OPERATION PRINCIPLE OF CYLINDRICAL GEOMETRY OZONE GENERATORS

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Se prezintă un principiu de funcţionare al generatoarelor de ozon cu geometrie cilindrică, alimentate de la surse statice de înaltă tensiune alternativă, în regim de rezonanţă în tensiune, având curentul şi tensiunea cvasisinusoidale. În lucrare sunt tratate: analiza funcţionării ozonizorului pe trei intervale de timp dintr-o semiperioadă, cu determinarea expresiilor şi a formelor de undă ale mărimilor electrice specifice fiecărui interval; relaţiile de calcul ale mărimilor electrice specifice ozonizorului; graficele unui exemplu de calcul.

The paper presents an operating principle of the cylindrical geometry ozone generators, supplied by alternating high voltage static sources, in voltage resonance regime, with cvasisinusoidal current and voltage. This paper covers: the ozonizer's operating analysis on three time intervals from a semi-period, determinating the wave forms and expressions of the electric quantities specific to each interval; calculation of the electric quantities specific of the ozonizer ; graphs for an example of calculation.

Keywords: ozonizer, operation principle, mathematical model

1. Introduction

The ozone (O_3) is obtained industrially by creating "still" corona type dischar- ges, using prepared air, dried up to *dew point* -50^0 C or oxygen as discharge environment. The corona discharge is carried out in plane or cylindrical geometry **ozone generators,** the last being the most used.

1.1. Cylindrical geometry ozone generators. Fig.1 schematically represents the longitudinal sections of the industrial variants of cylindrical geometry discharge tubes used by different producers.

Variant a): used on a large scale, it has two concentric tubes, the external one made from stainless steel connected to the earth terminal and the internal one made from glass (ceramics), centered with spacers, and connected to the high voltage terminal of the source through the metallic layer on the internal side of the tube. The electrical gas (air or O_2) discharge that produces the ozone takes place in the circulary space between the tubes, the radius between the tubes is of 1-3 mm. The stainless steel tube is cooled with water.

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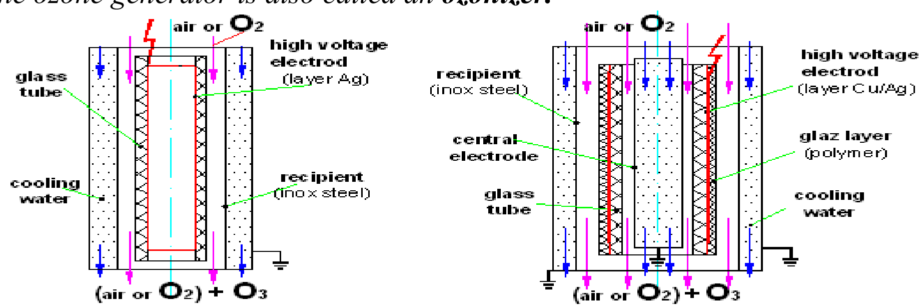
Variant b): the discharge tube is made of a glass (ceramic) cylinder over which is coated with a metallic (copper/silver) layer – the high voltage electrode and an insulating layer (enamel/polymer) which is centered inside a metallic recipient tube connected to the earth terminal. Inside the discharge tube the second metallic earth link electrode is centered, so that the corona discharge is produced on both sides – double discharge. Both tubes are earth linked and cooled with water.

The ozone generator is also called an ***ozonizer.***



a) b)

Fig. 1. Schematic representation of industrial discharge tubes variants used in cylindric geometry ozone generators

1.2. Recent status of the subject. There are a number of works worldwide concerning the simulation and the improvement of ozone generating systems.

Paper [1] highlights the liniar (RC) and non-linear (RCV_z) models of industrial ozone generators. This paper also presents theoretical results of the variation simulation of the converter's voltage frequency on the voltage from the ozonizer, obtaining a maximum at voltage resonance ($f=f_0$).

Paper [2] presents the functioning of the ozone generator using the inverter's switching at zero voltage with period modulation (PWM) adjusting the ozone production through the variation of the inverter's frequency by maintaining the voltage on the ozonizer constant.

The controlled and still corona discharge can be obtained only by using a glass (ceramic) dielectric barrier that prevents the discharge degeneration in a distructive electric arc. These aspects of the microscopic corona discharge and ozone forming reactions are presented in paper [3].

2. The operation analysis of the ozonizer with alternating high voltage

In this paper the author analyzes a non-linear model of the cylindrical geometry ozone generator, the voltage $u_1(t)$ being alternative, rectangular (easy to obtain in practice) (fig.2), with adjustable amplitude U_1 and auto-adjustable frequency *f* with zero current switching (ZCS) - voltage resonance regime (fig. 4).

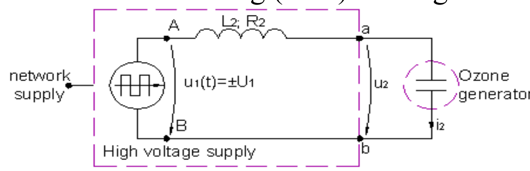


Fig. 2. Schematic representation of the high voltage source connected to the ozonizer

2.1. The physical-electrical parameters of the cylindrical geometry ozonizer; parallel n-tube ozonizer. This paper analyzes the functioning of the ozonizer tube with *simple* discharge. The glass tube from an electrical point of view is a cylindric capacitor of capacity c_d [4]. Similarly, the air space between surfaces(2) and (3) is also a capacitor with air (void) as a dielectric $\varepsilon_{ra}=1$, of capacity c_a:

$$c_d = \frac{2\pi\varepsilon_0\varepsilon_{rd} l}{\ln(1+d_1/r_1)}, \; c_a = \frac{2\pi\varepsilon_0 l}{\ln(1+d_2/r_2)}; \; \varepsilon_0 = \frac{10^{-9}}{36\pi}[F/m] \tag{1}$$

c_d and c_a from a tube are series connected and form the equivalent capacity

$$c:\; c = \sigma \cdot c_d/(1+\sigma) \text{ where: } \sigma = c_a/c_d. \tag{2}$$

In practice, the increase in production of an ozone generator is done by mounting *n* parallel identical tubes so the total electric capacities of the ozonizer are:

$$C_d = nc_d \text{ and } C_a = nc_a. \tag{3}$$

During the operation process with the alternating voltage $u_1(t)=\pm U_1$, on a voltage alternation, the author identified three functionally distinct time intervals:

-interval 1 (1^+ and 1^-)–the maximum electric field on the air space is below the air ionization level: the air space is *capacitive;*

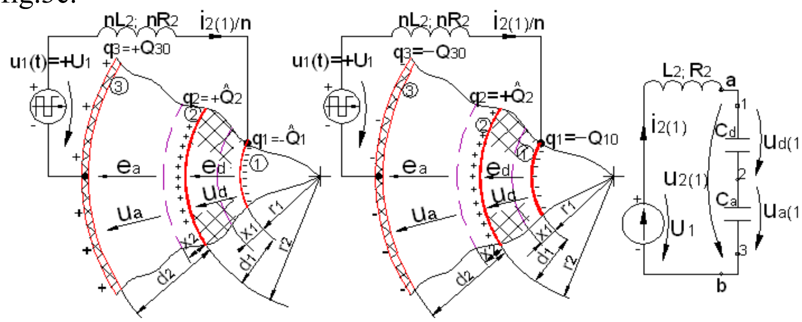
-interval 2 (2^+ and 2^-)–the maximum electric field on the air space is over the air ionization level: the air space *resistive;*

-interval 3 (3^+ and 3^-)–the corona electric discharge is carried out at the threshold voltage U_p=constant: the air space is an *ideal source of voltage* U_p.

2.2. The ozonizer operation analysis in the 1^+ interval below the corona discharge threshold $u_a<U_p$; $t=[0,\tau_1]$. The electric field in the tube dielectric and air space are (fig.3 a, b):

$$e_d(x_1,t) = \frac{q_1(t)}{2\pi(r_1+x_1)l\varepsilon_0\varepsilon_{rd}}; \; e_a(x_2,t) = \frac{q_1(t)+q_2(t)}{2\pi(r_2+x_2)l\varepsilon_0} \tag{4}$$

formulas valid on all intervals 1, 2 and 3. In interval 1, the maximum electric field in the air $e_a(0,t)$ is below the ionization level E_r: $|e_a(0,t)|<E_r$, so in the discharge space the conduction current is null, the equivalent diagram can be seen in fig.3c.



a) b) c)

Fig. 3. Representation of a sector of the ozone tube cross-section in the 1^+interval: a)-the electric state at the start of interval 1^+; b)-the electric state at the end of interval 1^+ and startof interval 2^+ ; c) the equivalent electric diagram of the ozonizer (*n* parallel tubes)

2.2.1. The voltage and current through the ozonizer.

$$u_2(t)=\int_{r_1}^{r_1+d_1} e_d(x_1,t)dx_1+\int_{r_2}^{r_2+d_2} e_a(x_2,t)dx_2=u_d+u_a=\frac{q_1(t)}{c_d}+\frac{q_1(t)+q_2(t)}{c_a}=\frac{q_1(t)}{c}+\frac{q_2(t)}{c_a} \qquad (5)$$

$$i_{2(1)}/n=dq_{1(1)}/dt=c\,du_{2(1)}/dt \quad ; \qquad (6)$$

Note 1. *Load* $q_2=+\hat{Q}_2=c_d\hat{U}_2-(c_a+c_d)U_p$ *=constant,* (7)

is the stationary space charge from the surface (2) of the dielectric;

Differential equation of the diagram ($R_2\approx 0$)(fig. 3c):

$$d^2u_{2(1)}/dt^2+\omega_1^2u_{2(1)}=\omega_1^2U_1 \qquad (8)$$

where: $\omega_1=1/\sqrt{L_2C}$ - the oscillating circuit's own angular frequency.

With the initial requirement that voltage $u_{2(1)}(0)=-\hat{U}_2$, these are obtained:

$$u_{2(1)}(t)=(U_1+\hat{U}_2)(1-\cos\omega_1 t)-\hat{U}_2;\ i_{2(1)}(t)=\hat{I}_{2(1)}\sin\omega_1 t \text{ with } \hat{I}_{2(1)}=C\omega_1(U_1+\hat{U}_2) \qquad (9)$$

2.2.2.The threshold voltage U_p at the corona discharge. The electric field in the discharge space is given by formula (4) where $(q_1+q_2)/c_a$ is substituted from relation(5)

$$e_{a(1)}(x_2,t)=\frac{u_{a(1)}}{(r_2+x_2)\ln(1+d_2/r_2)} \quad ; \qquad (10)$$

The gas discharge voltage is defined in the ionization electric field E_r – ***threshold voltage U_p,*** as a result of formula (10) at $x_2=0$:

$$U_p = |u_a(0)| = |u_a(\tau_1)| = g_0(T_0/T)(p/p_0)r_2 \ln(1 + d_2/r_2) \quad (11)$$

$g_0=3kV/mm$ –dry air; $g_0=2,8kV/mm$ –damp air; T- absolute temperature of the gas

$(T_0=273,15K)$; p-gas pressure in [atm.]($p_0=1atm$) (12)

2.2.3. The explicit expressions of the voltages on the dielectric, discharge space and of the current through the ozonizer. Relations (5) and (6) are obtained in a primary form, which substituted in (9) take a final, explicit form of the voltages and current through the ozonizer in interval 1.

$$U_1 + \widehat{U}_2 = \frac{2(\sigma+1)U_p}{1-\cos\omega_1\tau_1}\ ; \quad u_{d(1)}(t) = 2\sigma U_p \frac{1-\cos\omega_1 t}{1-\cos\omega_1\tau_1} - \widehat{U}_d\ ; \quad (13)$$

$$u_{a(1)}(t) = (2\frac{1-\cos\omega_1 t}{1-\cos\omega_1\tau_1} - 1)U_p;\ u_{2(1)}(t) = 2(1+\sigma)\frac{1-\cos\omega_1 t}{1-\cos\omega_1\tau_1}U_p - \hat{U}_2; \quad (14)$$

$$i_{2(1)}(t) = \widehat{I}_{2(1)}\sin\omega_1 t \quad \text{with}\ \hat{I}_{2(1)} = \left(2(1+\sigma)/(1-\cos\omega_1\tau_1)\right)\left(U_p/L_2\omega_1\right); \quad (15)$$

In relations (13), (14) and (15) the U_p voltage is a system parameter that remains constant for certain geometry of the ozone tube and certain gas environment con- ditions. The $\omega_1\tau_1$ angle, defined in the paper: ***corona starting angle,*** is a manda- tory variable, on which the system quantitie's values depend based on the interac- tion with the supply U_1 and threshold U_p voltage. The discharge break τ_1 must not exceed $T_1/4$; this means that the corona discharge has to start on the peak of the first alternation of $i_{2(1)}$, so this ***functional requirement 1***: $0,2<\omega_1\tau_1<1,5$ *rad* (16)

2.3. The ozonizer operation analysis in the 2⁺ interval over the discharge threshold: $U_a>U_p$; $t'=[0,\tau_2]$. At $t=\tau_1$ the corona discharge starting in the air space condition is fulfilled. The evolution of the electric quantities from the ozonizer tube has continuity when passing into interval 2^+ (fig. 4)

Fig. 5a presents the corona discharge process along with the space charge extraction $+\widehat{Q}_2$ under field $e_a>E_r$ and its substitution with $-\widehat{Q}_2$. During τ_2 the electric charge is transported on a radial direction in both ways, a electric conduction circuit (electronic and ionic) travels through the air space, so that the air space becomes mostly resistive (fig. 5b).

Functional requirement 2: *To simplify the calculations the following hypothesis is granted: at t'=0, when the corona discharge starts at threshold voltage U_p, in the air space the sudden passing from capacitive conduction to resistive conduction is done, so that the* ***air space is assimilated with an electric resistance R_a, which will be considered constant in τ_2 :***

$$R_a = \frac{U_p}{i_2(\tau_1)} = \sqrt{\frac{L_2}{\sigma(1+\sigma)C_d}}\,\frac{(1-\cos\omega_1\tau_1)}{2\sin\omega_1\tau_1} = constant \quad (17)$$

2.3.1. The current $i_{2(2)}(t)$ expression, has a sinus constricted form:

$$i_{2(2)}(t') = I_{2a(2)}e^{-\beta_2 t'} + I_{2s(2)}/\cos\varphi_{2i}e^{-\alpha_2 t'}\sin(\omega_2 t' + \varphi_{2i})\,; \quad \text{where} \quad (18)$$

$$I_{2a(2)} = \frac{\beta_2^2 I_{20(2)} - \beta_2 G + H}{(\alpha_2 - \beta_2)^2 + \omega_2^2} \quad - \text{ Aperiodic component;} \quad (19)$$

−Periodic component in sine

$$I_{2s(2)} = \frac{\left[(\alpha_2-\beta_2)(\omega_2^2-\alpha_2^2)-2\alpha_2\omega_2^2\right]I_{20(2)} + \left[\alpha_2(\alpha_2-\beta_2)+\omega_2^2\right]G - (\alpha_2-\beta_2)H}{\omega_2\left[(\alpha_2-\beta_2)^2+\omega_2^2\right]} \quad (20)$$

−Periodic component in cosine

$$I_{2c(2)} = \frac{\left[\omega_2(\omega_2^2-\alpha_2^2)+2\alpha_2\omega_2(\alpha_2-\beta_2)\right]I_{20(2)} + \omega_2\beta_2 G - \omega_2 H}{\omega_2\left[(\alpha_2-\beta_2)^2+\omega_2^2\right]}\,; \quad (21)$$

$$\varphi_{2i} = arctg\left(I_{2c(2)}/I_{2s(2)}\right);\ I_{20(2)} = 2(1+\sigma)\frac{\sin\omega_1\tau_1}{1-\cos\omega_1\tau_1}\frac{U_p}{L_2\omega_1}\,; \quad (22)$$

$$G = 2(1+\sigma)\frac{\cos\omega_1\tau_1}{1-\cos\omega_1\tau_1}\left(1+\frac{tg\omega_1\tau_1}{\omega_1 R_a C_a}\right)\frac{U_p}{L_2}\,;\ H = \frac{1+(1+2\sigma)\cos\omega_1\tau_1}{1-\cos\omega_1\tau_1}\frac{U_p}{L_2 R_a C_a} \quad (23)$$

$$\beta_2 = a/3 + 2v\sqrt{|p|}\cdot[\delta\cdot sh(\xi/3) + (1-\delta)\cdot ch(\xi/3)]\,; \quad (24)$$

$$\alpha_2 = a/3 - v\sqrt{|p|}\cdot[\delta\cdot sh(\xi/3) + (1-\delta)\cdot ch(\xi/3)]\,;$$

$\omega_2 = \sqrt{3|p|}[\delta\cdot ch(\xi/3) + (1-\delta)\cdot sh(\xi/3)]$; where ξ is an auxiliary variable:

$\xi = \delta\cdot arcsh\left(|q|/|p|\sqrt{|p|}\right) + (1-\delta)\cdot arcch\left(|q|/|p|\sqrt{|p|}\right)$, p and q have the expressions:

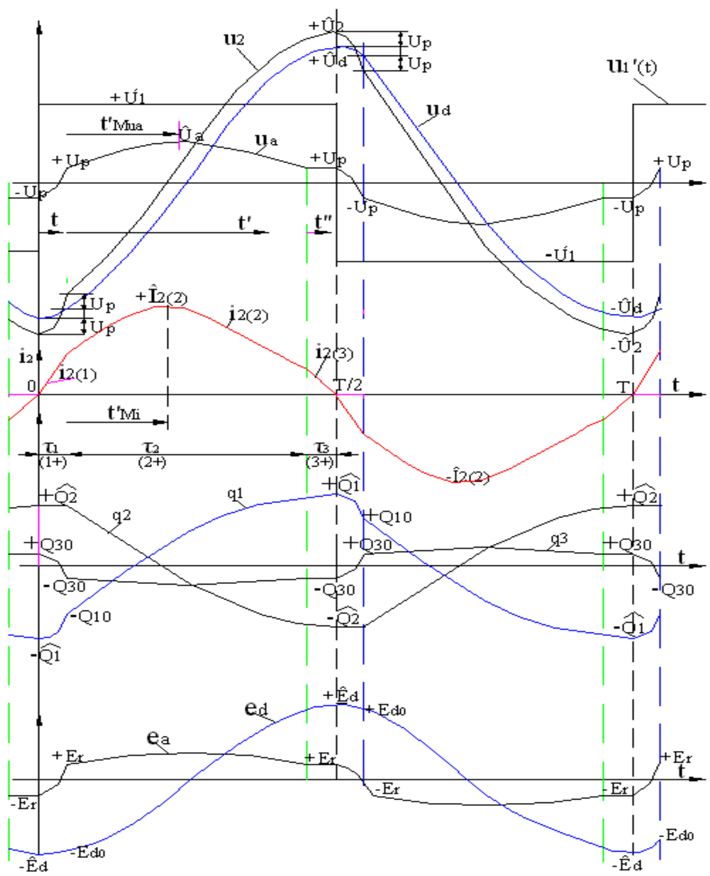
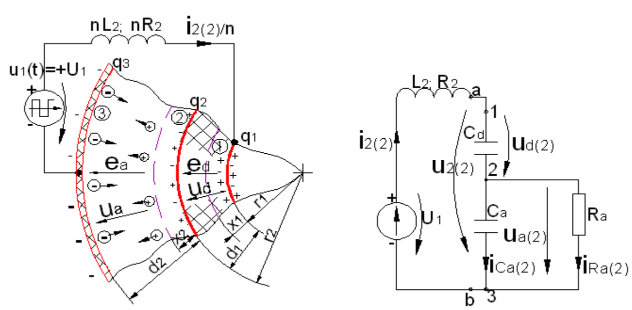


Fig. 4. Wave forms on a period, in stabilized regime, specific to the operation of the ozonizer with corona discharge



a) b)

Fig. 5. Representation of a sector of the ozone tube cross-section in interval 2^+: a) The corona discharge process with charge $+\widehat{Q}_2$ extraction and substitution with $-\widehat{Q}_2$; b) The electric diagram of the source-ozonizer system

$$p=\frac{b}{3}-\frac{a^2}{9};q=\frac{a^3}{27}-\frac{ab}{6}+\frac{c}{2};\text{ where:} \tag{25}$$

$$a=\frac{1+R_aC_aR_2/L_2}{R_aC_a};\quad b=\frac{1+C_a/C_d+R_2/R_a}{L_2C_a};\quad c=\frac{1}{L_2C_dR_aC_a} \tag{26}$$

In relations (24) variables v and δ cand take the following values depending on the p and q resulted from relations (25):

case 1	case 2	cases 3 and 4
$p>0\rightarrow\delta=1$	$p<0\,\&\,\lvert p\rvert^3<q^2\rightarrow\delta=0$	$p<0\,\&\,\lvert p\rvert^3=q^2 or$
$q>0\rightarrow v=+1 or$	$q>0\rightarrow v=+1 or$	$p<0\,\&\,\lvert p\rvert^3>q^2$
$q<0\rightarrow v=-1$	$q<0\rightarrow v=-1$	

(27)

Cases 1 and 2 have a practical interest because they generate a harmonic component of the angular frequency ω_2 current, damped with time constant $1/\alpha_2$ along with the aperiodic, transient, short time component with the time constant $1/\beta_2$ (rel. 18). Cases 3 and 4 generate aperiodic current as *beaks* and will not beanalysed in this paper.

2.3.2. The expression of the voltage $u_{d(2)}(t')$ on the dielectric (glass). It's obtained by directly integrating the expression of the current $i_{2(2)}(t')$,(relation 18), from which:

$$u_{d(2)}(t')=U_{d0(2)}+\frac{I_{2a(2)}}{\beta_2C_d}\left(1-e^{-\beta_2t'}\right)+\frac{I_{2s(2)}\cos^2\varphi_{2ud}}{\omega_2C_d}\cdot$$

$$\cdot\left[1+tg\varphi_{2ud}tg\varphi_{2i}-\frac{\cos(\omega_2t'+\varphi_{2i}-\varphi_{2ud})}{\cos\varphi_{2i}\cos\varphi_{2ud}}e^{-\alpha_2t'}\right];\text{ where } tg\varphi_{2ud}=r=\alpha_2/\omega_2 \tag{28}$$

2.3.3. The voltage $u_{a(2)}(t')$ on the air space. It's obtained from the differential equation resulted from the sum of the currents in node 2 (fig. 5b):

$$\frac{du_{a(2)}}{dt}+\frac{u_{a(2)}}{T_a}=\frac{I_{2a(2)}}{C_a}e^{-\beta_2t'}+\frac{I_{2s(2)}}{C_a\cos\varphi_{2i}}e^{-\alpha_2t'}\sin(\omega_2t'+\varphi_{2i});\text{ with the answer:}$$

$$u_{a(2)}(t')=U_pe^{-t'/T_a}+\frac{R_aI_{2a(2)}}{(1-\beta_2T_a)}\left(e^{-\beta_2t'}-e^{-t'/T_a}\right)+$$

$$+\frac{R_aI_{2s(2)}}{\left(1-\alpha_2T_a\right)}\frac{\cos\varphi_{2ua}}{\cos\varphi_{2i}}\left[e^{-\alpha_2t'}\sin(\omega_2t'+\varphi_{2i}-\varphi_{2ua})-e^{-t'/T_a}\sin(\varphi_{2i}-\varphi_{2ua}\right];\tag{29}$$

$$\text{where: } tg\varphi_{2ua} = \frac{\omega_2 T_a}{1-\alpha_2 T_a};\ T_a = R_a C_a \tag{30}$$

2.3.4. The current and voltage peaks on the air space in interval 2. The peaks are obtained when the respective quantity's derivative becomes null in interval 2.

a) Current peak $\widehat{I}_{2(2)}$: is obtained when $t_{Mi} >> T_a;1/\beta_2$:

$$\widehat{I}_{2(2)} = I_{2s(2)} \frac{\cos\varphi_{2ud}}{\cos\varphi_{2i}} e^{-r(\frac{\pi}{2}-\varphi_{2ud}-\varphi_{2i})}; \tag{31}$$

b) Voltage peak on the air space $\hat{U}_{a(2)}$: is obtained when $t'_{Mua} >> T_a;1/\beta_2$:

$$\hat{U}_{a(2)} = \frac{R_a I_{2s(2)}}{(1-\alpha_2 T_a)} \frac{\cos\varphi_{2ua}\cos\varphi_{2ud}}{\cos\varphi_{2i}} e^{-r(\frac{\pi}{2}+\varphi_{2ua}-\varphi_{2i}-\varphi_{2ud})} \tag{32}$$

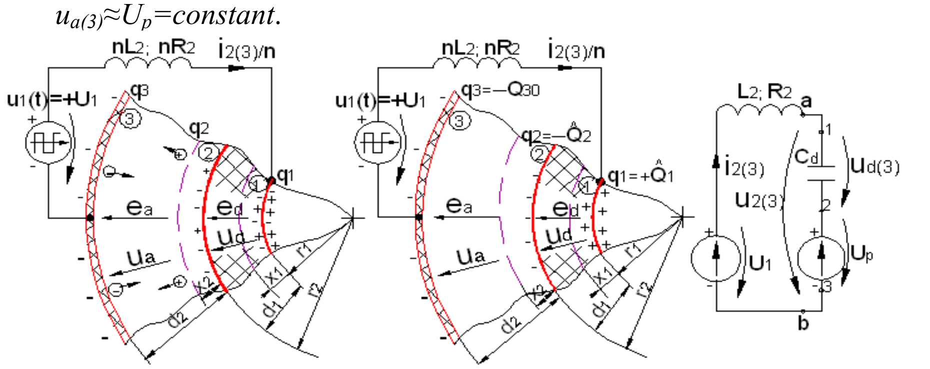
2.3.5. Determining period τ₂ of interval 2. Is obtained from the transcendental equation (33) which can be ***numerically*** answered:

$$u_{a(2)}(t')\big|_{t'=\tau 2} = U_p \tag{3}$$

2.4. The ozonizer operation analysis in interval 3⁺, at the limit of the corona discharge threshold: $u_a(t'')=U_p$. At the end of interval 2^+ the voltage on the discharge space reaches the threshold level U_p and has the tendency to drop to zero. Current $i_{2(3)}(t'')$ through the ozonizer evolves towards zero as well (fig.4).

In τ_3 the voltage on the air space maintains a pseudo-equilibrium:

$u_{a(3)} \approx U_p = constant$.



a) b) c)

Fig. 6. Representation of a sector of the ozone tube cross-section in interval 3^+.
a) the corona discharge process with extraction and accumulation of charge q_2; b) electric state at the end of interval 3^+ and start of interval 1^+; c) the electric diagram of the ozonizer in interval 3^+

2.4.1. Voltage $u_{d(3)}$ and current $i_{2(3)}$ through the dielectric. From the system diagram (fig.6c) where $R_2 \approx 0$, results the following differential equation and current:

$$\frac{d^2 u_{d(3)}}{dt''} + \omega_3^2 u_{d(3)} = \left(U_1 - U_p\right)\omega_3^2 \,;\; i_{2(3)} = C_d \frac{du_{d(3)}}{dt''} \text{ in care: } \omega_3^2 = 1/L_2 C_d \,; \quad (34)$$

The general answers are:

$$u_{d(3)}(t'') = \frac{\sum U_3}{\cos\varphi_{3i}} \cos\left(\omega_3 t'' + \varphi_{3i}\right) + U_1 - U_p \,;\; i_{2(3)}(t'') = \widehat{I}_{2(3)} \sin\left(\omega_3 t'' + \varphi_{3i}\right), \text{where} \quad (35)$$

$$\sum U_3 = \frac{I_{2a(2)}}{\beta_2 C_d} + \frac{I_{2s(2)}}{(1+r^2)\omega_2 C_d}\left[1 + r \cdot tg\varphi_{2i} - \frac{\cos(\omega_2\tau_2 + \varphi_{2i} + \varphi_{2ud})}{\cos\varphi_{2i}\cos\varphi_{2ud}} e^{-\alpha_2\tau_2}\right] - \frac{2(1+\sigma)\cos\omega_1\tau_1}{1-\cos\omega_1\tau_1} U_p \quad (36)$$

$$\widehat{I}_{2(3)} = -\frac{C_d \omega_3 \sum U_3}{\cos\varphi_{3i}} \,;\; I_{20(3)} = \frac{I_{2s(2)}}{\cos\varphi_{2i}} e^{-\alpha_2\tau_2} \sin\left(\omega_2\tau_2 + \varphi_{2i}\right);\; \varphi_{3i} = \pi - arctg \frac{I_{20(3)}}{C_d \omega_3 \sum U_3} \quad (37)$$

2.4.2. Duration τ_3 of interval 3. The voltage peak $\hat{U}_d$ on capacitor C_d

Duration τ_3 is determined by the passing of current *$i_{2(2)}(t'')$ through zero:*

$$i_{2(3)}(\tau_3) = \widehat{I}_{2(3)} \sin(\omega_3\tau_3 + \varphi_{3i}) = 0 \,;\text{ adica: } \tau_3 = \left(\pi - \varphi_{3i}\right)/\omega_3 \,; \quad (38)$$

Voltage peak $\hat{U}_d$ is obtained at the end of interval 3:

$$\widehat{U}_d = \frac{\sum U_3}{\cos\varphi_{3i}} \cos(\omega_3\tau_3 + \varphi_{3i}) + U_1 - U_p = -\frac{\sum U_3}{\cos\varphi_{3i}} + U_1 - U_p \,; \quad (39)$$

2.4.3. Expliciting the supply source voltage U_1, the voltage peak on the dielectric $\hat{U}_d$ and on the ozonizer $\hat{U}_2$. From relations (13) and (39) the algebraic equation system with variables *U_1 and $\hat{U}_2$* is obtained from which:

$$U_1 = \frac{(1+\sigma)U_p}{1-\cos\omega_1\tau_1} + \frac{\sum U_3}{2\cos\varphi_{3i}} \,;\; \widehat{U}_2 = \frac{(1+\sigma)U_p}{1-\cos\omega_1\tau_1} - \frac{\sum U_3}{2\cos\varphi_{3i}} \,;\; \widehat{U}_d = \widehat{U}_2 - U_p \quad (40)$$

2.5. The expressions of the electric and the tube's electric field charges on intervals 1,2 and 3. The expressions of the electric charges valid on the three intervals are obtained from relation (5) which takes separately into consideration the dielectric voltage *$u_d(t)$* and the air space voltage *$u_a(t)$*:

$$q_1(t) = c_d u_d(t) \,;\; q_2(t) = c_d[\sigma \cdot u_a(t) - u_d(t)] \,;\; q_3(t) = -(q_1 + q_2) = -c_a u_a(t) \quad (41)$$

The expressions of the electric field in the dielectric $e_d(x_1,t)$ and the air space $e_a(x_2,t)$ valid on the three intervals are obtained from relations (4):

$$e_d(x_1,t)=\frac{u_d(t)}{(r_1+x_1)\ln(1+d_1/r_1)}\ ;\ e_a(x_2,t)=\frac{u_a(t)}{(r_2+x_2)\ln(1+d_2/r_2)} \qquad (42)$$

In relations (41) and (42), $u_d(t)$ and $u_a(t)$ have corresponding expressions for each interval.

3. The ozone production mechanism on intervals 2 and 3

In intervals 2 and 3 the corona discharge takes place in the tube's air space moving on the tube's radial direction of the electrons (negative electric charges) in the opposite direction of field $e_a(t)$ and of the positive ions (positive electric charges) in the direction of the field $e_a(t)$. The electrons will be strongly accelerated by the field $e_a(t)$, because they have a specific charge (e/m) much bigger than the positive ions. The gas (air) under pressure of 0.2…0.6 atm., at normal temperature (20 – 25^{0}C) and well dried, can be ozonated through corona discharges, according to the equations[3]:

$$O_2+e\rightarrow 2O+e;\ \ M+O+O_2\rightarrow O_3+M \qquad (43)$$

from which can be observed that an oxygen molecule O_2 is dissociated by an accelerated electron *e* by the electric field $e_a(t)$, resulting 2 oxygen atoms and a free electron that will generate a new reaction type (43) because it's also accelerated; hence it's absolutely mandatory that oxygen atoms are obtained. Ozone O_3 is produced after reaction (43) in the presence of a type M molecule that could be nitrogen, O_2 or even the walls of the discharge tube.

4. General quantities of the source-ozonizer system

The quantities that describe the operation of the source-ozonizer system will be analysed, covering all three intervals.

4.1. Supply voltage period (frequency) –

$$T=2(\tau_1+\tau_2+\tau_3)\rightarrow f=1/T \qquad (44)$$

The system can be defined as a *autopilot system in frequency* and operating in voltage resonance meaning that the supply voltage $u_1(t)$ changes the direction simultaneously with the current from the main circuit $i_2(t)$.

4.2. Active power P_s from the alternating voltage source $u_1(t)$

$$P_s=\frac{2}{T}\int_0^{T/2}u_1 i_2(t)=\frac{2}{T}U_1\int_0^{T/2}i_2(t)dt=U_1\bar{I}_2 \ \text{ where} \qquad (45)$$

$$\bar{I}_2 = f\left\{4C_a U_p - 2C_d(\sum U_3)\left(1 + \frac{1}{\cos\varphi_{3i}}\right) + 2\tau_0 \sum_{k=1}^{m} i_{2(2)}\left[(k-0,5)\tau_0\right]\right\}; \qquad (46)$$

4.3. The R.M.S. current through the ozonizer

a) interval 1: $$I_{2(1)}^2 = \frac{2}{T}\hat{I}_{2(1)}^2 \int_0^{\tau_1} \sin^2 \omega_1 t dt = \frac{f}{2\omega_1}\hat{I}_{2(1)}^2 \left(2\omega_1\tau_1 - \sin 2\omega_1\tau_1\right); \qquad (47)$$

b) interval 2: $$I_{2(2)}^2 = 2f \cdot \tau_0 \sum_{k=1}^{m} i_{2(2)}^2\left[(k-0,5)\tau_0\right] \;;$$

c) interval 3: $$I_{2(3)}^2 = \hat{I}_{2(3)}^2 f\left(\pi - \varphi_{3i} + \sin\varphi_{3i}\cos\varphi_{3i}\right)/\omega_3 \;. \qquad (48)$$

The expression of the total r.m.s. current is:

$$I_2 = \sqrt{I_{2(1)}^2 + I_{2(2)}^2 + I_{2(3)}^2}\;; \qquad (49)$$

4.4. Active power cosumed by the ozonizer P_{oz}. It's obtained by integrating the instantaneaous power received from the a-b terminals by the ozonizer on a semi-period T/2.

a) Active power consumed in the air space.

$$P_{a(1)} = \frac{2}{T}\left[\int_0^{\tau 1} \hat{I}_{2(1)}(\sin\omega_1 t)U_p\left(2\frac{1-\cos\omega_1 t}{1-\cos\omega_1\tau_1} - 1\right)dt\right] = 0\;; \qquad (50)$$

This means in interval 1, the air space DOES NOT consume active power, because it has a purely capacitive behaviour.

$$P_{a(2)} = \frac{2}{T}\int_0^{\tau_2} u_{a(2)}(t')i_{2(2)}(t')dt' = \frac{2}{T}\tau_0 \sum_{k=1}^{m} u_{a(2)}\left[(k-0,5)\tau_0\right]\cdot i_{2(2)}\left[(k-0,5)\tau_0\right] \neq 0 \quad (51)$$

Where $u_{a(2)}(t')$ comes from relation (29) and $i_{2(2)}(t')$ from relation (18).

$$P_{a(3)} = \frac{2U_p \hat{I}_{2(3)}}{\omega_3 T}\left(1 + \cos\varphi_{3i}\right) \neq 0 \;\;; \qquad (52)$$

b) Active power consumed in the dielectric P_d:

$$P_d = \frac{2}{T}\int_0^{T/2} u_d i_2 dt = \frac{2}{T}C_d \int_{-\hat{U}_d}^{+\hat{U}_d} u_d du_d = \frac{2C_d}{T}\left(\hat{U}_d^2 - \hat{U}_d^2\right) = 0\;; \quad (53)$$

This means the dielectric DOES NOT consume active power, with the exception of the leaks in the dielectric, which are practically negligible.

In conclusion the ozonizer consumes active power only on the air space and only during the corona discharge process:

$$P_{oz} = P_a = P_{a(2)} + P_{a(3)}\;; \qquad (54)$$

5. Results

Based on this study, the theoretical results and the calculation formulae established in chapters 2 and 4, the main electric parameters of a cylindric geometry ozone generator have been calculated, with practical development perspectives.

a) Nominal electric charecteristics:

•nominal voltage peak: $\hat{U}_2=17kV$ (adjustable: *4… 20kV* at peak); •frequency: $f=1000Hz$; •voltage/current regime: deforming sinusoidal;

b) Electric parameters of the i.t. source- ozonizer system (n=15tubes):

$C_d=41,5nF$; $C_a=16,3nF$; $L_2=0,63H$; $R_2=40\Omega$. Fig. 7 presents the graphs for the computed (theoretical) values of the ozonizer's main parameters in terms of the supply voltage U_1 from the high voltage source at $U_p=1,05kV$.

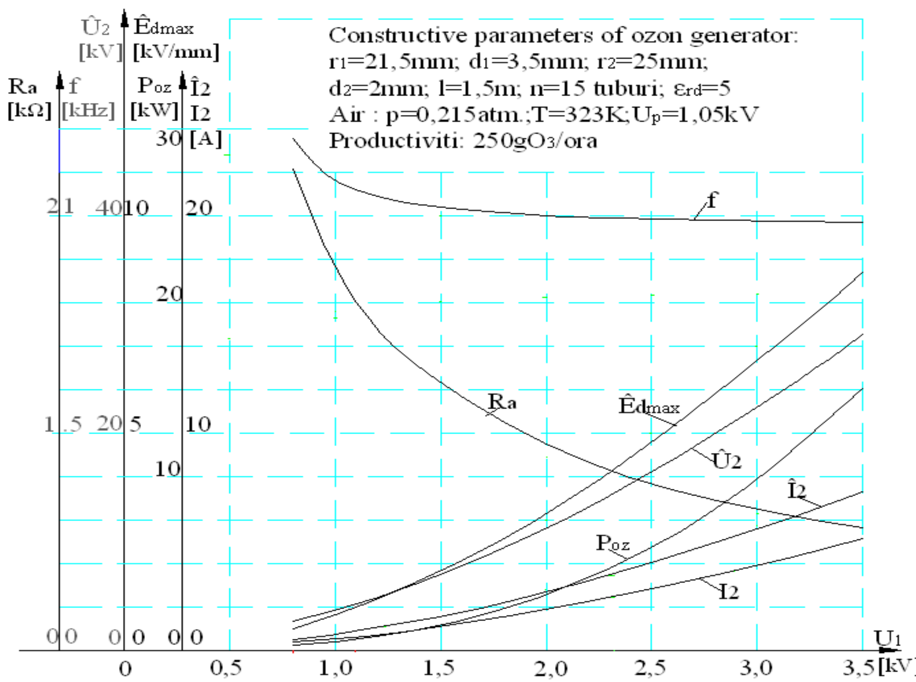


Fig.7. Cylindric geometry ozonizer's main electric quantities, in terms of supply source voltage U_1

6. Conclusions

1. The design of the non linear mathematical model used to describe the system's behaviour belongs entirely to the author of this paper and proved to be essential to understand the various phenomenons and demands which appear in the

ozone tube during the corona discharge; the degeneration of the corona discharge in electric arc inevitably leads to the penetration of the dielectric i.e. the destruction of the ozonizer tube.

2. According to the operating principle addressed in the paper, a few functional requirements have been established by the author of this paper, that lead to the improvement of the source and the ozonation process:

   a) The physical-electric (structural) parameters of the ozonizer connected to the high voltage source must allow operation in damped oscillatory regime;

   b) The ozonizer current and voltage have a deforming sinusoidal shape that ensure a corona discharge duration of 75…85% out of a supply voltage period;

   c) The alternating high voltage supply source operates in voltage resonance with the ozonizer, i.e. the voltage and the current at the terminals of the source are in phase, resulting a maximum source efficiency;

   d) During the corona discharge (interval 2) the air space is assimilated with resistance $R_a=U_p/i_2(\tau_1)$ *=constant, which is easy to determine.*

3. The author has elaborated the mathematical realations that simulate the operation of the ozonizer on the three intervals, without estimations, cropping or eliminating apparently negligible quantities.
4. If the discharge characteristics $i_2=f(u_a)$ is determined, the non-linear mathematical model proposed allows the exact simulation of the ozonizer's operation.
5. Based on the non-linear model characterized by the three intervals, the author elaborated mathematical relations equivalent with *RC* series linear model, absolutely necessary to identify the dimensions of the ozonizer and h. v. source.

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