frequency, the maximum voltage gain ($A_{max} = \left|\frac{V_{out}}{V_{in}}\right|$) can be expressed as:

$$A_{max} = \frac{R}{\sqrt{\frac{L}{c} - \frac{L^2}{4\,R^2c^2}}} \tag{6}$$

And the resonance frequency will be obtained as:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{Lc} - \frac{1}{2\,c^2R^2}} \tag{7}$$

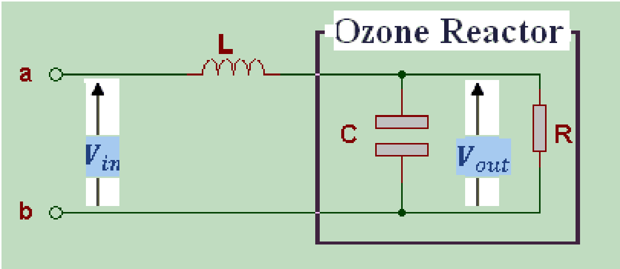

Fig. 5. An equivalent circuit of ozone reactor and variable inductor

The values of chamber capacitance and discharge resistance can be obtained using two procedures. One of them is by approaching the last two equations to become [11]:

$$A_{max} = \frac{Q_p}{\sqrt{1 - \frac{1}{4Q_p^2}}} \tag{7}$$

$$f = f_p\sqrt{1 - \frac{1}{2Q_p^2}} \tag{8}$$

Where, $f_p = \frac{1}{2\pi\sqrt{LC}}$ and $Q_p = 2\pi f_p CR$. For $Q_p \gg 1$, thus, $A_{max} \cong Q_p$ and $f \cong f_p$.

In this paper C & R will be graphically obtained without approaching. Table I demonstrates a comparison between these two methods.

TABLE I: A COMPARISON BETWEEN APPROACH AND GRAPHICAL METHODS.

f (KHz)	Q_p	L (mH)	Approach		Graphical	
			C(pF)	R(KΩ)	C(pF)	R(KΩ)
29.3	12.8	193	152.5	454.8	151	452
31.5	13	168	153	432.3	153	431
33.7	13.1	145	155	402.2	155	403
35.4	13.26	128	157	377.5	158	378
37.2	13.47	116	158	365.2	159	365

As illustrated in the table; there are no differences between approach and graphical results. Fig. 6 demonstrates obtaining the values of chamber capacitance and discharge resistance graphically for $A_{max} = 12.43$, $L = 336.7$ mH and $f = 22.8$ KHz.

3. Proposed theoretical method

Now, we are going to analyze the determination of the dielectric barrier discharge ozone generator parameters. In this regard, the ionization voltage can be calculated by determining the required ionization energy. The gap and the dielectric capacitances will be theoretically calculated by the using of Gauss's Law.

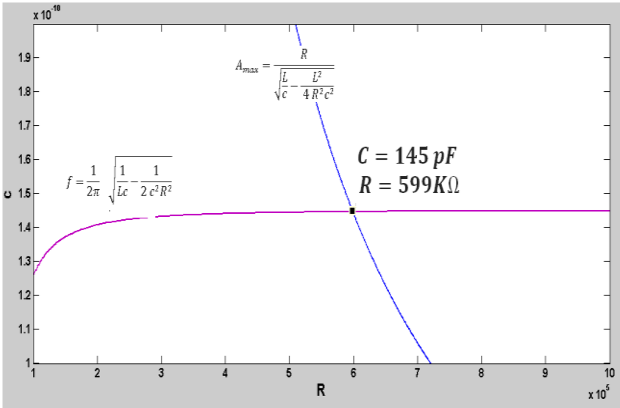

Fig. 6. Determination of capacitance and discharge resistance of ozone chamber graphically

A. 3.1 The ionization threshold voltage

For co-core cylindrical ozone reactor; the electrical field has a mathematical form given by:

$$E(r) = \frac{V}{r\ln\frac{r_2}{r_1}} \qquad r_1 < r < r_2 \tag{10}$$

E denotes the electric field between the two cylindrical electrodes; the value of which depends on the applied voltage V and the radius of the reactor. r_1 & r_2 represent the inner and outer cylinders radius, respectively. As Eq.(10) demonstrates, the electric field is maximized at $r = r_1$ and as a result of this, the ionization or the threshold voltage can be calculated as [8]:

$$V_{th} = \frac{E_{max}}{r_1\ln\frac{r_2}{r_1}} \tag{11}$$

As mentioned earlier, ionization energy has a range between 1.17243 kWh/m3 and1.620 kWh/m^3 for oxygen and as a consequence of that range, the threshold voltage can be calculated from the minimum required energy (1.17243 kWh/m^3). Thus, the ionization energy can be expressed as

$$W = \frac{1}{2}\iiint_{vol} \epsilon_o E^2\, dv \tag{12}$$

ϵ_o is the free space permittivity, and dv is the differential volume. For co-core cylindrical ozone generator; the electric field has maximum value at the inner cylinder and minimum value at the outer one. In other words, Emin and Emax have mathematical forms given by:

$$E_{max} = \sqrt{\frac{2W_{max}}{\epsilon_o V_g}}\ , E_{min} = \sqrt{\frac{2W_{min}}{\epsilon_o V_g}} \tag{13}$$

V_g is the gap volume between the two electrodes. For ozone generator model with inner cylindrical radius 1.45 cm, outer cylindrical radius 1.59 cm and of length 30cm, the maximum and minimum values of the electric field can be evaluated to give $E_{max} = 19.129$ KV/cm and $E_{min} = 16.273$ KV/cm [8]. The electric field flux is perpendicular to the electrode surface and therefore the required threshold voltage for 1.4 mm ionization gap is 2.28 KV.

B. 3.2 Air gap and dielectric capacitances

This section concerns with capacitance calculations of two parallel plates and co-core cylindrical ozone generators. Two parallel plates construction has two medium; one of them depends on dielectric material and the other for air or oxygen gap. The ionization gap permittivity is air or oxygen permittivity at the operating pressure and temperature. Fig. 7 illustrates the parallel plates ozone reactor construction. k_e & ϵ_0 are the relative dielectric and the ionization gap permittivities, respectively, whilst t & d are the dielectric and air gap thicknesses, respectively.

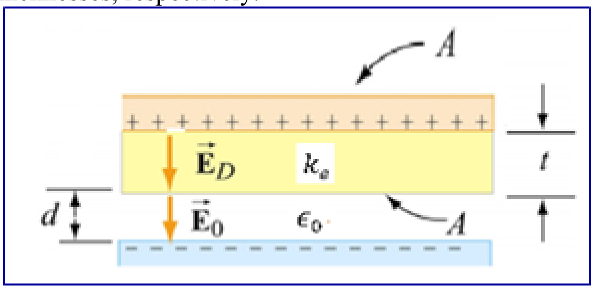

Fig. 7. Cross section parallel plates ozone generator

The potential difference between the two electrodes can be formulated as [15]:

$$V = -\int_{+}^{-} E\,dl = -E_0 d - E_D = -\frac{Q}{\epsilon_0 A} d - \frac{Q}{\epsilon_0 k_e A} t \quad (14)$$

E_0 & E_D are the electric field values through the ionization gap and the dielectric layer, respectively. A is the electrode surface area and Q is the quantity of electric charges on each electrode.

$$C = \frac{Q}{|V|} = \frac{1}{\frac{d}{\epsilon_0 A} + \frac{t}{\epsilon_0 k_e A}} = \frac{1}{\frac{1}{C_g} + \frac{1}{C_d}} \quad (15)$$

Thus,

$$C_g = \frac{\epsilon_0 A}{d} \quad , \quad C_d = \frac{\epsilon_0 k_e A}{t} \quad (16)$$

C_g & C_d are the capacitances of the ionization gap and the dielectric layer, respectively, whilst C represents the total capacitance.

For ozone generator with electrode surface area of $0.045\ m^2$, dielectric thickness of 1 mm, ionization gap thickness of 3 mm , and silica dielectric relative permittivity of 8 [8]; the resulting gap capacitance C_g = 132 pF and the dielectric capacitance C_d = 3.186 nF.

The previous procedure will be applied for co-core cylindrical ozone reactor. Fig. 8 demonstrates co-core cylindrical ozone generator where a is the inner cylindrical radius, b is the dielectric radius, whilst c denotes the outer cylindrical radius.

$$V = -\int_a^c E\,dr = -\frac{Q \ln(\frac{b}{a})}{2\pi\epsilon_0 k_e L} - \frac{Q \ln(\frac{c}{b})}{2\pi\epsilon_0 L} \quad (17)$$

$$C = \frac{Q}{|V|} = \frac{1}{\frac{\ln(\frac{b}{a})}{2\pi\epsilon_0 k_e L} + \frac{\ln(\frac{c}{b})}{2\pi\epsilon_0 L}} = \frac{1}{\frac{1}{C_d} + \frac{1}{C_g}} \quad (18)$$

Thus,

$$C_g = \frac{2\pi\epsilon_0 L}{\ln(\frac{c}{b})} \quad , \quad C_d = \frac{2\pi\epsilon_0 k_e L}{\ln(\frac{b}{a})} \quad (19)$$

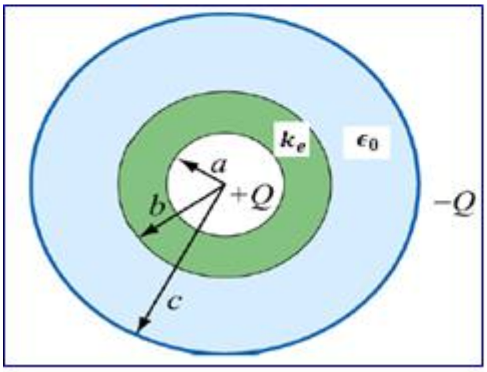

Fig. 8. Cross section of co-core cylindrical ozone generator

4. Conclusion

In this paper, determination topologies of ozone generator parameters have been studied. Lissajous plot achieved good results in frequency range (15-20 KHz). This belongs to the plotting shape which will be distorted outside this range. As a result of this distortion, uncertainty will be occurred in determination of I_0 and Q_0 values. Differential evolution (DE) method, on the other hand, depends on the resonance frequency. This means that as the resonance frequency increases, accuracy of parameter values will be enhanced. A new theoretical methodology is proposed. It is concerned with calculations of the initiation or threshold voltage, dielectric and gap capacitances for parallel and co-axial ozone reactors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mohamed B. El_Mashede suggested the paper title and presented the conclusion after his final revision of the research; Magdy M. Zaky and M. EL_Hanash presented and wrote sections (II and III); A. A. Saleh wrote the introduction; all authors had approved the final version.

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Conflicts of Interest

The author(s) declare no potential conflicts of interest concerning the research, authorship, or publication of this article.

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

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