B) as an initial voltage (t=0) where the resistance is at its maximum.

This requirement is achieved here as follows: first the breakdown voltage (V_B) is determined for a given pressure and electrodes separation by the known Paschen curve equation given as [8]:

$$V_B = \frac{B\,p\,d}{ln(pd)+C}\ ;$$

Where $C = ln\left[\frac{A}{ln\left(1+\frac{1}{\gamma}\right)}\right]$.

Here, A and B are constants for a given gas and experimental conditions and are determined experimentally, and γ is the third Townsend coefficient. The values of these quantities are published in ref. (8).

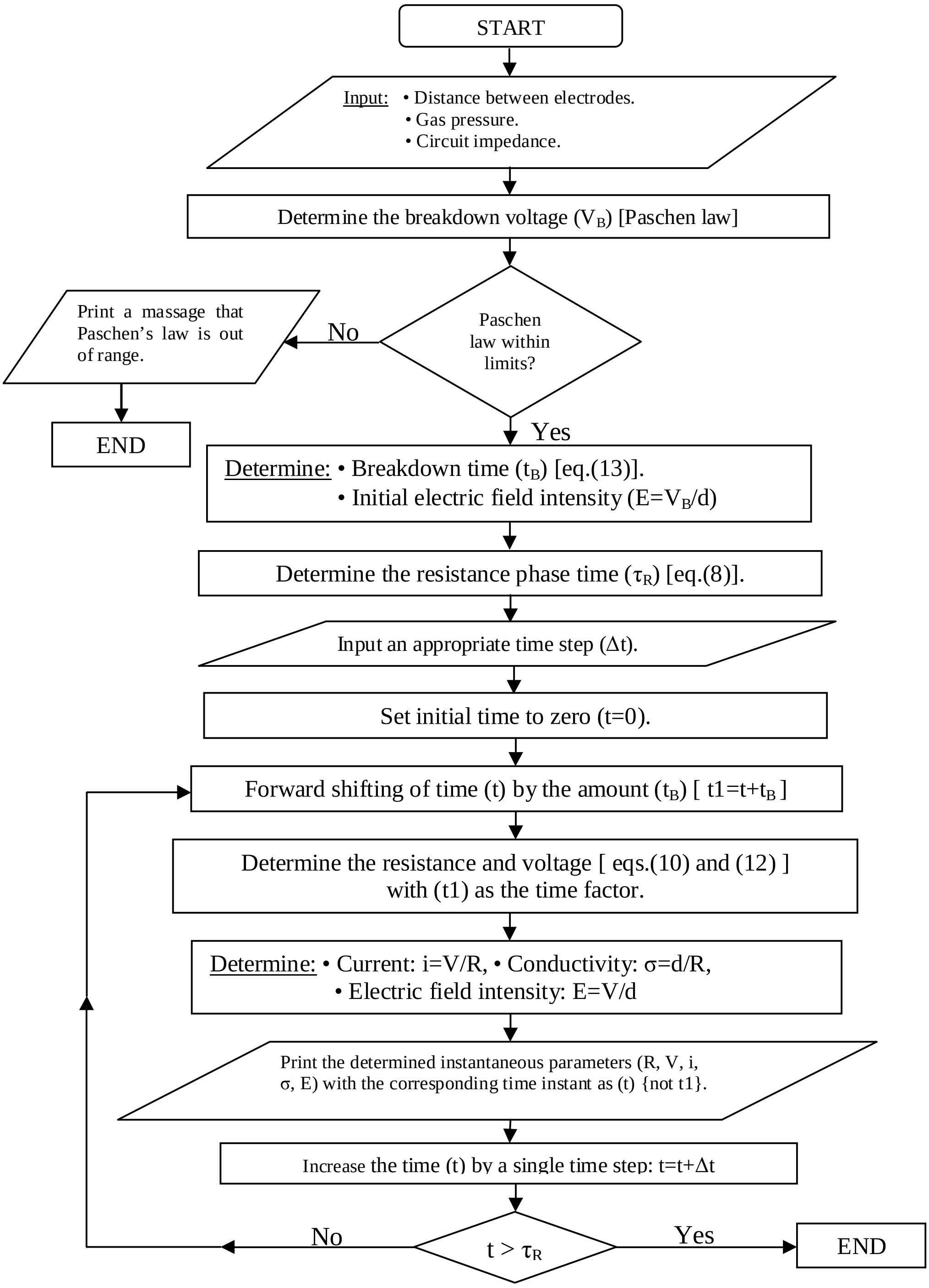
Then the time (t_B) that corresponds to the occurrence of the breakdown voltage (V_B) is determined from eq.(12), where we may write:

$$t_B = \frac{3\,P\,d^2}{K_R\, V_B^2} \qquad \ldots (13)$$

The time factor (t) in eqs.(10) and (12) is forward shifted by an amount (t_B) so as to avoid infinite R(t) and V(t) at the initial time (t=0), hence, the time (t_B) will be regarded as the initial moment for breakdown [where the voltage is (V_B)], as a result, the whole time instances throughout the resistive phase will be forward shifted by (t_B). After determining R (t) and V (t), the corresponding current may be found, where i(t) = V(t) / R(t) [This is done easier than employing eq.(11) for the same purpose].

To achieve as realistic results as possible, the validity condition limits for the Paschen equation [8] are checked in the program to insure that the input data are compatible with the range of applicability for this equation.

The Calculation procedure is summarized throughout the following flow chart:



RESULTS AND DISCUSSION

Firstly, it is appropriate here to mention that the instantaneous time values assigned to the determined parameters are those without the t_B-shifting (as indicated in the block diagram above) so that the time at which breakdown occurs may appear as the zero instant (t=0) in the time evolution curves, however, the shifted time values were adopted in the calculation processes. This does not make any contradiction with any computational issue since the time value assigned to any initial event (like the instant of breakdown) is a relativistic concept.

Figures (2) to (6) show the determined spark gap discharge parameters throughout the resistive phase period (τ_R) as determined by the present program. The program is applied for two chosen values of gas pressure (1 atm., and 1.5 atm.). Electrodes separation distance (D) is taken as (0.1 mm) and the circuit impedance as (50 Ω).

Figure (2) shows the gap resistance variation with time as described mathematically by Sorensen- Ristic equation. It is noticed that a higher pressure leads to a higher resistance, however, when the time exceeds 0.3ns approximately, the two curves coincide. Figure (3) illustrates the voltage curves where it is seen that the higher pressure leads to higher potential differences across the gap. It is noticed from this figure that the shifting between the two curves is apparent throughout the whole resistive phase period.

The two curves do not approach each other appreciably as the resistive curves do in Figure (2). Hence it is expected that higher pressure will result in higher currents especially at the end of the resistive phase. This is illustrated in Figure (4).

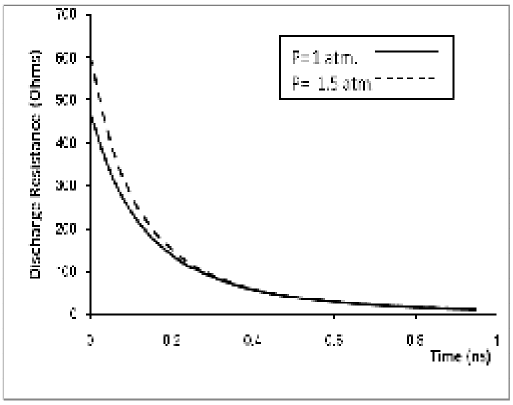
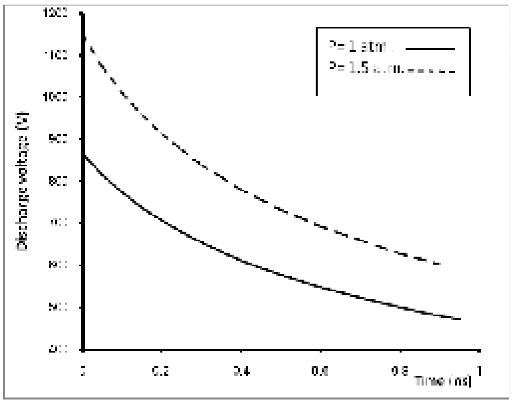


Figure (2)Discharge resistance versus time as determined by Sorensen and Ristic equation.



Figure(3)Discharge voltage versus time during the resistive phase.

The discharge conductivity curves are shown in Figure (5), which indicates that a higher pressure leads to a higher conductivity in spite of the higher resistance conjugated

With higher pressure as noticed in Figure (2). This is due to the higher currents associated with the higher pressure {Figure (4)}. Figure (6) illustrates the profile of the electric field intensity between the electrodes. It is expected that the trends of these curves resemble those of the voltage curves in Figure (3) since the electric field intensity was determined simply by the relation: E=V/d.

It may be noticed from Figures (3)-(5) that the resistive phase period (τ_R) is somewhat longer for the lower pressure condition (1 atm.). At first this may seem to contradict with Sorensen and Ristic formula {eqn.(8)}. However the voltages involved in the higher pressure case are higher compared to those for the lower pressure (according to Paschen curve equation), which means higher electric fields (E) at the higher pressure. As a result, τ_R will be lower for higher pressures.

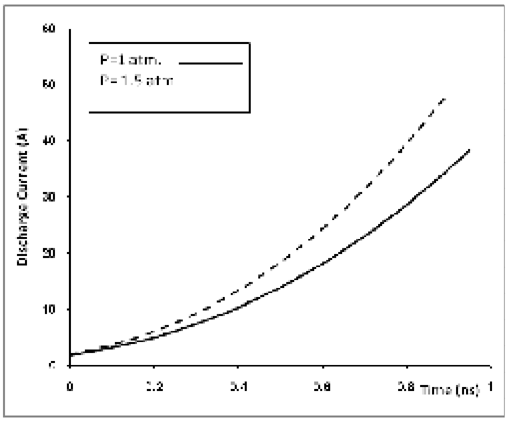


Figure (4) Discharge current versus time during the resistive phase.

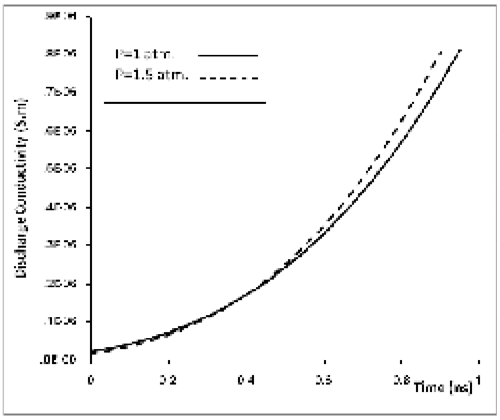


Figure (5) Discharge conductivity versus time during the resistive phase.

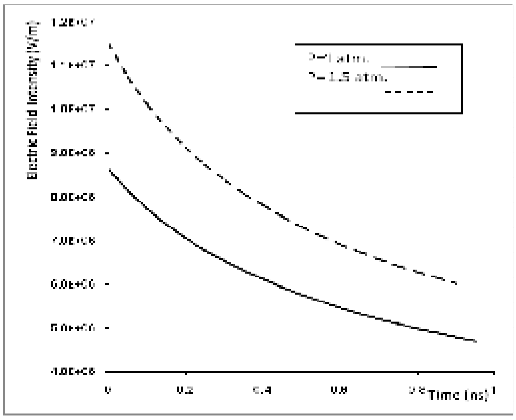


Figure (6) Electric field intensity between the electrodes Between the resistive phase.

Table (1) presents some related quantities that are determined by the program for the two cases mentioned above.

It may be concluded from Table (1) that higher pressures result in higher breakdown voltages (hence higher electric fields and currents). However, the resistive period (τ_R) is somewhat shorter for the higher pressure.

A comparison is performed with measurements reported in Ref.(9). Unfortunately, no newer measurement data were found for comparison purpose.

In Ref.(9) the circuit impedance value is taken as 50Ω and the pressure ranges from approximately 0.27 to 1.01 atm. Electrode materials used were brass, steel, and aluminum. A final time for the discharge was considered as 1 ns [9].

The comparisons of the present calculations with the measurements of Ref.(9) are illustrated through Tables (2) and (3),where the measured data are approximated since they were extracted from curves obtained in that reference.

Table (2) shows the current and voltage values at the end of the resistive phase period (τ_R) for a certain measured case, while Table (3) contains only current values for four different cases, where no voltage measurements were found for these cases in Ref.(9).

Table (1) some characteristic quantities as determined by the present calculations for the two chosen cases (P=1 atm. and 1.5 atm.). Electrodes separation distance is 0.1 mm, and the circuit impedance is 50 Ω.

P	V_B (V)	t_B (ns)	τ_R (ns)	E(t=0) (kV/mm)	I(τ_R) (A)	V(τ_R) (V)	E(τ_R) (kV/mm)
1 atm.	~865	0.4	~1.4	8.6	38	471	~4.7
1.5 atm.	~1151	~0.34	1.27	11.5	48.6	602.5	~6

Table (2)Measured and determined values of discharge current, voltage, and electric field intensity at the end of the resistive phase period (τ_R). D= 60 µm, P(used in calculations) = 0.2 atm.

	τ_R (ns)	I(τ_R) (A)	V(τ_R) (V)	E(τ_R) (kV/mm)
Ref.(9) [measurements] Electrodes material: Brass	1	10.5	~150	~2.5
Present calculations	1.04	12.413	143.77	2.39

Table (3) Measured and determined values of discharge current for different cases. The period of the measurements in Ref.(9) was considered as 1 ns.

D (μm)	Measurements [Ref. (9)		Present Calculations		
	Electrodes material	I (A)	I (A)	P [used] (atm.)	τ_R [determined] (ns)
50	Brass	~9	12.01	0.25	0.972
60	Steel	~23.6	23.36	0.8	1.19
60	Aluminum	~22.7	22.4	0.75	1.19
90	Brass	16.4	15.9	0.2	1.43

CONCLUSIONS

The present approach of calculation, though simple, does give reasonable trends of temporal variation curves of discharge characteristics (voltage, current, and field intensity) during the resistive phase. Also, an acceptable conformity could be obtained with experimental measurement found so far. The simplicity of the present approach results in a simple computer program that operates easily and swiftly no matter what the computer capabilities are.

However, more developed and accurate simulations may be achieved by including more affecting factors like the electric circuit formulation (where this is done here via the circuit impedance only). Other factors like the electrodes material and surface properties, the gas nature, emission mechanisms at the electrodes, ionized gas dynamics for example may be included to achieve more development of the simulation.

To sum up, it can be concluded that the present approach of calculation provides a plain and smooth contribution toward understanding and formulating an important period throughout the electric discharge process, which is the resistive phase period.

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